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Evaluating Landsat Thematic Mapper Derived Vegetation Indices for Estimating Above-Ground Biomass on Semiarid Rangelands

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Ground data from the Central Plains Experimental Range in northeast Colorado and Landsat satellite images of that area acquired in August 1989, June 1990, and September 1990 were used to evaluate the level of association that can be expected from a univariate model relating spectrally derived vegetation indices (difference, ratio, and normalized difference vegetation indices) and dried green vegetation biomass. The vegetation indices were related to the ground sample estimates using a sample point, spectral class, and greenness strata approach. No strong relationships were found between the vegetation indices and sample estimates of dried green biomass using the sample point approach. The spectral class approach produced significant results only for the June 1990 sample period ($r^2 = 0.96$). Significant relationships were found for the August 1989, June 1990, and September 1990 samples periods ($r^2 = 0.95$, 0.71, and 0.95, respectively) when the data were aggregated by greenness strata. The high degree of association between green biomass and the NDVI, obtained when the data were combined into greenness strata, indicated that it is possible to predict green biomass levels on semiarid rangelands using univariate regression models.

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INTRODUCTION

Vegetation indices derived from remotely sensed data have long been proposed as a source of information for predicting green biomass levels. Numerous studies have found significant relationships between vegetation indices and green biomass (Pearson et al., 1976; Bedard and LaPointe, 1987; Hardisky et al., 1984; Deering and Haas, 1980), while others have reported little or no

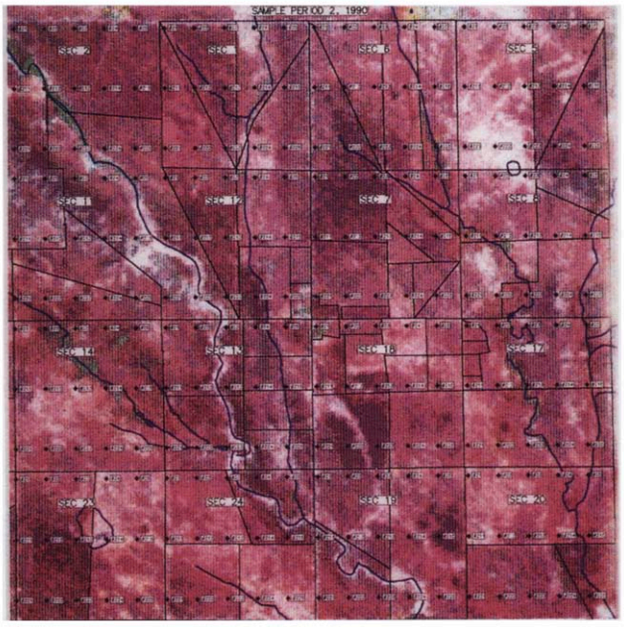


Figure 1. Grid sampling pattern for 42-km^2 sample area. Pasture boundaries and sample points are superimposed on a Landsat TM-5 (red), -4 (green), and -3 (blue) image.

association (Waller et al., 1981; Anderson and Hanson, 1992). The results of these studies indicate that vegetation indices do respond to varying levels of green biomass. However, our ability to predict mathematical coefficients that describe the relationship is confounded by factors such as changing sun angle, albedo, foliar cover, atmospheric haze, shadow, plant condition, and standing dead biomass (Richardson and Everitt, 1992; Jasinski, 1990; Holben, 1986; Bedard and LaPointe, 1987; Waller et al., 1981; Hardisky et al., 1984; Anderson and Hanson, 1992). Therefore, functional relationships reportedly must be developed from concomitant collections of ground biomass estimates, remotely sensed data, and estimates of other variables that affect the relationship.

The use of vegetation indices to predict green biomass levels over large areas of semi-arid rangeland have been limited. The number of samples and the myriad of variable measurements needed to develop the relationship have discouraged its use. This study was designed 1) to evaluate the level of association that can be expected from a univariate model relating spectrally derived vegetation indices and green biomass at specific times during the growing season and 2) to determine the best method of combining ground sample data with the satellite imagery.

STUDY SITE

The study site was a 42 km^2 area of the Central Plains Experimental Range (CPER) located 12 km north of Nunn, Colorado. The CPER is approximately 6275 ha in area and is located on the western edge of the shortgrass prairie. In June, forage yields from grasses and forbs average 730 kg ha^{-1} dry weight. Mean annual precipitation is approximately 310 mm year^{-1} and mean monthly temperatures vary from $-3°C$ in January to 21°C in July (WRCC-40, 1988). Grass production begins in mid to late April and ends in late September or early October. A midsummer senescence caused by drought is common.

METHODS

Ground Data Acquisition

A systematic sampling pattern, consisting of 240 sample points, was used to sample the study area. Sample points were located at 320 m intervals along east–west line transects; each set of three line transects was 640 m apart (Fig. 1). The geographic location of each point was approximated through interpolation from a known starting point and recorded as a geographic information system (GIS) data layer. An attempt was made to sample all 240 points within a 5-day period to minimize the effect of vegetation change.

