Use of Hand-Held Radiometers to Evaluate the Cover and Hydrologic Characteristics of Semiarid Rangelands

DONALD F. POST
E. SCOTT MARTIN

Department of Soil, Water, and Environmental Science
University of Arizona
Tucson, Arizona, USA

J. R. SIMANTON

U.S. Department of Agriculture
Southwest Watershed Research Center
Agricultural Research Service
Tucson, Arizona, USA

E. E. SANO

Embrapal (Empresa Brasileira de Pesquisa)
Agropecvária Ministério da Agricultura, Brazil

The spectral reflectance characteristics of 11 rainfall simulator plots were measured with a hand-held radiometer on semiarid rangeland surfaces, of the U.S. Department of Agriculture, Agricultural Research Service, Walnut Gulch Experimental Rangeland Watershed, Tombstone, Arizona. Rainfall simulations were made in May and June 1984 for plots characterized by natural vegetation, natural vegetation clipped and removed, and natural vegetation clipped and rock fragments >5 mm removed. In 1994, reflectance and cover data were collected on the same plots to evaluate changes over time. Measurements were taken at 38–43° and 74–77° sun elevation angles with a four-band hand-held radiometer (blue 0.45–0.52 μm, green 0.52–0.60 μm, red 0.63–0.69 μm, and near-infrared 0.76–0.90 μm). Correlation and regression relationships were computed between spectral reflectance and percent soil, rock, and vegetative cover; percent runoff; and eroded sediments. Highly significant correlations were measured between vegetative cover and percent runoff; relationships with soil-rock cover and eroded sediment were poorly correlated. The normalized difference vegetation index (NDVI) was the best predictor of percent vegetative cover, with shrubs-forbs being most strongly correlated to reflectance. The regression relationships between 1984 and 1994 spectral reflectance and vegetative cover were very different, even though cover percentages were similar. The amount of standing live and dead biomass and the proportion of green biomass strongly affect spectral reflectance, and the 1984 and 1994 conditions were quite different. Spectral

Received 20 July 1998; accepted 14 October 1998.
The authors thank the field staff at the Walnut Gulch Experimental Watershed for their assistance in the rainfall simulation experiments, and Ms. Georgia Turner in collection of the 1984 reference data.
Address correspondence to Prof. Donald F. Post, Department of Soil, Water, and Environmental Science, Room 429 Shantz Bldg., University of Arizona, Tucson, AZ 85721, USA. E-mail: postdf@ag.arizona.edu.

Arid Soil Research and Rehabilitation, 13:201–217, 1999

0890-3069/99 $12.00 +.00

reflectance data can be used to predict rangeland cover characteristics, which in turn, can be used to determine parameters needed for models that predict hydrologic processes on rangeland surfaces.

Keywords erosion-runoff, rainfall simulation, rangeland cover, spectral reflectance, vegetation index

The spectral, spatial, and temporal characteristics of remotely sensed data make these data useful for evaluating the properties of rangelands, and they may have potential for modeling hydrologic processes that occur on these landscapes. The Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978), Revised USLE (RUSLE) (Renard et al., 1997), Water Erosion Prediction Project (WEPP) (Foster & Lane, 1987; Nearing & Lane, 1989), and models that evaluate water storage and fluxes at local and regional scales (Moran et al., 1994) require soil information and cover data as inputs. Many researchers have identified vegetation as a dominant factor affecting erosion and runoff from rangelands (Packer, 1953; Rauzi et al., 1968; Meeuwig, 1970; Blackburn, 1975, 1984, 1978; Blackburn et al., 1986).

This research had the following objectives:

1. Evaluate the usefulness of spectral reflectance data, collected with hand-held radiometers, to predict the soil, rock, and vegetative cover on semiarid rangeland surfaces.
2. Determine which individual spectral bands and vegetation indices are most strongly correlated to vegetative cover, soil properties, runoff, and erosion.

Blackburn and Pierson (1994) state that societal demands for environmentally sustainable management practices and the growing trend to fulfill these demands through increased regulation require improved erosion prediction technology for rangelands. The USLE, and more recently, the RUSLE, are the predictive models; however, these models have limitations (Wischmeier, 1976; Foster et al., 1981; Foster 1982, and others). The WEPP (Laflen et al., 1991) was initiated to develop a state-of-the-art model for prediction of erosion from croplands and rangelands. Blackburn and Pierson (1994) state that this technology for modeling erosion processes on rangelands has improved through greater model complexity, but much of the improvement in simulation accuracy is lost in techniques used to estimate model parameters.

Blackburn et al. (1990, 1992), Wilcox et al. (1992), Wood et al. (1994), and Simanton and Emmerich (1994) further show that the estimation of model parameters for rangelands is also hampered by significant spatial and temporal variations in the erosion process. Laflen et al. (1994) discuss in detail the WEPP model and its applicability (shortcomings and advantages) for predicting erosion on rangelands. They concluded that its major limitations on rangelands are accurate representation and parameterization of rangeland soils, surfaces, and ecosystems. Kustas and Goodrich (1994) state the need for an accurate characterization and quantification of the components of the hydrologic cycle and surface energy balance to advance our understanding and ability to model land surface and climatic interactions. These authors coupled remotely sensed data and traditional measurements to study semiarid rangelands.

