PEER-REVIEWED ARTICLE

Two Indices to Characterize Temporal Patterns in the Spectral Response of Vegetation

Abstract

Two proposed indices characterize the shape of a curve developed from a seasonal profile of normalized difference vegetation indices (NDVI). These indices complement the area-under-the-curve integral index. The first index reflects the time in the seasonal profile when the highest NDVI values occur. This is accomplished by bisecting the time domain of the observations and determining the proportion of the area under the curve in the first half of the season to the total area under the curve. The second index is associated with the range of NDVI values observed over the temporal sequence. This index reflects the relative change in NDVI values observed over the growing season.

The indices were tested using NOAA-10 Advanced Very High Resolution Radiometer (AVHRR) data for ten dates during 1987. The calibrated data were transformed into NDVIs before the determination of the curve-characterization indices. Initial review of the products of the indices indicate distinct separation between grasslands and cultivated areas, and land-cover differences within the cultivated areas. Correlation coefficients among the three indices show little redundancy. The low correlations suggest that the three indices each include unique information about the land cover and phenological properties observed with the AVHRR data.

Introduction

Time-series analysis of data permits the observation of seasonal trends in the measured phenomena. With the relatively inexpensive Advanced Very High Resolution Radiometer (AVHRR) digital data that are available through the National Oceanic and Atmospheric Administration (NOAA), time-series analysis can be conducted upon the spectral properties of a vegetated surface. After georegistration of multiple digital image data sets, it is possible to observe the spectral character of a specific ground location over time. This "spectral profile" characterizes morphological and biochemical changes as the vegetation develops throughout the growing season. Each plant species, as well as the same species in different climates, exhibits different spectral profiles over the same period.

Multi-temporal remotely sensed data have been shown to be successful in monitoring seasonal trends in plant phenology or meteorological conditions that are reflected in phenology, such as in the Sahel (Justice and Hiernaux, 1986; Townshend and Justice, 1986) and in the United States (Lo *et al.*, 1986; Walsh, 1987). A problem that is encountered with the analysis of multi-temporal image data is the difficulty in evaluating the temporal trends as well as spatial trends. One approach to simplify this multi-dimensional problem is to reduce the dimensionality of the temporal data through the determination of the area-under-the-curve, or the integral. In this transformation, seasonal trends in plant phenology are summarized by a single number which is associated with the seasonal accumulation of measures, such as biomass and leaf area. However, the temporal characteristics of the spectral profile are not evident with this transformation (e.g., when does the greatest accumulation of biomass occur during the season and how much variation in the measurements was observed during this time). The purpose of this paper is to introduce two indices that reduce the multidimensionality of the seasonal profile to two values which, when used with the area-under-the-curve integral, can be used to characterize seasonal trends in plant phenology.

Current Approaches to Characterizing Temporal Trends in Vegetation Indices

Vegetation indices have been associated with some morphological or physiological stage at a point in time of plant growth, such as biomass (Dusek *et al.*, 1985; Gardner, 1985), leaf area index (Richardson and Wiegand, 1977; Hinzman *et al.*, 1986; Lloyd, 1990), and intercepted photosynthetically active radiation (Hatfield *et al.*, 1984; Gallo *et al.*, 1985). Information derived from these indices can be related to long-term meteorological events, plant species distribution, or human-induced changes in terrestrial vegetation. Miller (1981), Perry and Lautenschlager (1984), Price (1987), and Gallo and Daughtry (1987) describe the development and application of these various indices. One of the most often used vegetation indices is the normalized difference vegetation index (NDVI). The NDVI is computed as the product of the ratio (near infrared − red)/(near infrared + red).

Indices can be computed from remotely sensed data obtained at intervals throughout a growing season to show relative differences in plant phenology. For a given pixel, the indices can be plotted against time to provide a visual summary of the phenological cycle (Figure 1). However, interpretation is restricted to the visual examination of the temporal sequence of individual pixels. This approach has been used extensively (Tucker *et al.*, 1980; Philipson and Teng, 1988; Teng, 1990; Achard and Blasco, 1990). This form of data display, though, presents some graphical limitations if an image is to be produced to summarize the seasonal patterns of the vegetation indices for all pixels in an image.