At each sample point, crews clipped all vegetation within a 0.3 m × 0.6 m quadrat. During the August 1989 sample period, ocular estimates of foliar cover within the quadrate were collected before clipping. No ocular estimates were taken during the 1990 sample period because individual observers changed frequently and time became limiting. The clipped samples were separated into major plant components (cool-season grass, warm-season grass, forbs, and shrubs) and dried at 100°C for 5 days, weighed, and subsampled to determine dry weight and the percentage composition of dead and green plant material. Sample periods began on 28 August 1989, 4 June 1990, and 10 September 1990.

Satellite Data

Three Landsat TM scenes were acquired over the area on the 31 August 1989, 23 June 1990, and 11 September 1990, satellite overpasses. Satellite data were not available for the 7 June 1990 overpass, because of an orbital correction made on that date. The three TM scenes were registered to standard U.S. Geological Survey 7.5-minute quadrangle maps (Lambert Conformal Conic Projection), incorporated as data layers within a raster GIS, resampled (nearest neighbor) to a 30-m resolution, and the red (RED) TM Band 3 (0.63–0.69 μm) and near-infrared (NIR) TM Band 4 (0.76–0.90 μm) digital count values transformed to the difference (DVI), ratio (RVI), and normalized difference (NDVI) vegetation indices, where

$$\mathrm{DVI} = \mathrm{NIR} - \mathrm{RED}, \quad (1)$$

$$\mathrm{RVI} = \mathrm{NIR} / \mathrm{RED}, \quad (2)$$

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED}) / (\mathrm{NIR} + \mathrm{RED}). \quad (3)$$

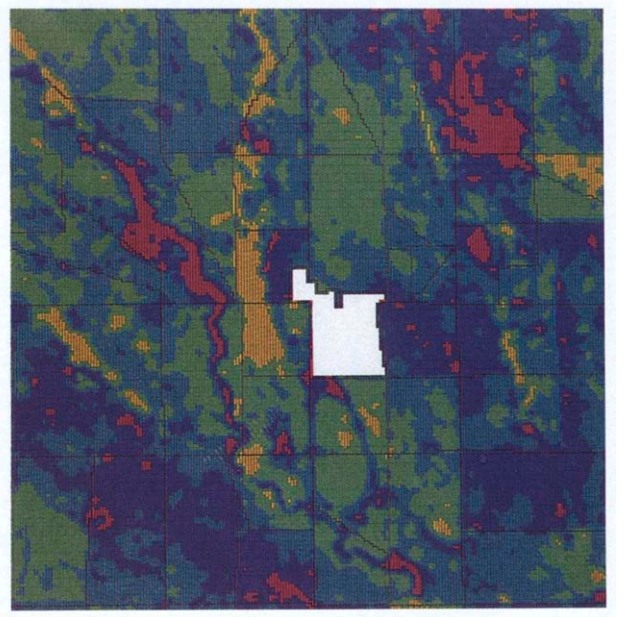


Figure 2. Spectral classification map for the June 1990 sample period. The yellow, green, blue, dark blue, and red regions represent a steady progression from areas of high cover to bare soil areas, respectively.

Combining the Data and Data Analysis

Determining how to combine the data was difficult. A direct pixel to sample point comparison was impractical because: 1) the clipped area was small in comparison to the 30-m TM resolution, 2) the registration of the images had, at best, a 1-pixel or 30-m accuracy, and 3) the location of ground sample points could only be approximated. To reduce the effect of registration error on the relationship, the data were grouped into regions of similar biological and spectral response. The first method of grouping the data combined each sample point estimate with the average vegetation index value for a 3-pixel × 3-pixel area surrounding the sample site. This procedure was used to reduce the effect of image and sample data misregistration.

The second data combination method combined the data into similar spectral classes. Classes were developed using nonsupervised spectral classification with the red (Band 3), near-infrared (Band 4), and midinfrared (Band 7, 2.08–2.35 μm) TM bands. The nonsupervised classification technique was chosen as one potential method of stratifying the area because the classes generated will spectrally relate to vegetation density as do spectral vegetation indices. The water absorption band (Band 7) was chosen for the third component in the classification because it produced a greater statistical separation of the classes than did the other water absorption band (Band 5, 1.55–1.75 μm). Five classes were specified in the routine and a 98% convergence was achieved within 10 to 15 iterations (Fig. 2). Pixels (red and near-infrared) and ground sample estimates occurring within each class were extracted, the vegetation indices calculated, and the mean sample biomass estimate (dry weight) and vegetation index response evaluated.

The third data combination technique combined the data into greenness strata. The idea of combining the range of vegetation index values into arbitrary greenness classes was developed after the examination of two-dimensional histograms of TM spectral Bands 3 and 4 (Fig. 3). The figure demonstrates the typical triangular shape seen in areas of varying amounts of cover and green vegetation (Richardson and Wiegand, 1977; Pech et al., 1986). The three points of the triangle have been associated with bare soil (upper right corner), 100% cover composed of dry vegetation (lower left corner), and green vegetation (upper left corner). Most of the variance in the data