Huete and Escadafal (1991) and Horvath et al. (1984) used these "noninvasive" remote sensing techniques to make predictions about land for evaluating soil properties and for making vegetative cover estimations or other predictions. This is accomplished with measurements of electromagnetic radiation emitted and reflected from the earth's surface. The spectral composition and intensity of this energy are then related to features of the earth's surface, such as soil, vegetation, and other biophysical properties. The spectral reflectance in the visible and near-infrared (NIR) portions of the electromagnetic spectrum are used to monitor vegetation and compute various spectral indices (Tucker, 1979).

Three indices are commonly used to evaluate vegetation, particularly the photosynthetically active biomass; however, they may also have applications related to biodiversity, wind, and water erosion processes. They are the NIR to red ratio vegetation index (RVI), the normalized difference vegetation index (NDVI), and the soil adjusted vegetation index (SAVI). Huete and Jackson (1987), Huete (1988), and Tueller and Oleson (1989) discuss the suitability of spectral indices for evaluating vegetation characteristics on arid rangelands. Huete and Jackson (1988) further studied the affects of soil and atmospheric influences on the spectra of partial canopies. The RVI and NDVI were significantly different over darker soils, and less detectable changes were noted with the same canopies over light colored soils. They further concluded that SAVI is the better index to use when soil backgrounds are more variable. Vegetation indices are commonly used to evaluate the photosynthetically active biomass; however, in arid regions the nonphotosynthetically active vegetation (litter, bark) and soil background greatly affect vegetation indices. The relationships between vegetation indices and soil-plant biophysical parameters need to be validated and calibrated for different vegetative cover conditions.

Van Leeuwen (1995), Van Leeuwen and Huete (1996), and Van Leeuwen et al. (1994) studied a shrub savannah landscape in Niger, Africa, and reported how standing dead vegetation and soil backgrounds affect these indices. They concluded that the reflectance characteristics were a function of sun and view geometry, and both the soil and vegetation had anisotropic reflectance properties. Also, in spectral characteristics, leaf litter resembled soil, and the amount and vertical distribution of the nonphotosynthetic biomass and green vegetation were shown to be equally important in controlling the response of spectral vegetation indices. They further reported that biophysical plant parameters (leaf area index and photosynthetically active biomass) tended to be overestimated for randomly distributed, sparse green and litter vegetation cover mixtures, while these parameters tended to be underestimated for randomly distributed, dense green vegetation and litter cover. All spectral indices and their interpretations were significantly altered by the optical properties of the green leaf, leaf litter, and plant bark; the position of standing leaf litter; leaf angle distribution; and soil background. The NDVI response to these variables was inconsistent but was strongly affected by the nonphotosynthetic biomass.

Huete and Jackson (1987) studied mixtures of live and senesced grass and found the greatest variation occurred in the red spectral band, whereas the NIR signal showed little variation. They reported a higher red reflectance factor as a function of greater dry biomass. Lumbuenamo (1987) studied the spectral behavior of various mulched soils and reported that dead grass, like soil, exhibits a high red reflectance in comparison to green vegetation. He stated that the red signal variation was also a function of the brightness of the underlying background. A layer of mulch of a given brightness would increase the red reflectance of darker backgrounds and decrease it over the brighter ones. For nongrazed vegetation stands the brightness portion is the protruding dry phytomass. Apparently, the red signal bounces off the canopy's surface, but the NIR penetrates deeper and gets trapped or reoriented. Vegetation indices are expected to be good predictors of green, photosynthetically active biomass; however, the presence of standing dead or dormant vegetation, litter, and different soil backgrounds found on semiarid rangelands greatly affects these indices.

Materials and Methods

Rainfall simulator plots located on the Walnut Gulch Experimental Rangeland Watershed near Tombstone, Arizona (31°43′N, 110°41′W), were utilized for this study. This watershed is representative of brush and grass rangelands found throughout the semiarid Southwest and occurs in a transition zone between the Chihuahuan and Sonoran Deserts. The average annual precipitation is 320 mm, bimodally distributed, with 60–70% occurring during the summer thunderstorm season of July to mid-September. Three sites were selected that had different soil and vegetation complexes. The soil series and taxonomic classification of the soils were McAllister (fine-loamy, mixed, thermic Ustic Calciargid), Stronghold (coarse-loamy, mixed, thermic Ustic Haplocalcid), and Sutherland (loamy-skeletal, mixed, thermic, shallow Ustic Petrocalcid). These soils are well drained, and the surface horizons are calcareous gravelly sandy loams with a large percentage of rock fragments on the surface. Major vegetation includes the shrub-forb species of creosote bush [*Larrea tridentata* (de Candolle) Cov.], whitethorn (*Acacia constricta* Benth.), tarbush (*Flourensia cernua* de Candolle), snakeweed [*Gutierrezia sarothrae* (Pursh) Britton & Rusby], and burroweed [*Aplopappus tenuisectus* (Greene) Blake]; and grass species of black grama [*Bouteloua eriopoda* (Torr.) Torr.], blue grama [*B. curtipendula* (Michx.) Torr.], bush muhly (*Muhlenbergia porteri* Scribn.), and Lehmann lovegrass (*Eragrostis lehmanniana* Nees von Esenbeck).