Some analysts of temporal patterns (Tucker *et al.*, 1981;

Photogrammetric Engineering & Remote Sensing,
Vol. 59, No. 4, April 1993, pp. 511–517.

0099-1112/93/5904-511$03.00/0

Scott A. Samson
Department of Geography, University of Alabama, Tuscaloosa, AL 35487.

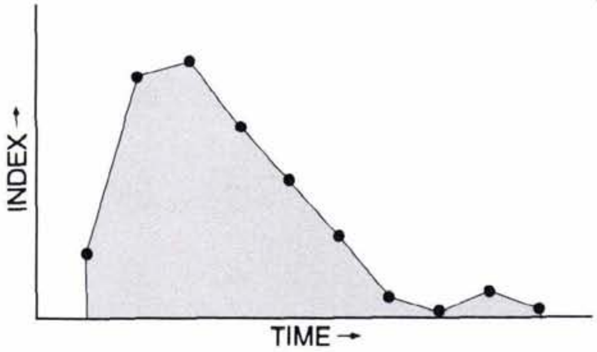

Figure 1. Vegetation indices may be observed as discrete entities over time or by the integral of the curve formed by the indices.

Justice and Hiernaux, 1986; Prince and Tucker, 1986) have subscribed to the calculation of the integral of the curve formed by the indices determined over the growing season as a means to summarize these seasonal patterns (Figure 1). The integral produces a single number that is associated with total dry matter accumulation (Tucker *et al.*, 1981). When working with digital image data, the integral is calculated for each pixel and an integrated image is produced.

Tucker *et al.* (1980) introduced a variation to the integral technique that reflected temporal differences in the accumulated vegetation index. The observed growing season was subdivided into three sections that corresponded to stages of development for wheat. The integral for each of the three areas was correlated with yield data. The correlation was the greatest with the interval associated with the period when peak biomass occurred.

One shortcoming of the curve integral as an indicator of seasonal trends is that it represents only the cumulative effect of the vegetation indices. It does not provide any information about the pattern of the vegetation indices over the time the data were compiled. For example, different curve patterns can mathematically produce the same integral but represent different seasonal vegetative growth patterns (Figure 2). It is important not only to recongnize the cumulative effect of the vegetation indices over time but also to evaluate the pattern of the seasonal profile associated with the indices. For this reason, it is necessary to complement the integral index with additional indices that summarize temporal changes in the spectral profile associated with plant phenology. These indices should reflect the nature of the shape of the curve rather than the area under the curve.

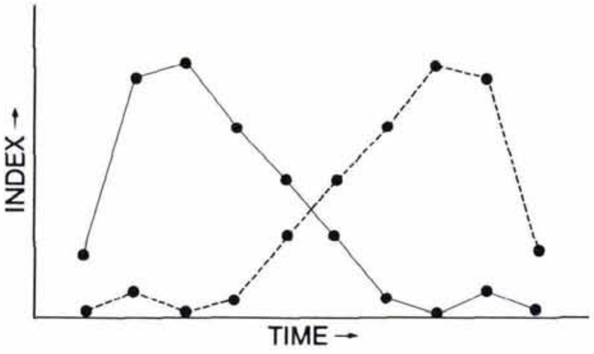

Figure 2. Even though the trend of the vegetation indices for two locations are different over the same period, the integrals of the two curves are equal.

TABLE 1. AVHRR HRPT DATA SETS FOR 1987

Scene ID #	Calendar Date	Julian Date
108711914581	29 April	119
108715714293	6 June	157
108716514562	14 June	165
108717614171	25 June	176
108719715015	16 July	197
108720714442	26 July	207
108721714315	5 August	217
108724014323	28 August	240
108726615083	23 September	266
108727614510	3 October	276

Development of Curve Indices

The shape of the seasonal profile may be used to evaluate the type of vegetative cover on the basis of the magnitude and shape of the curve. For example, coniferous forest will have relatively unchanging NDVI values over the season while deciduous forests will reflect the cyclic pattern of leaf emergence to senescence. Mixed warm- and cool-season grasslands would differ from coniferous forest cover in the amount of accumulated biomass although the relative change in NDVI values over the season could be similar. In addition, the seasonal profile based on NDVI values can provide information that, over a series of years, may be related to meteorological events that influence phenology, such as delayed emergence brought about by mild drought conditions. Collected over several years, the curve shapes could be used as climatic indicators when ground-level instrumentation is not available. For these reasons, it is necessary to develop profile indices that retain information relating to the shape of the seasonal profile of NDVI values.