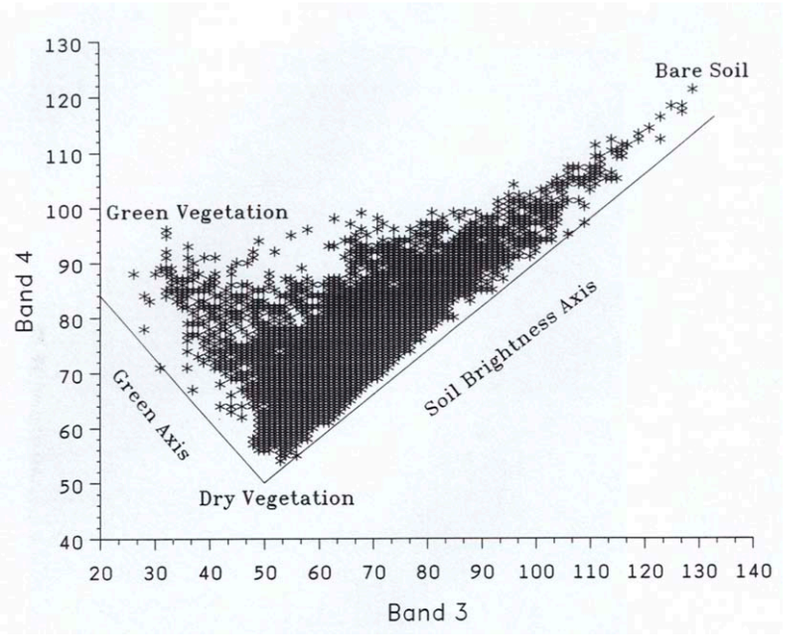


Figure 3. A total of 1356 reflectance samples of various landscape components plotted in the red (TM Band 3) and near-infrared (TM Band 4) wavelengths (August 1989 image). The major landscape features are marked.

occurred along the soil brightness axis (upper right to lower left vertices). A proportionally small amount of the variance existed along the greenness axis (lower left to upper left vertices). If we assume that greenness is associated with the NDVI and green biomass, then strata must be developed that partition the total greenness variation so that as much as possible is assigned to differences among strata. In this way, variation within strata is kept small, and the number of samples required to sample each class is reduced.

The greenness range was divided into discrete classes by slicing the range of NDVI values into narrow bands (Table 6; Fig. 4). Narrower classes were delineated at lower NDVI values because most of the pixels occurred close to the soil brightness axis (Fig. 3). NDVI was the only vegetation index used to develop greenness classes. Eight classes were developed for the August 1989 and June 1990 sample periods (Fig. 5), and seven classes were developed for the September 1990 sample period (the NDVI range in September did not exceed 0.40). All pixels (NDVI) and ground sample estimates occurring within each greenness

Figure 4. Schematic representation of greenness slicing. NDVI classes, listed in Table 6, are shown in relation to increasing greenness.

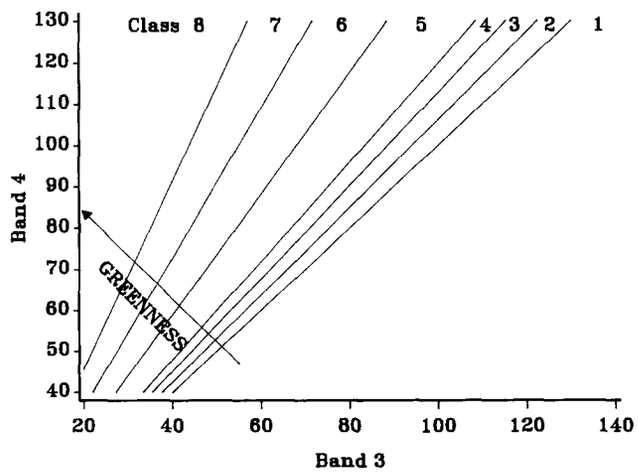


Figure 5. Greenness map for the August 1989 sample period. The yellow, green, blue, dark blue, and red regions represent a steady progression from areas of higher greenness to bare soil respectively.

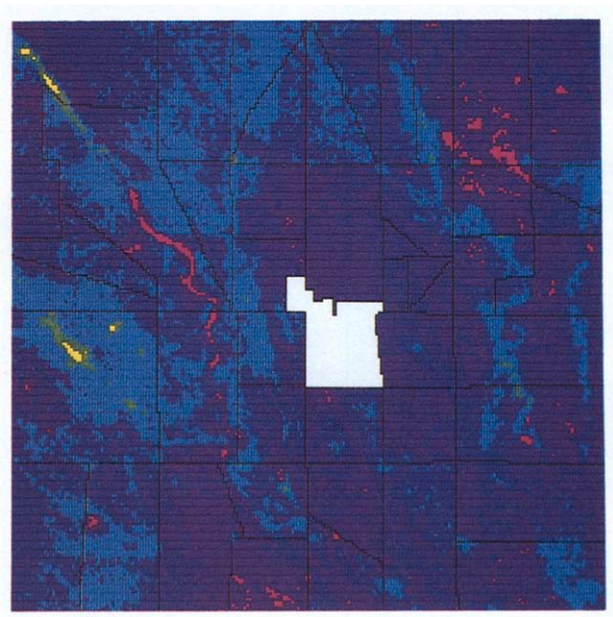


Table 1. Relationship (r^2) between Sample Estimates of Green Biomass and the Three Vegetation Indices (Sample Point Approach)

Date	*NDVI*	*RVI*	*DVI*
31 Aug 1989	0.149	0.162	0.140
23 Jun 1990	0.019	0.018	0.018
11 Sep 1990	0.040	0.029	0.039

Table 2. Mean Green Biomass Estimates (kg ha^{-1}) and Standard Deviation for the Three Sample Periods over the Entire Study Area

Date	*Mean*	*S*
30 Aug 1989	470.3	301.3
06 Jun 1990	511.7	259.5
12 Sep 1990	346.0	284.9

class were extracted, and the average green biomass sample estimate (dry weight) and NDVI response evaluated.