The procedures used in this study are described by Simanton and Renard (1986) and included the use of a rotating boom rainfall simulator (Swanson, 1965). Rainfall simulations were made in May and June 1984 on plots 10.7 m long by 3.05 m wide, where slopes ranged from 8 to 11%, with three treatments under three soil moisture conditions: dry (existing soil moisture condition), wet (field capacity), and very wet (saturated). The rainfall intensities used ranged from 54 to 60 mm h^{-1}, and the rain was applied for 1 h on the dry condition and 30 min for the wet and very wet conditions. The treatments were natural cover (control), clipped (vegetation clipped to a 20-mm height, and clippings removed), and bare (vegetation clipped at the soil surface, and all clippings, surface litter, and rock fragments >5 mm removed). Ten 3.05-m-long line transects, placed perpendicular to each plot and equally spaced along the plot, were measured to produce 490 point readings of cover per plot. The material that made the initial contact with the pin-point was noted, and the following cover categories were recorded: rock (>20 mm), gravel (5–20 mm), bare soil (<5 mm), litter, grass, shrubs, and forbs. Percent vegetative cover included the sum of the litter, grass, shrubs, and forbs identified on each plot, and for this study, shrubs and forbs were combined. Litter in this paper refers to dead organic materials lying on the soil surface. The color (hue, value, and chroma) of the <5 mm soil fractions for each plot transect were measured using a Chromameter (Post et al., 1993), and percent sand (0.05–2 mm) was determined by wet sieving (Gee & Bauder, 1986).

Reflected incident radiation was measured on each plot in May and June of 1984 and 1994. The measurements were made for dry plot conditions only (prior to rainfall simulation) with a portable Exotech Model 100AX, four-channel radiometer with bandwidths in the blue (0.45–0.52 μm), green (0.52–0.60 μm), red (0.63–0.69 μm), and NIR (0.76–0.90 μm). The radiometer had a 15° field of view, and it was held vertically by hand approximately 1 m above the soil surface. Five dry reflectance readings were taken over the same line transects where the plot cover data were collected, giving a total of 50 readings per plot. An individual index was computed using the mean band reflectances for each plot transect; the indices were computed for these means, and then a plot mean was computed by averaging the 10 transect data per plot. Two separate measurements were taken between 0830 and 1030 h (Mountain Standard Time) at sun elevation angles of 38–43° and 74–77° to evaluate the effect of sun angle on spectral reflectance. Reflectance readings were collected on cloudless days with low relative humidity, and irradiance was measured using a barium sulfate reference plate to standardize the reflectance measurements.

The individual bands, the sum of the four bands, and three vegetation indices were used to evaluate relationships between the percent vegetative cover, percent runoff, and grams of sediment eroded on each plot. The vegetation indices were calculated as follows:

$$\mathrm{RVI} = (\mathrm{NIR})/\mathrm{Red}$$

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red})$$

$$\mathrm{SAVI} = [(\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red} + 0.5)] \times 1.5$$

Correlation coefficients plus simple and multiple linear regression analyses were calculated to determine the relationship between the hand-held radiometer data and rangeland surface characteristics, percent runoff, and sediment eroded from each plot.

Results and Discussion

Correlations Between Spectral Reflectance Data and the Properties of Semiarid Rangeland Surfaces

Tables 1 and 2 list the plot cover characteristics and spectral reflectance data for 1984 and 1994. Post et al. (1994) reported that the reflectance of radiant energy from the earth's surface in sparsely vegetated rangelands is mostly determined by the color of soil and geologic materials. Therefore the hue, value, and chroma color characteristics and percent sand were also determined, and these data are included in Table 1.

Simple linear correlations were computed to evaluate relationships for the six data sets listed below:

- mean characteristics of the plots in 1984 ($n = 11$)
- mean characteristics of the plots in 1994 ($n = 11$)
- individual plot transects in 1984 ($n = 107$)
- individual plot transects in 1994 ($n = 110$)
- individual plot transects in 1984 for natural plots ($n = 47$)
- individual plot transects in 1984 for bare and clipped plots ($n = 60$)

(Note: There were three missing transect data in 1984, making a total of 107 rather than 110 transects.) A correlation matrix was computed for each data set, and all significant correlations ($P > 0.05$) were noted ($r > 0.60$ for the mean of the 11 plots, $r > 0.20$ for 107 and 110 transects, $r > 0.29$ for 47 transects, and $r > 0.25$ for

TABLE 1 Plot cover characteristics, soil properties, and spectral reflectance data for 1984