Various statistical and mathematical approaches may be used to analyze a seasonal profile. However, few are designed to maintain the sequence of the observations in the course of the analysis. For example, the average of ten NDVIs determined over a season will produce a single value, but it does not indicate at what point in the sequence the peak NDVI value occurred or if there was much variation in the NDVI values. Other series analysis techniques either produce a multivariate product in the analysis, such as first and second derivatives or polynomial curve fitting, or are inappro-

TABLE 2. ROOT-MEAN-SQUARE ERROR (RMSE) RESULTING FROM GEOREFERENCING OF IMAGES TO GROUND CONTROL POINTS

Image Date	*X* RMSE	*Y* RMSE	Total RMSE
29 April	0.24795	0.24900	0.35140
6 June	0.35003	0.27752	0.44670
14 June	0.71269	0.24904	0.75495
25 June	0.61997	0.58539	0.85267
16 July	0.61437	0.17724	0.63943
26 July	0.61437	0.24904	0.66293
5 August	0.83531	0.17724	0.85391
28 August	0.82970	0.23938	0.86354
23 September	0.31109	0.15664	0.34831
3 October	0.94987	0.24904	0.98197

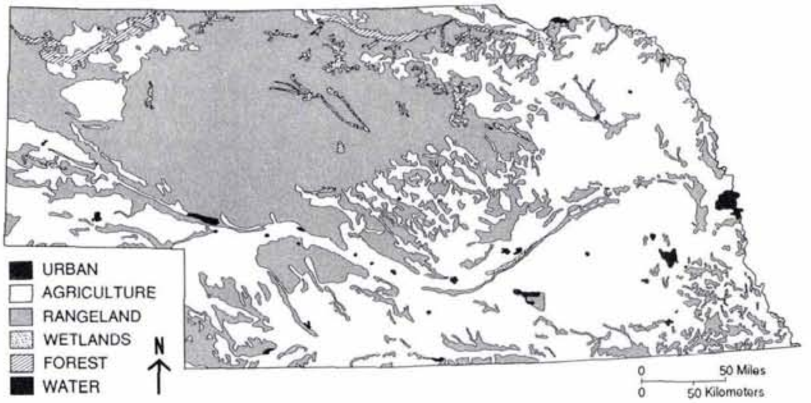

Figure 3. Land Cover of Nebraska (Nebraska Conservation and Survey Division, 1973).

priate, such as autocorrelation, cross-correlation, or principal component analysis, when attempting to characterize the unique pattern attributed to a seasonal profile of the spectra.

Integrating the area under the curve is a mathematical approach that produces a single value. It is possible to compute the integral for each pixel in an image from two or more digital images. The resultant image is a composite of the input images. This technique has been documented extensively (Tucker *et al.*, 1981; Justice and Hiernaux, 1986; Justice *et al.*, 1986; Prince and Tucker, 1986). However, the integral of the curve does not indicate when the highest NDVIs are accumulated nor how much variation in the NDVI values was observed over the season.

Because the location in time where the highest NDVI values accumulate can be associated with the physical maturity of the plant cover, it is necessary to be able to identify the associated sequence in the seasonal profile. There are several possible approaches to identify this point, or series of points, in the profile. For example, the maximum NDVI may be selected as the point when physical maturity occurs. However, this may result in either the selection of an anomalously high NDVI value or, in rare situations, the identification of two points with the same NDVI value.

Two other approaches are related to the integral of the curve. If the curve is divided into two parts, it is possible to compute the integral for each part and generate the difference between the areas or a ratio of one area to the other. Dividing the curve into more than two parts would result in computations that would produce more than one value. The curve may be bisected at the point along the time domain (X axis) when the areas under each curve are equal to each other. The index value would be determined on the point along the time domain when the two areas were determined to be equal. However, this method requires several iterations, resulting in a time consuming analysis.