Standard analysis of variance techniques were used to evaluate the relationships between clipped estimates of dried green biomass and the 9-pixel vegetation index average (Steel and Torrie, 1980). The same analysis procedure was used to evaluate the relationships between average clipped estimates of dried green biomass and the mean vegetation index response for each class.

RESULTS

Sample Point Comparison

No strong relationships were found between the clipped-plot estimates of green biomass and the 9-pixel average for each of the vegetation indices (Table 1). The vegetation indices explained from 1.8% to 16.2% of the variation in green biomass. The highest degree of association occurred between green biomass and the RVI during the August 1989 sample period ($r^2 = 0.16$).

While no strong relationships between the vegetation indices and dried green biomass existed within sample periods, the data did exhibit trends between sample periods. The average estimates of green biomass for the entire study area were highest during the June 1990 sample period (511.7 kg ha^{-1}), lowest in September 1990 (346 kg ha^{-1}), and intermediate in August 1989 (470.3 kg ha^{-1}) (Table 2). The same trend was observed for each of the vegetation indices. Average vegetation index response for the entire study area was highest in June 1990 (NDVI = 0.13), lowest in September 1990 (NDVI = 0.03), and intermediate in August 1989 (NDVI = 0.05) (Table 3). Thus, the vegetation indices were responding to temporal changes in green biomass. The lack of a clear correlation within sample periods probably resulted from the inability of the small ground sample to represent the 9-pixel area.

Spectral Class Comparison

Five spectral classes were developed using unsupervised classification on the August 1989, June 1990, and September 1990 images. Of the five classes identified for each sample period, only four contained ground sample points. Comparison of the average dried green biomass and vegetation indices for each class revealed a positive correlation for the June 1990 sample period (DVI, $r^2 = 0.96$; RVI, $r^2 = 0.96$; and NDVI, $r^2 = 0.93$) (Table 4). Clipped-plot data indicated a steady increase of dried green biomass from 354.2 kg ha^{-1} (Class 1) to 529.5 kg ha^{-1} (Class 4). The same trend was observed for all three of the vegetation indices. The NDVI values increased from 0.07 to 0.15 as the estimates of green biomass increased from Class 1 to Class 4, respectively.

No significant relationships between the vegetation indices and dried green biomass were found during the August and September sample periods.

Table 3. Mean and Standard Deviation of the Three Vegetation Indices for the Three Sample Periods Using the Average Index Value for Each Nine-Pixel Area

	DVI		*RVI*		*NDVI*	
Date	*Mean*	*Std*	*Mean*	*Std*	*Mean*	*Std*
31 Aug 1989	6.64	4.05	1.12	0.08	0.05	0.03
23 Jun 1990	21.44	6.19	1.31	0.12	0.13	0.04
11 Sep 1990	3.14	3.61	1.06	0.09	0.03	0.03

Table 4. Average Clipped-Plot Estimate (kg ha^{-1}) and Mean Vegetation Index Response in Each Class for the Three Sample Periods (Unsupervised Spectral Classification Approach)

Class	*kg/ha*	*DVI*	*RVI*	*NDVI*
		August 1989		
1	628.0	1.1	1.01	0.01
2	379.1	4.8	1.07	0.03
3	420.9	5.8	1.09	0.04
4	477.4	6.9	1.11	0.05
r^2		0.55	0.52	0.41
		June 1990		
1	354.2	14.7	1.16	0.07
2	397.5	18.0	1.24	0.11
3	479.2	20.1	1.29	0.13
4	529.5	22.7	1.35	0.15
r^2		0.96	0.96	0.93
		September 1990		
1	320.6	−0.7	0.98	0.00
2	264.2	1.2	1.02	0.01
3	356.2	2.7	1.05	0.02
4	343.8	4.2	1.07	0.04
r^2		0.23	0.21	0.24

Biomass estimates were similar to those recorded in June; however, the estimates displayed no linear trend. In August, average clipped-plot estimates of green biomass ranged from 379.14 kg ha^{-1} to 628.03 kg ha^{-1} (Table 4). The largest average biomass estimate occurred in Class 1 (628 kg ha^{-1}). This value was influenced by high forb production at a single sample point located in the bottom of a large catchment (1227.9 kg ha^{-1}). The forbs were probably responding to late July and early August precipitation (5.2 cm). The NDVI value (−0.78) for the sample point appeared to be influenced by high red band reflection from the bare soil associated with the sample point. In September, estimates of green biomass varied from 264.18 kg ha^{-1} to 356.18 kg ha^{-1} with no detectable pattern.