	Percent cover						Soil properties				38–43° Reflectance				74–77° Reflectance			
Plot	Rock	Gravel	Soil	Litter	Grass	Shrubs-forbs	Hue[a]	Value	Chroma	Percent sand	Blue	Green	Red	NIR	Blue	Green	Red	NIR
McB	3	0	97	0	0	0	3.67	3.68	2.76	79.2	.066	.144	.183	.244	.087	.160	.208	.279
McC	19	28	53	0	0	0	3.69	3.78	2.93	83.1	.070	.175	.189	.291	.097	.176	.225	.297
McN1	8	5	8	1	58	20	3.73	3.66	2.85	81.6	.053	.119	.116	.218	.079	.126	.145	.228
McN2	8	7	13	0	27	45	3.74	3.67	2.78	82.3	.039	.101	.099	.235	.062	.113	.126	.233
StB	3	0	97	0	0	0	3.95	4.22	1.72	60.7	.071	.119	.140	.176	.113	.155	.188	.239
StC	22	28	48	2	0	0	3.94	4.30	1.85	76.5	.081	.131	.151	.199	.137	.182	.223	.285
StN1	10	12	8	0	48	22	4.00	3.94	1.69	75.1	.051	.095	.101	.202	.093	.141	.163	.261
StN2	11	8	9	1	52	19	4.02	3.98	1.75	69.7	.051	.101	.109	.205	.100	.144	.166	.263
SuB	6	0	94	0	0	0	4.31	4.88	2.19	68.7	.109	.173	.214	.258	.139	.198	.238	.296
SuC	15	22	60	3	0	0	4.35	4.89	2.22	71.7	.125	.185	.221	.261	.150	.207	.242	.294
SuN	11	13	24	3	10	39	4.35	4.59	2.14	64.8	.068	.120	.120	.226	.079	.123	.129	.247

McB, McAllister bare; McC, McAllister clipped; McN1, McN2, McAllister natural; StB, Stronghold bare; StC, stronghold clipped; StN1, StN2, stronghold natural; SuB, Sutherland bare; SuC, Sutherland clipped; SuN, Sutherland natural.

[a] Code for hue: 3.0, 5YR; 4.0, 7.5YR; 5.0, 10YR (Post et al., 1993).

TABLE 2 Plot cover characteristics and spectral reflectance data for 1994

	Percent cover						38–43° Reflectance				74–77° Reflectance			
Plot	Rock	Gravel	Soil	Litter	Grass	Shrubs-forbs	Blue	Green	Red	NIR	Blue	Green	Red	NIR
McB	14	52	15	0	11	8	.088	.135	.197	.255	.098	.153	.214	.293
McC	13	21	0	0	45	21	.076	.101	.131	.162	.081	.108	.135	.179
McN1	8	19	3	0	32	38	.063	.087	.106	.138	.067	.090	.109	.161
McN2	4	9	1	1	25	60	.052	.075	.080	.130	.056	.079	.085	.149
StB	27	32	1	0	32	8	.140	.168	.215	.255	.067	.179	.212	.285
StC	21	27	1	1	28	22	.112	.148	.154	.222	.109	.140	.165	.210
StN1	9	18	1	1	47	24	.081	.103	.114	.175	.093	.123	.134	.182
StN2	9	14	3	1	54	19	.094	.107	.132	.186	.092	.119	.136	.182
SuB	24	52	8	1	3	12	.142	.199	.231	.273	.147	.203	.212	.283
SuC	15	42	3	0	7	33	.115	.165	.187	.223	.101	.165	.183	.231
SuN	7	14	2	4	13	60	.081	.108	.108	.152	.105	.105	.115	.169

See Table 1 footnote for plot abbreviations.

TABLE 3 Correlations between spectral reflectance data and properties of semiarid rangeland surfaces

Spectral band vegetative index	Sun angle	Rock	Gravel	Soil	Litter	Grass	Shrubs-forbs	Vegetative cover	Hue	Value	Chroma	Percent sand
Blue	38–43°	NS	NS	SM^+	SM^+	ST^-	ST^-	ST^-	ST^+	ST^+	NS	SM^-
	74–77°	SM^+	SM^+	SM^+	SM^+	$SM^\pm$	ST^-	ST^-	SM^+	ST^+	SM^-	SM^-
Green	38–43°	NS	NS	SM^+	NS	ST^-	ST^-	ST^-	SM^+	SM^+	SM^+	NS
	74–77°	SM^+	SM^+	SM^+	NS	ST^-	ST^-	ST^-	SM^+	ST^+	NS	NS
Red	38–43°	NS	NS	SM^+	NS	ST^-	ST^-	ST^-	SM^+	SM^+	SM^+	NS
	74–77°	SM^+	SM^+	SM^+	NS	ST^-	ST^-	ST^-	SM^+	SM^+	NS	NS
NIR	38–43°	NS	NS	SM^+	NS	SM^-	NS	NS	NS	NS	ST^+	SM^+
	74–77°	SM^+	SM^+	SM^+	NS	NS	SM^-	ST^-	SM^+	SM^+	$SM^\pm$	SM^+
Brightness	38–43°	NS	NS	ST^-	NS	ST^-	ST^-	ST^-	SM^+	SM^+	SM^+	NS
	74–77°	SM^+	SM^+	ST^-	NS	SM^-	ST^-	ST^-	SM^+	SM^+	NS	NS
RVI	38–43°	NS	NS	SM^-	NS	ST^+	ST^+	ST^+	SM^-	SM^-	NS	SM^+
	74–77°	NS	NS	ST^-	NS	ST^+	ST^+	ST^+	NS	SM^-	NS	NS
NDVI	38–43°	NS	NS	SM^-	NS	ST^+	ST^+	ST^+	SM^-	SM^-	NS	SM^+
	74–77°	NS	NS	ST^-	NS	SM^+	ST^+	ST^+	NS	SM^-	NS	NS
SAVI	38–43°	NS	NS	ST^-	NS	ST^+	ST^+	ST^+	SM^-	SM^-	SM^+	SM^+
	74–77°	NS	NS	SM^-	NS	SM^+	ST^+	ST^+	NS	SM^-	NS	NS