The other technique is to divide the curve at the mid-point along the time domain and then calculate the area under each of the curves. This can be most easily accomplished by selecting a scene in the sequence that was obtained at or near the mid-point in the season. The computations can be produced much faster than the previous method as well as provide a constant reference point along the time domain. A single index value is calculated as 100 percent (total area under the curve) minus the percentage of the area of the early season curve as a part of the total area. The index value increases as the highest NDVI values occur later in the growing

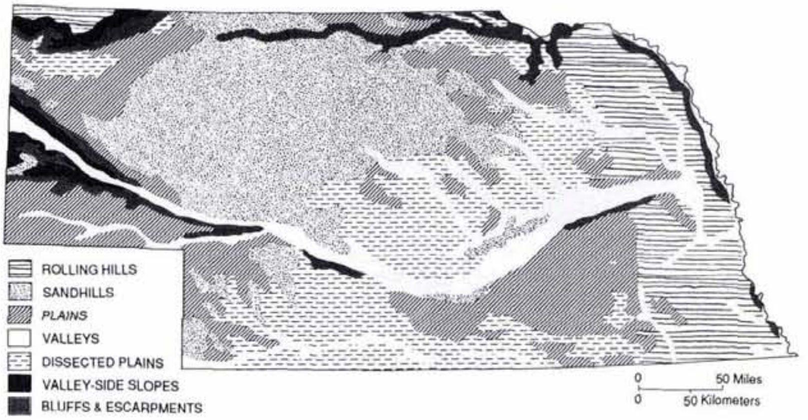

Figure 4. Topography of Nebraska (Baltensperger, 1985).

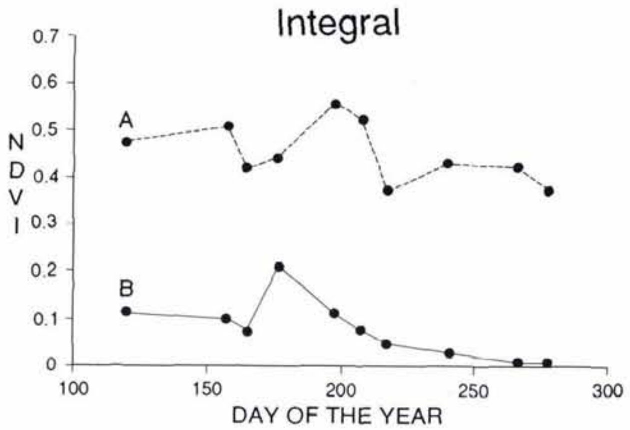

Figure 5. Curve "A" represents a high integral index while curve "B" is characteristic of a relatively low integral index.

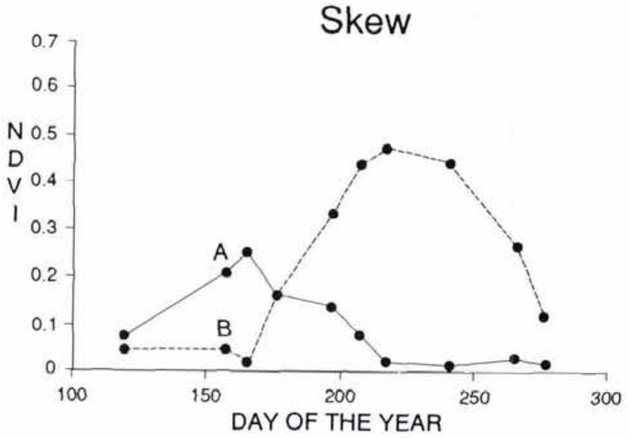

Figure 7. Curve "A" represents a low skew index while curve "B" is characteristic of a high skew index.

season. Because this index reflects the time in the season when the largest accumulation of NDVI values occur, it can be thought of as a measure of the skew of the observed data values. This "skew" index complements the magnitude measurement of the integral index with a measure of when the highest NDVI values occurred in the observed sequence.

Another seasonal parameter that may be derived from the spectral profile relates to the variation in the NDVI values over the observed season. Some plant species, such as conifers, maintain a relatively constant spectral response over time, while deciduous vegetation will have a changing response throughout its growing season. Along with differences in plant species, NDVI values will vary through the season with land tenure. For example, an extensive tract of plowed agricultural land that is planted to corn will exhibit a wide range of NDVI values in contrast to smaller fields interspaced with pasture. This additional temporal index, to be referred to as the "range index," will reflect the range of NDVI values which can be observed for a given geographic area. Small range index values indicate little change in NDVI values over the observed season for a given area, while relatively higher index values show a greater variation in NDVI values.