Spectral classes were strongly influenced by the amount of foliar cover. In August 1989 and September 1990 the classes were aligned primarily along the soil brightness line with little displacement along the greenness axis (Figs. 6 and 7). For June 1990, the amount of green vegetation was sufficient to displace the classes into higher greenness regions (Fig. 8). An interesting note is that the mean percentage of foliar cover, based on ocular estimates for August 1989, was linearly related to the mean red band (TM Band 3) response ($r^2 = 0.98$, Fig. 9). The mean percentage of foliar cover for the classes increased steadily from 62% (Class 1) to 76% (Class 5), while the red band digital count values decreased from 87 to 54. Determining the repeatability of this association was not possible because ocular estimates of foliar cover were not taken during the 1990 sample season.

Greenness Class Comparison

Estimates of dried green biomass were highly related to the NDVI when the data were combined into greenness strata (Table 5). Significant relationships existed for the three sample periods; the highest relationships occurred in August 1989 and September 1990 ($r^2 = 0.95$, both periods) and the lowest in June 1990 ($r^2 = 0.71$). Clipped-plot estimates of dried green biomass in August increased from 429.9 kg ha^{-1} to 1904 kg ha^{-1} and the average NDVI value for each class ranged from −0.02 to 0.34 (Table 6). Only classes containing one or more sample points were used in determining the range of greenness information. Biomass estimates for September ranged from 441.5 kg ha^{-1} to 1904.3 kg ha^{-1}; however, the

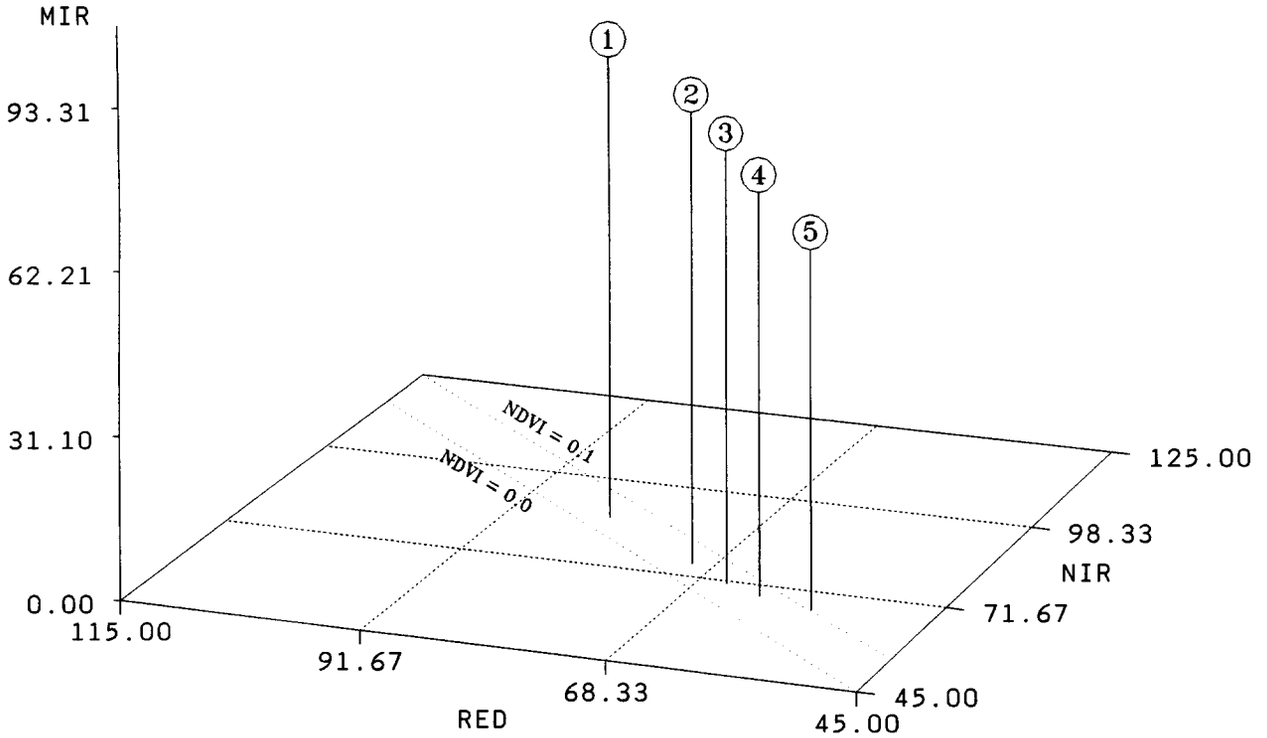
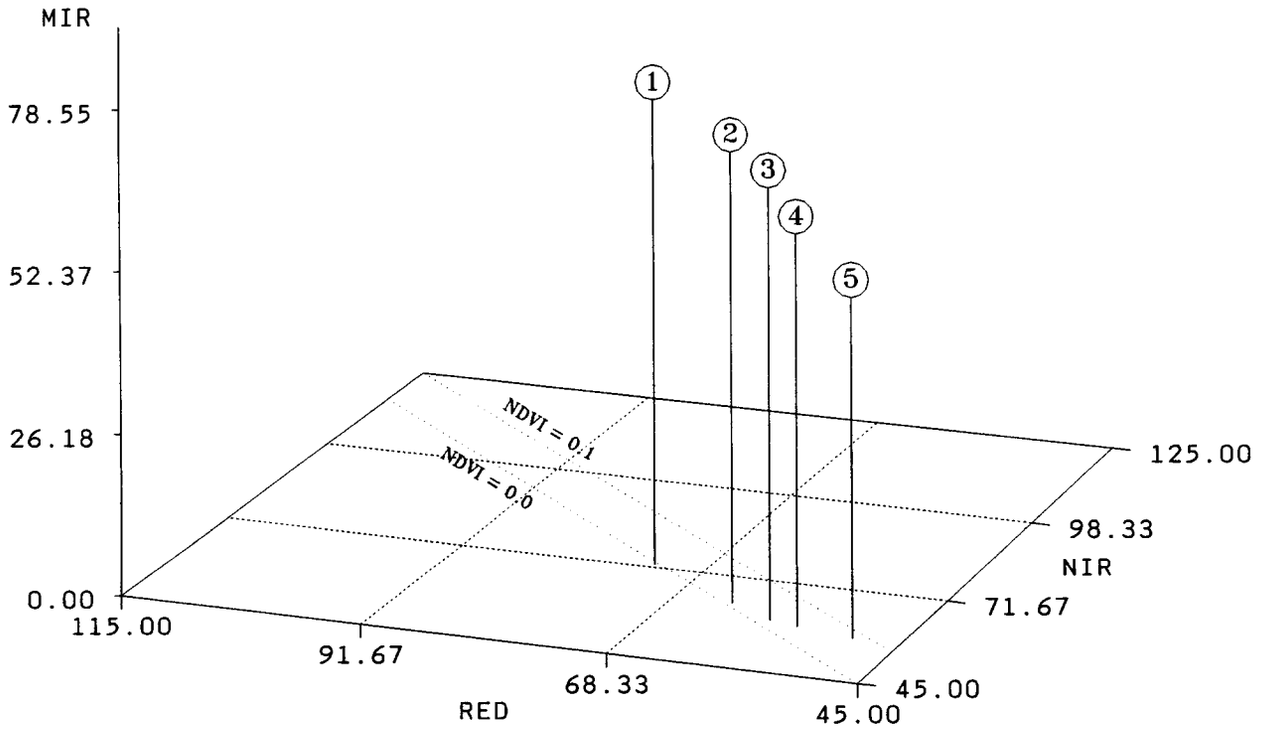