NS, none to slight correlation (0 or 1 significant correlations among six data sets); SM, slight to moderate correlation (2, 3, or 4 significant correlations among six data sets); ST, strong correlation (5 or 6 significant correlations among six data sets).

$^+$ Positive relationship, $^-$ negative relationship, $^\pm$ both positive and negative relationships.

60 transects). This approach evaluated the very different conditions of bare plots versus the natural plots and also represented an averaging of reflectances when using the mean data for each plot.

These correlations between spectral reflectance data and surface cover properties and selected soil characteristics are summarized in Table 3. The following categories were developed to interpret the results. If there were none or one significant correlation among the six data sets, the NS notation was used (none to slight); if there were two, three, or four significant correlations, the SM notation was used (slight to moderate); and if five or six of the data sets showed a significant correlation, ST was noted (strong). Also, the relationships were identified as being positive, negative, or both.

The obvious conclusion is that grass, shrubs-forbs, and total vegetative cover are strongly correlated to reflectances for the individual bands, the sum of the bands, and the three vegetation indices. An exception is the NIR band and some 74–77° sun angle data, which showed a poor correlation. Rock and gravel cover had SM correlations for the 74–77° sun angles for the individual bands, but the correlations were NS at the 38–43° sun angles. Soil had an SM positive correlation with the four bands, and it was ST correlated to the sum of the bands and either ST or SM correlated with the vegetation indices. Hue and value color components were SM or ST correlated to the blue, green, and red individual bands; but again, there was a poor correlation to the NIR band, but in this case for the 38–43° sun angle. Litter, chroma, and percent sand mostly had NS correlations with individual bands and the vegetation indices. Note that the vegetation variables were negatively, and the soil properties positively, correlated to the individual bands. The 74–77° sun angles also were more positively correlated to the nonvegetative variables, and the 38–43° sun angles were better for the vegetative parameters.

Relations Between Spectral Reflectance and Vegetative Cover

Table 1 lists the spectral reflectance data for 1984. The mean 38–43° reflectances for the three bare and three clipped plots in 1984 were 0.179 and 0.187, and 0.226 and 0.250 for the red and NIR, respectively. The five natural plots had mean red and NIR reflectances of 0.109 and 0.217, respectively. This equals a mean NDVI of 0.117 for the bare, 0.144 for the clipped, and 0.311 for the natural plots. Figure 1 is a plot of the regression relationship between the NDVI and percent vegetative cover for 1984 and 1994. All three vegetation indices were strongly correlated to the percent vegetative cover; however, the NDVI had a slightly better correlation coefficient than the SAVI or RVI indexes, but it was not a significant difference. Clearly, the NDVI values for the vegetated plots are lower in 1994. The bare and clipped plots in 1984 had a similar NDVI to plots in 1994, which had significant amounts of vegetative cover. We interpret these data as explained below.

Reflected energy is greatly affected by the quantity of standing biomass. The percent cover measurements in this study did not evaluate standing biomass; only the first "hit" was noted, even though an extensive understory of vegetation could be present. Van Leeuwen (1995), Van Leeuwen and Huete (1996), and Van Leeuwen et al. (1994) concluded that vegetation indices in semiarid regions are sensitive to photosynthetically active vegetation, nonphotosynthetically active vegetation (litter, bark), and soil background, which controls the radiative interaction among these components. In 1984 the natural plots were protected from grazing, and the rainfall