Example of the Application of the Curve Indices

To demonstrate the application of the skew and range indices, ten scenes of NOAA-10 AVHRR HRPT data from 1987 were selected for an area centering on Nebraska. The scenes were chosen on the basis of availability, near-nadir location of the evaluation site, and minimal cloud cover. The scene identification numbers and dates of the images are given in Table 1. Digital numbers associated with cloud cover were determined through manual thresholding of their thermal properties, using Channel 4. Pixels with cloud coverage on any of the ten dates were assigned a value of zero. If a zero was encountered on any of the ten images during the computation of an index, the pixel was automatically given a value of zero.

Digital counts were converted to radiance values, using the coefficients developed by Neckel and Labs (Price, 1988). The radiance values were also adjusted for solar angle bias. The normalized difference vegetation index (NDVI) was com-

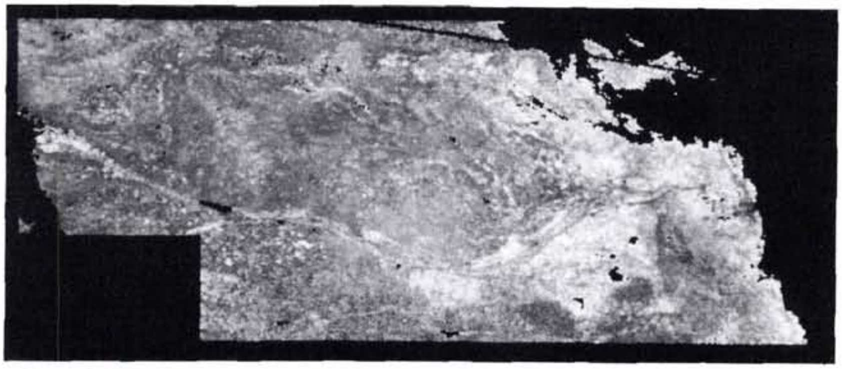

Figure 6. "Integral" image generated from ten AVHRR scenes. Light tones are indicative of high biomass while darker tones represent relatively lower biomass.

Figure 8. "Skew" image generated from ten AVHRR scenes. Dark tones represent early season physical maturity while light tones are indicative of physical maturity later in the season.

puted for each image, using the equation

$$\text{NDVI} = \frac{\text{Chan 2} - \text{Chan 1}}{\text{Chan 2} + \text{Chan 1}}$$

where "Chan 1" is the first channel (0.58 to 0.68 micrometres) and "Chan 2" is the second channel (0.72 to 1.10 micrometres) from the AVHRR. After data analysis, the index images were resampled to an Albers Equal Area projection. Images were georeferenced to within a root-mean-square error (RMSE) of 1 pixel (Table 2). The eight ground control points were selected from the reservoir side of eight large water bodies that were impounded by dams.

The trapezoidal method of determining the integral of the curve (Riddle, 1974) was used because the dates of the images were obtained at unequal time intervals. As described earlier for the skew index, the ten scenes were divided into two groups to correspond to the first and second halves of the total time period. The first interval was from 29 April to 16 July and the second interval from 16 July to 3 October. For each pixel in the scene, the integral of each half of the curve was calculated. The sum of the two areas provided the measurement of the total area under the curve. The skew and range indices were calculated as previously described. A general land-cover map (Figure 3) and a topography map (Figure 4) of Nebraska are provided as references for discussion on land cover and landform influences on the indices.

Figure 5 shows examples of two pixels in the study area with low and high integral values. While integration has been used often in previous studies, these examples are provided for comparison with the skew and range indices. Assuming that the NDVI is a measure of biomass, as noted in previously cited works, the integral for the upper curve ("A") indicates a relatively greater amount of biomass over the observed season than that of the lower curve ("B").

Figure 6 is the image created by integrating the curve that was formed for each pixel from the ten NDVI images. Low integral values (low biomass) are represented by dark tones on the image while high integral values (high biomass) correspond to light gray tones. The rangelands of north-central and western Nebraska (top center and left) are darker gray than the cultivated cropland (primarily, corn, soybeans, and grain sorghum) in the eastern sections of the state (right) and along the river valleys. As expected, the biomass observed for cropland over the observed period is much higher than that found with grasses on rangeland.