Figure 6. Three-dimensional plot of spectral class means (red = red Band 3, NIR = near-infrared Band 4, and MIR = midinfrared Band 7) for the August 1989 sample period. The NDVI 0 and NDVI 0.1 lines are superimposed on the near-infrared / red plane.

Figure 7. Three-dimensional plot of spectral class means (red = red Band 3, NIR = near-infrared Band 4, and MIR = midinfrared Band 7) for the September 1990 sample period. The NDVI 0 and NDVI 0.1 lines are superimposed on the near-infrared / red plane.



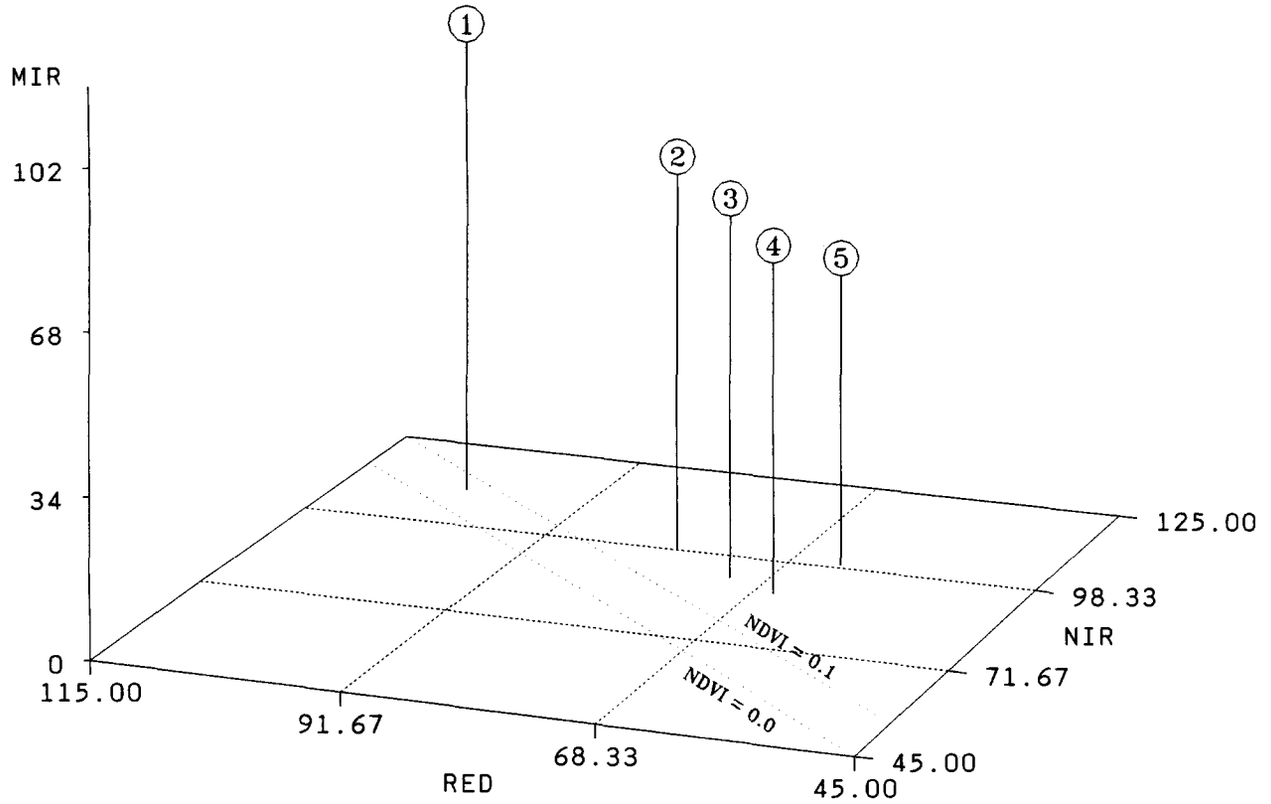
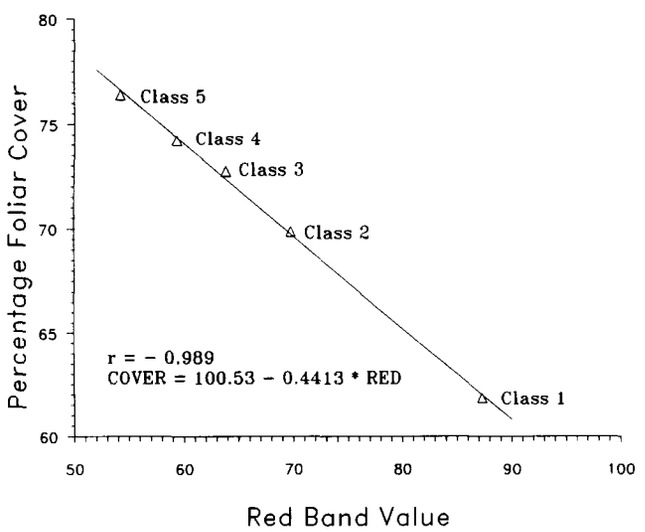