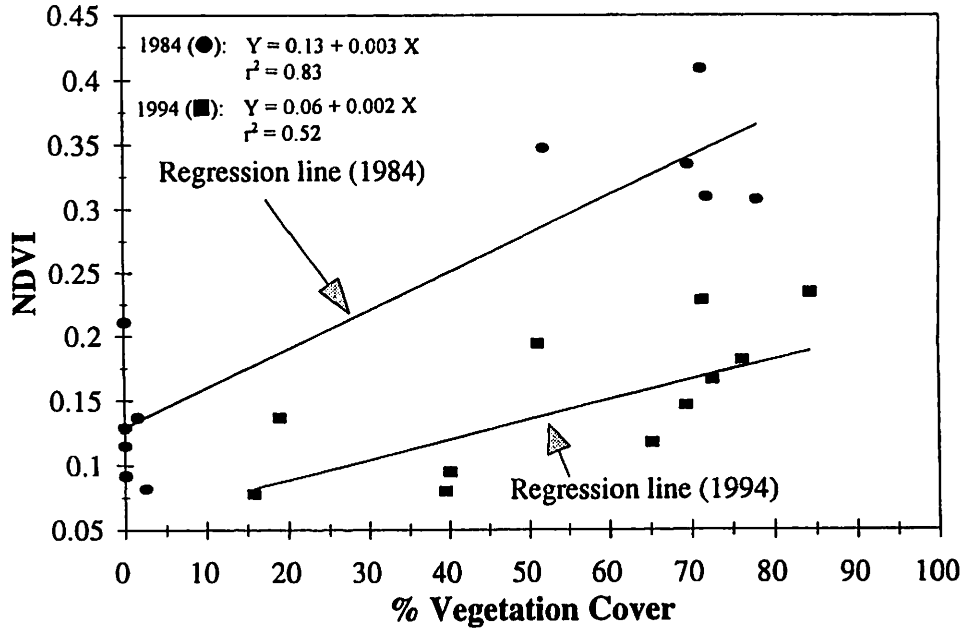

FIGURE 1 Relationship between the Normalized Difference Vegetation Index (NDVI) and percent vegetative cover, 1984 and 1994 plot data, 38–43° sun angle.

simulation studies completed in 1983 provided additional rainfall. Thus the aboveground biomass was large, and it was also slightly "greener," contributing to an increased NIR reflectance. The 1994 percent covers for the five natural plots were very similar to 1984 (Tables 1 and 2), yet the single-band reflectances and NDVI were quite different. This suggests that both percent cover and amount of biomass should be evaluated to best understand and interpret spectral reflectance data. Also, the interaction of radiant energy with standing biomass (photosynthetically active and nonphotosynthetic), litter, soil, rock, and gravel needs to be better understood to correctly interpret remotely sensed data.

Multiple linear regression equations in Table 4 show how the relationships between spectral reflectance and vegetative cover vary among the different data sets. If the plot means are used [Eqs. (1) and (6)], excellent R^2 are noted; however, in 1984 the NDVI index was the best predictor ($R^2 = 0.81$), but in 1994 the red band ($R^2 = 0.84$) was selected. When 1984 transect data for the natural plots were evaluated [Eq. (2)], the R^2 was poor and the NDVI was not in the regression equation; but it was significant when all transect data were included [Eq. (3)]. The R^2 for the 110 transects in 1994 [Eq. (7)] were much better, and brightness ($R^2 = 0.65$) was most significant, and NDVI again was not a part of the model. Equations (4), (5), (8), and (9) present regression relationships relating percent shrubs-forbs and grass cover to the spectral variables listed above. Both the 1984 and 1994 results showed that shrubs-forbs had the greatest effect on spectral reflectance from the vegetated plots. Some shrubs-forbs tended to be greener at this time of year, which probably explains why they had the greater effect. These equations show there are different relationships between the spectral data and vegetative cover, depending on the data set.

TABLE 4 Multiple linear regression equations relating vegetative cover to the 38–43° sun angle blue, green, red, NIR, brightness, and NDVI index spectral data (n for each equation is noted)

Number	Equation
	1984
(1)	% Total Veg. Cover = −129.77 + 1078 (NDVI) − 2292 (NIR) + 2248 (Red) + 815 (Green)
	(Means of 11 plots) 0.81[a] 0.84[a] 0.91[a] 0.93[a]
(2)	% Total Veg. Cover = 95.34 − 939 (Blue) + 459 (Green) − 161 (NIR) + 67 (Red)
	(47 transects, natural plots) 0.11 0.15 0.19 0.20
(3)	% Total Veg. Cover = −22.88 + 487 (NDVI) − 1359 (NIR) + 481 (Bright) − 34 (Blue)
	(107 transects, all plots) 0.69 0.74 0.77 0.77
(4)	% Shrubs-Forbs = −47.09 + 193 (NDVI) + 171 (Blue) − 297 (Green) + 299 (Red)
	(47 transects, natural plots) 0.50 0.50 0.51 0.51
(5)	% Grass = 117.95 − 112 (NDVI) − 1112 (Blue) + 845 (Green) − 336 (NIR)
	(47 transects, natural plots) 0.24 0.33 0.36 0.38
	1994
(6)	% Total Veg. Cover = 129.4 − 86 (Red) + 1283 (Blue) − 300 (Brightness) − 106 (Green)
	(Means of 11 plots) 0.84 0.95 0.99 0.99
(7)	% Total Veg. Cover = 118.2 − 196.8 (Brightness) + 362 (Blue) + 105 (Green) + 8 (NDVI)
	(110 transects, all plots) 0.65 0.69 0.69 0.69
(8)	% Shrubs-Forbs = 63.34 − 14 (Red) − 243 (NIR) + 43 (NDVI) + 64 (Green)
	(110 transects, all plots) 0.35 0.37 0.38 0.38
(9)	% Grass = 47.73 − 152 (Green) + 271 (Blue) − 41 (Brightness) − 29 (Red)
	(110 transects, all plots) 0.16 0.18 0.20 0.20

[a] Partial R^2 for variables.