Examples of the skew index for two pixels are given in Figure 7. As explained previously, the lower skew index values indicate that relatively high NDVI values accumulated early in the first half of the observed time sequence, while larger skew index values indicate that the NDVIs accumulated later in the season. Under the smaller curve ("A"), the biomass accumulation is not as great as that represented by the larger curve ("B"). The curve labeled "A" was selected from the region of the cool-season grasslands where biomass accumulation occurs early in the growing season but becomes dormant by the mid-summer months. The larger curve ("B"), selected from an area of cultivated cropland, shows a greater accumulation of NDVIs after the mid-point of the observed period. This is attributed to the cultivated areas where biomass is limited in the early months of the growing season but accumulates as the crop reaches full maturity by mid-summer.

Figure 8 is the skew index image created from the NDVI images. Dark gray tones (low index values) are indicative of

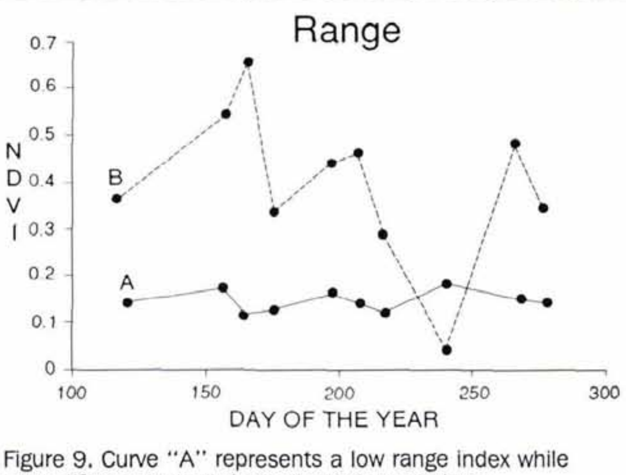

Figure 9. Curve "A" represents a low range index while curve "B" is characteristic of a high range index.

early season physical maturity (when biomass is at its greatest) while light gray patterns (high index values) represent later physical maturity in the observed sequence. The darker tones in the image show early season biomass accumulation in the cool-season grasses throughout the state. The higher values are indicative of cultivated land where biomass accumulation occurs in mid to late summer. A very dark pattern is present in the northwest region in the state (upper left), an area referred to as the Pine Ridge. The vegetation of the Pine Ridge is composed of coniferous forests and cool-season grasslands and is a unique physiographic region in the state. Immediately to the south of this area (far left), along the Platte River, are very high index values associated with cropland. Cultivated crops in the higher elevations of western Nebraska mature later in the growing season than do similar crops in the eastern part of the state, resulting in lighter gray tones in the former area than in the latter.

Extremes observed in the range index are represented by two pixels in Figure 9. An image derived from this index is shown in Figure 10. The lower curve ("A") in Figure 9 represents a relatively unchanging condition in the NDVI values. Areas having low range index values are indicative of somewhat consistent NDVIs through the observed period of data collection. The overlying curve ("B") shows greater variation in the NDVIs throughout the observed period. This curve reflects dynamic seasonal changes in biomass conditions at a given pixel. The variations can be attributed to the alterations in land cover, such as a change from bare soil to high biomass crop cover.

As with the skew index image, the consistent, or low range, index values are found on grasslands while the higher range index values are associated with cultivated land. However, there appears to be a greater amount of detail in the land cover presented in the cultivated areas of southeastern Nebraska (lower right). A large amount of variation in the range index values over the growing season is apparent on the Loess Plains (located in the southeast portion of the state), immediately to the west of a glaciated region, which exhibit relatively lower index values. A greater percentage of the land in the Loess Plains is cultivated than the area to the east of the Plains. This would account for the wide range in NDVI values for a given pixel on the Loess Plains. The relatively lower values in the adjacent glaciated areas reflect a mix of pasture and cultivated land. Major urban areas in southeast Nebraska – Lincoln and Omaha – have low index values because of the relatively static spectral response over the observed period.