Figure 8. Three-dimensional plot of spectral class means (red = red Band 3, NIR = near-infrared Band 4, and MIR = midinfrared Band 7) for the June 1990 sample period. The NDVI 0 and NDVI 0.1 lines are superimposed on the near-infrared / red plane.

estimate for Class 5 did not increase as the NDVI increased (Table 6). Four of the five sample points occurring within Class 5 were located close to other classes with lower vegetation index estimates. The low biomass estimate was probably caused by the improper assignment of these sample points to Class 5. In the one instance where the sample point fell within a large Class 5 region, the biomass estimate was 1236.5 kg ha^{-1}. The NDVI greenness values in September 1990 were similar to those observed in August 1989 (− 0.02–0.36). The similarity between the August 1989 and September 1990 sample periods led to similar regression models (Table 5). The slope estimates for August 1989 and September 1990 were 4344.8 and 4020.9, respectively. The estimate of *Y*-intercept (minimum amount of green biomass that can be estimated using this approach) for August was 307.9 kg ha^{-1}, compared to the September estimate of 376.6 kg ha^{-1}.

Figure 9. Relationship of mean TM red band (Band 3) response to the average percentage foliar cover for each class. Classes were defined by spectral classification.



The June sample period had the poorest relationship between dried green biomass and the NDVI ($r^2 = 0.71$). The lower relationship may have resulted, in part, from the 16-day separation between ground sampling and image acquisition. Green biomass estimates and average class NDVI values ranged from 374.5 kg ha^{-1} to 1163.9 kg ha^{-1} and 0.02 to 0.33, respectively (Table 6).

Table 5. General Linear Model Coefficients, for Estimating Green Biomass from Average NDVI Values, and r^2 Values for Each of the Three Sample Periods (Greenness Stratification Approach)[a]

Date	*Slope*	*Y-Intercept*	r^2
Aug 1989	4344.8	307.9	0.95
Jun 1990	2016.1	321.8	0.71
Sep 1990	4020.9	376.6	0.95

[a] All relationships are significant at $\alpha = 0.05$.

Green biomass estimates for Classes 5, 6, and 7 (June 1990) were lower than those recorded in August 1989 and September 1990. This resulted in a substantial reduction in the slope estimate (slope = 2016.1); however, the *Y*-intercept remained fairly constant (321.8 kg ha^{-1}). One anomaly in the June data was the dried green biomass estimate of 580.6 kg ha^{-1} for Class 3. The Class 3 estimate was substantially higher than the estimates recorded for Classes 4, 5, and 6 (Table 5). All Class 3 samples bordered higher NDVI classes (Classes 4 and 5) so that their location was probably in error. The association between the average dried green biomass estimates and the class average NDVI response was improved for the June 1990 sample period when the Class 3 samples were eliminated ($r^2 = 0.78$).