Relations Between Spectral Reflectance and Runoff-Erosion

The correlations relating spectral reflectance and vegetation indices to percent runoff and grams of sediment eroded for the 1984 plots are shown in Table 5. There were significant correlations between spectral reflectance and the percent runoff; however, the relationships between reflectance and the mass of sediment eroded from the plots were mostly not significant. The RVI, NDVI, and SAVI indices were overall the best correlations, and the 38–43° sun angle was consistently better than the 74–77° sun angle data.

Percent vegetative cover strongly affects the amount of runoff and erosion from rangeland surfaces, and it is strongly correlated to vegetation indices. We therefore evaluated the NDVI as a predictor of runoff and sediment recorded from these plots. Figure 2 plots the linear regression relationships between percent runoff at 38–43° and the NDVI for the dry, wet, and very wet plot conditions, and the r^2 values were 0.52, 0.75, and 0.78, respectively. These are significant correlations, suggesting this can be used to predict runoff.

The prediction of runoff is improved if multiple linear regression equations are used. Table 6 presents equations that relate the following six spectral reflectance variables to percent runoff from the eleven plots: blue, green, red, NIR, brightness, and NDVI. In every equation, the NDVI variable was entered first into the model, and the partial R^2 values are noted for each equation. The percent runoff models for the wet and very wet rainfall simulator runs [Eqs. (2) and (3)] had an overall R^2 of 0.94 and 0.87, respectively; the dry percent runoff [Eq.(1)] R^2 was 0.70. We studied extreme plot conditions ranging from bare to the natural plant cover, and percent runoff was accurately predicted using the spectral data. These relationships would likely be less significant if the vegetative cover conditions were less extreme.

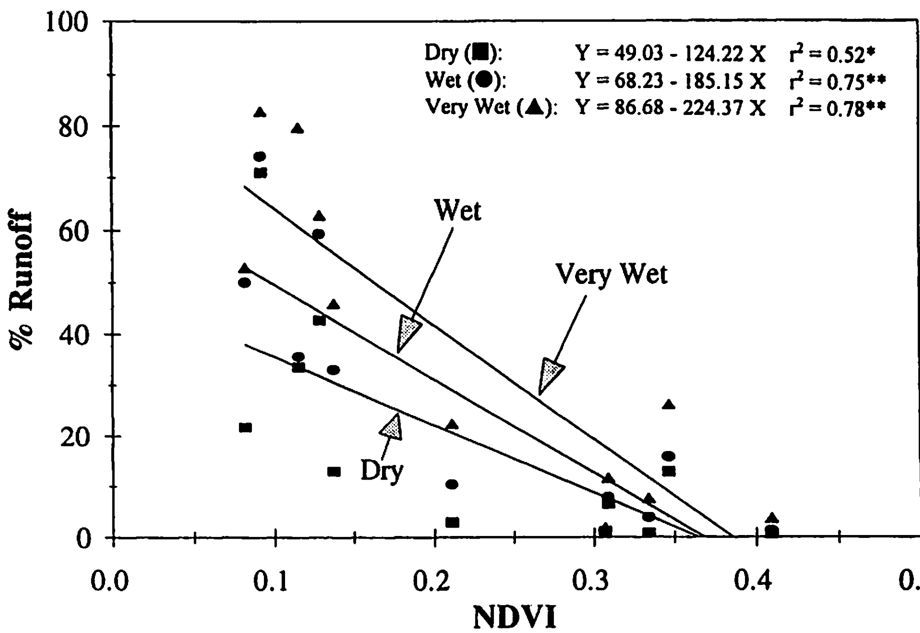

FIGURE 2 Regression relationships between percent runoff and the 38–43° sun angle Normalized Difference Vegetation Index (NDVI) for dry, wet, and very wet plot conditions, 1984 data.

TABLE 5 Correlations between spectral reflectance data and percent runoff and grams of sediment eroded from the 1984 rangeland plots ($n = 11$)