Table 3. Pearsons Correlation Coefficients for the Images Compiled from the Three Vegetation Indices

	Integral	Skew	Range
Integral	1.000		
Skew	0.600*	1.000	
Range	0.484*	0.354*	1.000

* Significant at 0.001

Pearson's correlation coefficients were computed among the three indices to determine if the skew and range indices were redundant with the index calculated from the integral. The correlations given in Table 3 indicate that there is little redundancy among the indices. While the qualitative interpretation of the three images compiled from the indices initially appear to show that the grasslands can be delineated from the cultivated areas in the state, these indices are also providing information about the phenology of the vegetation across the state. Concurrent interpretation of the three indices can be used not only to identify differences in cover type but also to provide a relative indication when physiological maturity occurs among similar cover types.

Conclusions

Two temporal indices have been formulated to be used as a complement to the integral index. The skew and range indices differ from the integral index in that they characterize the shape of the seasonal spectral profile. When used in combination, it is possible to characterize the vegetative landscape in terms of biomass, the approximate time of physical maturity, and the amount of variation in the biomass accumulated throughout the observed season. Although several data sets are required to use these indices, the cost of AVHRR data for one growing season is less than the cost of one SPOT or Landsat TM digital scene. The number of AVHRR scenes will depend upon the anticipated amount of variation that would be observed in the NDVI values over a given time. Vegetated areas that experience relatively dynamic changes

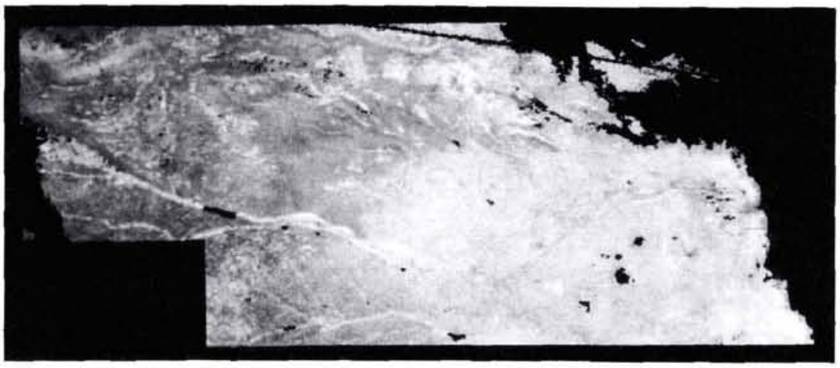

Figure 10. "Range" image generated from ten AVHRR scenes. Dark tones represent small change in biomass accumulation over the observed season while light tones are indicative of a relatively greater range in biomass change.

in phenology over a short time will require more AVHRR scenes than areas that exhibit slower changes in phenology.

These indices offer an alternative approach to the conventional techniques used in remote sensing to classify plant types. Rather than evaluate the multispectral properties of plant types obtained from one or more periods during a growing season, the proposed indices, when used in combination, can distinguish plant types on the basis of their respective phenologies. The indices can also be used to identify deviations in phenology from "norms" defined by crop calendars. These deviations may be associated with drought, unseasonably cool or warm periods, or disease or insect damage.

Additional work is needed to evaluate these indices as they are compiled over several years. Changes in the indices over time may reflect variations in land tenure or the impact of some type of climatological event, such as a drought. In cases where the type of vegetative cover does not change from year to year, such as with grasslands, it may be possible to use these indices as a substitute for ground-level meteorological measurements. This application would be especially important in semi-arid areas where the placement of field recorders for temperature and precipitation would be economically prohibitive.

References

Achard, Frederic, and Francois Blasco, 1990. Analysis of vegetation seasonal evolution and mapping of forest cover in West Africa with the use of NOAA AVHRR HRPT data, *Photogrammetric Engineering & Remote Sensing*, 56(10):1359-1365.

Baltensperger, Bradley H., 1985. *Nebraska: A Geography*. Westview Press, Boulder, Colorado.

Dusek, D.A., R.D. Jackson, and J.T. Musick, 1985. Winter wheat vegetation indices calculated from combinations of seven spectral bands, *Remote Sensing of Environment*, 18(3):255-267.

Gallo, K.P., and C.S.T. Daughtry, 1987. Differences in vegetation indices for simulated Landsat-5 MSS and TM, NOAA-9 AVHRR, and SPOT-1 sensor systems, *Remote Sensing of Environment*, 23(3):439-452.