DISCUSSION

Two problems with the sample point method were sample point location error and poor representation of the sample area by the 9-pixel average estimate of greenness. For the procedure to work, the ground samples must adequately portray the conditions contributing to vegetation index response. By averaging the vegetation index over a 9-pixel area, a single ground sample had to capture the average condition of a 8100 m^2 region. A more desirable situation would be the comparison of the sample point to the vegetation index value obtained for a single pixel (900 m^2 area). The method used to locate each sample point,

Table 6. Greenness Class Range, Average NDVI Value, Clipped-Plot Estimate of Green Biomass, and the Number of Sample Points for the August 1989, June 1990, and September 1990 Sample Periods (Greenness Stratification Approach)

Class	*Range*	*Avg. NDVI Value*	*Avg. Clipped-Plot Estimate (kg/ha)*	*N*
		August 1989		
1	< 0	−0.02	429.9	1
2	0.00–0.03	0.02	405.7	78
3	0.04–0.06	0.05	455.2	103
4	0.07–0.09	0.08	481.0	39
5	0.10–0.19	0.12	805.2	12
6	0.20–0.29	0.23	1236.5	1
7	0.30–0.39	0.34	1904.0	1
8	> 0.40	0.48	–	0
		June 1990		
1	< 0	−0.03	–	0
2	0.00–0.03	0.02	374.5	2
3	0.04–0.06	0.05	580.6	3
4	0.07–0.09	0.08	439.0	26
5	0.10–0.19	0.13	516.0	191
6	0.20–0.29	0.23	549.0	11
7	0.30–0.39	0.33	1163.9	1
8	> 0.40	0.43	–	0
		September 1990		
1	< 0	−0.02	441.5	24
2	0.00–0.03	0.02	433.6	135
3	0.04–0.06	0.05	466.1	60
4	0.07–0.09	0.08	807.3	10
5	0.10–0.19	0.13	689.9	5
6	0.20–0.29	0.23	–	0
7	> 0.30	0.36	1904.3	1

however, must be accurate enough to place the point within the 30 m × 30 m pixel. No relationships between dried green biomass and the vegetation indices were found because the sample area did not adequately characterize each 9-pixel area or because other unmeasured variables adversely affected the relationship.

The spectral class approach improved the ability of the vegetation indices to predict green biomass. This procedure, however, produced a significant relationship only during the June 1990 sample period. The classification routine using the red, near-infrared, and midinfrared TM bands produced classes based primarily on spectral brightness. The average NDVI response for each spectral class was low because most of the greenness information existed close to the soil brightness axis (average NDVI values within each class ranged from 0 to 0.05 for the August and September sample periods). Only during the June sample period was there sufficient green biomass to shift the classes (and subsequently the average NDVI response) into regions of higher greenness (June average NDVI range 0.07–0.15). The relationship between average red band values and the percentage foliar cover for each class during the August 1989 sample period illustrated the dependence of spectral class on foliar cover and albedo. The ability of the spectral stratification technique to identify relationships between dried green biomass and the vegetation indices may improve if vegetation indices that account for spatial changes in soil brightness (Richardson and Everitt, 1992) are used and more classes are delineated.

The greenness class approach produced highly significant results over a wide range of conditions. The advantage of combining data into discrete strata is the reduced variance associated with each strata (Steel and Torrie, 1980). By reducing the variance, fewer samples are required to characterize the area. The effect of data registration error was also minimized by averaging multiple observations within each class. The relationship between the NDVI and dried green biomass was affected by registration error when the number of samples occurring within a class was small. Improper class / sample-point assignment occurred when the sample points were located close to the border between two or more classes. Accurate sample point locations, determined using a global positioning system, would improve the assessment of ground conditions within each class.

Another problem with the data combined into greenness strata was the uneven distribution of sample points within each class. The systematic sampling scheme was developed before the idea of greenness stratification was conceived; therefore, sample point placement was not optimal. A timely method for stratifying the area before satellite overpass must be developed. One approach would be to use historical Landsat TM imagery. Another approach would use high altitude multispectral digital video data to develop the greenness strata. Multispectral video data can be obtained and used to produce greenness strata the same day as the satellite overpass and sample crews could begin sampling within a day of satellite image acquisition. Additional research is needed to validate this approach.

CONCLUSIONS

Vegetation indices derived from remotely sensed data are capable of estimating green biomass levels on semiarid grasslands. However, the degree of association is substantially influenced by the method used to combine the two sources of information. This may, in part, explain the range of relationships reported in the literature.

A direct sample point to pixel (or aggregated pixel) comparisons requires accurate pixel to sample point registration. In addition, physical factors can obscure the green biomass and vegetation index relationship when a single variable (biomass) is measured within a small sample area. Small sample areas may be adequate when investigating homogeneous plant communities; however, if conditions within the community change rapidly, as do most semiarid rangelands, additional information must be collected.

Stratified sampling can reduce the effect of misregistration and small sample plots by averaging multiple observations within each class. The method used to develop the stratification, however, can influence the relationship between green biomass and the vegetation indices. Semiarid rangelands are characterized by limited rainfall, low biomass production, and a wide range of foliar cover. Under these conditions spectral

classification will develop classes based primarily on foliar cover and albedo. The use of multivariate vegetation indices that compensate for changing soil brightness conditions and the development of more spectral classes could improve relationships developed using the spectral classification approach.

The high degree of association between green biomass and the NDVI, obtained when the data were combined into greenness strata, indicates that it is possible to estimate green biomass levels using a univariate model. This is not to say that other influences (standardized reflectance values, sun angle, albedo, cover, atmospheric haze, etc.) are not important. Multivariate models are needed for multitemporal investigations. However, using the greenness stratification approach during a single sample period can produce highly significant associations over a wide range of conditions without using a multivariate model approach.

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