Spectral bands vegetative index	Sun angle	Spectral reflectance and percent runoff			Spectral reflectance and grams eroded		
		Dry	Wet	Very wet	Dry	Wet	Very wet
Blue	38–43°	0.61*	0.78**	0.70*	0.29	0.19	0.18
	74–77°	0.51	0.67*	0.66*	0.27	0.15	0.15
Green	38–43°	0.51	0.67*	0.55	0.22	0.18	0.15
	74–77°	0.56	0.74**	0.67*	0.28	0.21	0.20
Red	38–43°	0.66*	0.82**	0.70*	0.39	0.36	0.33
	74–77°	0.56	0.74**	0.69*	0.34	0.31	0.29
NIR	38–43°	0.17	0.25	0.04	−0.16	−0.16	−0.21
	74–77°	0.43	0.61*	0.46	0.07	0.05	0.01
Brightness	38–43°	0.55	0.70*	0.56	0.22	0.18	0.14
	74–77°	0.55	0.74**	0.66*	0.27	0.21	0.19
RVI	38–43°	−0.69*	−0.83**	−0.86**	−0.59	−0.58	−0.57
	74–77°	−0.53	−0.67*	−0.69*	−0.49	−0.46	−0.46
NDVI	38–43°	−0.72*	−0.86**	−0.89**	−0.62*	−0.60*	−0.60*
	74–77°	−0.57	−0.71*	−0.74**	−0.50	−0.47	−0.47
SAVI	38–43°	−0.72*	−0.86**	−0.89**	−0.64*	−0.62*	−0.62*
	74–77°	−0.57	−0.71*	−0.76**	−0.53	−0.49	−0.49

* Significant ($P < 0.05$).
** Highly significant ($P < 0.01$).

TABLE 6 Multiple linear regression equations relating percent runoff to the 38–43° sun angle blue, green, red, NIR, brightness, and NDVI spectral data ($n = 11$)

Number	Equation
(1)	% Runoff $= 16.46 - 5$ (NDVI) $+ 1210$ (Red) $- 1340$ (Green)
	(Dry) 0.52[a] 0.52[a] 0.70[a]
(2)	% Runoff $= 27.87 - 172$ (NDVI) $+ 275$ (Red) $- 2396$ (Green) $+ 539$ (Brightness)
	(Wet) 0.74 0.76 0.91 0.94
(3)	% Runoff $= 126.31 - 362$ (NDVI) $- 1773$ (Green) $+ 280$ (Brightness) $+ 275$ (NIR)
	(Very wet) 0.78 0.82 0.86 0.87

[a] Partial R^2 for variables.

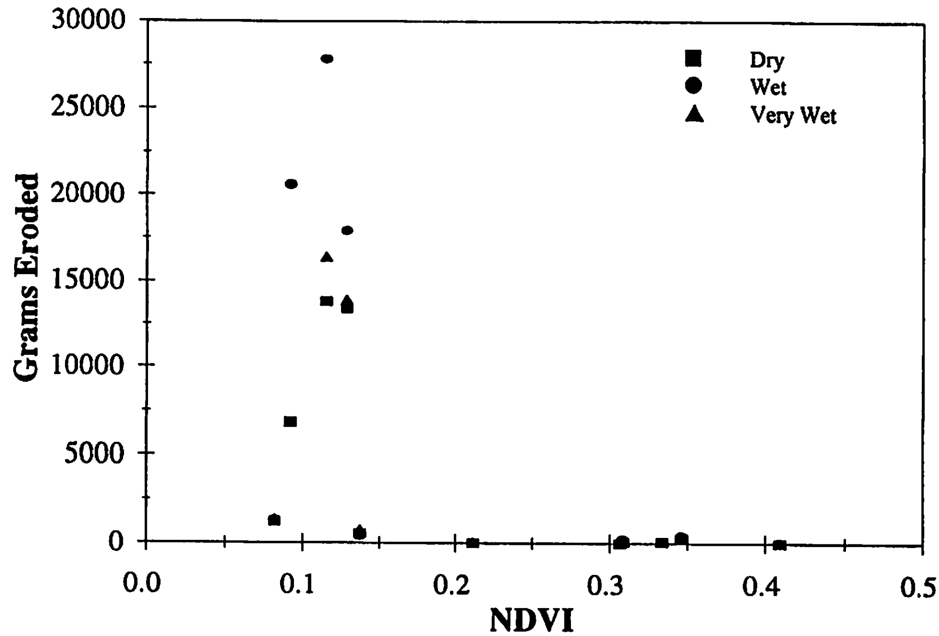

FIGURE 3 Relationships between grams of sediment eroded from the plots and the 38–43° sun angle Normalized Difference Vegetation Index (NDVI) for dry, wet, and very wet plot conditions, 1984 data.

Figure 3 shows the relationships between the grams of sediment eroded from these plots and the NDVI. It poorly predicts the amount of eroded sediments, and it is not a linear relationship. It does, however, show that erosion is greatest when the NDVI is near 0.1, which indicates the percent vegetative cover is minimal.

Conclusions

These experimental results show spectral reflectance data can be successfully used to predict vegetative cover and runoff on semiarid rangeland surfaces. The lower sun angle (38–43°) was better for characterizing vegetative cover, which can be used in RUSLE, WEPP, or other hydrologic models. However, the algorithms to predict vegetative cover from spectral reflectance data were quite different in 1984 and 1994, showing these relationships are not constant over time. The multiple interactions between vegetative cover and standing biomass, rock, soil, and litter make it difficult to analyze and interpret spectral reflectance data, and additional research is needed to further evaluate these interactions. The experimental results reported in this paper can be used by rangeland managers who might use hand-held radiometer data to inventory and monitor semiarid rangelands, or for evaluating hydrologic processes that occur on these lands. This ground-based data could be correlated to aircraft or satellite data for other nearby rangelands.

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