Gallo, K.P., C.S.T. Daughtry, and M.E. Bauer, 1985. Spectral estimation of absorbed photosynthetically active radiation in corn canopies, *Remote Sensing of Environment*, 17(3):221-232.

Gardner, B.R., B.L. Blad, D.R. Thompson, and K.E. Henderson, 1985. Evaluation and interpretation of thematic mapper ratios in equations for estimating corn growth parameters, *Remote Sensing of Environment*, 18(3):225-234.

Hatfield, J.L., G. Asrar, and E.T. Kanemasu, 1984. Intercepted photosynthetically active radiation estimated by spectral reflectance, *Remote Sensing of Environment*, 14(1-3):65-75.

Hinzman, L.D., M.E. Bauer, and C.S.T. Daughtry, 1986. Effects of nitrogen fertilization on growth and reflectance characteristics of winter wheat, *Remote Sensing of Environment*, 19(1):47-61.

Justice, C.O., and P.H.Y. Hiernaux, 1986. Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger 1983, *International Journal of Remote Sensing*, 7(11):1475-1497.

Justice, C.O., B.N. Holben, and M.D. Gwynne, 1986. Monitoring East African vegetation using AVHRR data, *International Journal of Remote Sensing*, 7(11):1453-1474.

Lo, Thomas H.C., Frank L. Scarpace, and Thomas M. Lillesand, 1986. Use of multitemporal spectral profiles in agricultural land-cover classification, *Photogrammetric Engineering & Remote Sensing*, 52(4):535-544.

Lloyd, D., 1990. A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery, *International Journal of Remote Sensing*, 11(12):2269-2279.

Miller, G.E., 1981. *A Look at the Commonly Used Landsat Vegetation Indices*, NASA, Texas.

Nebraska Conservation and Survey Division, 1973. *General Land Use in Nebraska - Summer 1973*. University of Nebraska, Lincoln, Nebraska.

Perry, Charles R., Jr., and Lyle F. Lautenschlager, 1984. Functional equivalence of spectral vegetation indices, *Remote Sensing of Environment*, 14(1-3):169-182.

Philipson, Warren R., and William L. Teng, 1988. Operational interpretation of AVHRR vegetation indices for world crop information, *Photogrammetric Engineering & Remote Sensing*, 54(1):55-59.

Price, John C., 1987. Calibration of satellite radiometers and the comparison of vegetation indices, *Remote Sensing of Environment*, 21(1):15-27.

———, 1988. An update on visible and near infrared calibration of satellite instruments, *Remote Sensing of Environment*, 24(4):419-422.

Prince, S.D., and C.J. Tucker, 1986. Satellite remote sensing of rangelands in Botswana II. NOAA AVHRR and herbaceous vegetation, *International Journal of Remote Sensing*, 7(11):1555-1570.

Richardson, A.J., and C.L. Wiegand, 1977. Distinguishing vegetation from soil background information, *Photogrammetric Engineering & Remote Sensing*, 43(12):1541-1552.

Riddle, Douglas F., 1974. *Calculus and Analytical Geometry, Second Edition*, Wadsworth Publishing Company, California, 848 p.

Teng, William L., 1990. AVHRR monitoring of U.S. crops during the 1988 drought, *Photogrammetric Engineering & Remote Sensing*, 56(8):1143-1146.

Townshend, J.R.G., and C.O. Justice, 1986. Analysis of the dynamics of African vegetation using normalized difference vegetation index, *International Journal of Remote Sensing*, 7(11):1435-1452.

Tucker, Compton J., Brent N. Holben, James H. Eglin, Jr., and James E. McMurtey III, 1980. Relationship of spectral data to grain yield variation, *Photogrammetric Engineering & Remote Sensing*, 46(5):657-666.

———, 1981. Remote sensing of total dry-matter accumulation in winter wheat, *Remote Sensing of Environment*, 11(2):171-189.

Walsh, Stephen, 1987. Comparison of NOAA AVHRR data to meteorologic drought indices, *Photogrammetric Engineering & Remote Sensing*, 53(8):1069-1074.

(Received 19 February 1991; revised and accepted 8 July 1992)