HARMONIC ANALYSIS OF TIME-SERIES AVHRR NDVI DATA FOR CHARACTERIZING US GREAT PLAINS LAND USE/LAND COVER

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ABSTRACT

Harmonic analysis of a nine-year time series of NOAA AVHRR Normalized Difference Vegetation Index (NDVI) data was used to develop an innovative technique for land use/land cover identification based on temporal changes in NDVI values. Different land cover types exhibit distinctive seasonal patterns of NDVI variation that often have strong periodic characteristics. Harmonic analysis, also termed spectral analysis or Fourier analysis, decomposes a time-dependent periodic phenomenon into a series of sinusoidal functions, each defined by unique amplitude and phase values. Each harmonic term accounts for a proportion of the variance in the original time series. Amplitude and phase angle images were produced from analysis of the time-series NDVI data and correlated with information on vegetation and crop type for the region to develop a methodology for land use/land cover identification. Agricultural land use/cover occurring in the western US Great Plains, including corn, winter wheat, alfalfa, and native prairie grasslands, were characterized and identified using harmonic analysis and biweekly AVHRR composite data for 1992-1997. High amplitude values for a given term indicate a high level of variation in temporal NDVI, and the term in which that variation occurs indicates the periodicity of the event. For crops with a simple phenology, such as corn, the majority of the variance is captured by the first and additive terms of the harmonic analysis, while winter wheat exhibits a bimodal NDVI periodicity with the majority of the variance accounted for by the second harmonic term. Changes in seasonal amplitude or phase indicate changes in land use/cover type or in vegetation condition from drought, flooding, or overgrazing.

1 INTRODUCTION

Land use and land cover mapping projects are increasingly using seasonal changes in vegetation spectral response to improve the accuracy of vegetation and land cover classes (Egbert et al., 1995; Loveland et al., 1995; Schriever and Congalton, 1995). The temporal domain of multispectral data often provides more information about land cover type and condition than the spatial, spectral, or radiometric domains (Reed et al., 1994; Eastman and Fulk, 1993; Samson, 1993). While excellent results have been obtained in multi-temporal studies that use a small number of multispectral images (e.g., two to ten), multitemporal analysis is moving toward exploiting the information contained in temporally-dense (daily, weekly, or biweekly) data sets that may contain upwards of several dozen to several hundred images.

Characterization and mapping of land use/land cover types using the NOAA Advanced Very High-Resolution Radiometer (AVHRR) biweekly 1 km resolution data has typically taken one of two approaches: classification of multitemporal data using maximum likelihood or other classification algorithms (Loveland et al. 1995; Brown et al. 1993; Loveland et al. 1991); and temporal profiles of land cover phenology as manifested in the Normalized Difference Vegetation Index (NDVI) (DeFries et al., 1995; Reed et al., 1994; Lloyd, 1990). To date, only a few researchers in remote sensing have applied true time series analysis methods to temporally dense sequences of remotely sensed imagery (Andres et al., 1994; Sellers et al.,1994; Menenti et al., 1993) .

This paper describes an application of harmonic analysis to a nine-year time series (1989 - 1997) of NOAA-AVHRR NDVI biweekly composite data to model seasonal and interannual variation in vegetation condition as manifested in the NDVI. Temporal profiles of seasonal NDVI for several land cover and land use types in western Kansas were decomposed by harmonic analysis into component cosine curves with term-specific phase and amplitude coefficients. Interannual variation in harmonic terms was assessed by computing year-to-year changes in per-term amplitude and phase.

2 METHODS

2.1 Study area: Southern Great Plains

The southern Great Plains region encompasses the geographic area 40° N 103° W to 34° N 98° W. Dryland and irrigated agriculture, sandsage prairie, shortgrass prairie, and shrubland dominates the land cover in this region. Dryland agriculture consists primarily of winter wheat with the heaviest concentrations located in the “wheat belt” (north-central Oklahoma and south-central Kansas). Irrigated agriculture (predominately corn, milo, and alfalfa) is concentrated in several areas including areas along the Arkansas River and in the lower portion of the Texas panhandle. The study area has relatively flat landscape with the exception of the sandhills in southwest Kansas, the Oklahoma and Texas panhandle, and eastern Colorado and the steep slopes along rivers such as the Cimarron.

2.2 AVHRR times-series NDVI data

Nine years of NOAA-AVHRR NDVI biweekly composites for 1989 - 1997 were acquired from the US Geological Survey EROS Data Center in Sioux Falls, South Dakota. Each biweekly NDVI composite image consists of the maximum NDVI value within a defined two-week period for each pixel (Eidenshink, 1992). Vegetation index data are rescaled by EROS during processing from a range of -1.0 to +1.0, to 0 to 200. Values less than 100 typically represent snow, ice, water, and other non-vegetated earth surfaces. Data were downloaded from CD-ROMs, co-registered, and images for missing biweekly composite periods were created by averaging image data for periods bracketing the missing period (e.g., the previous and succeeding periods). Each year of the nine-year data set contained 26 biweekly images.

2.3 Harmonic analysis

Briefly defined, harmonic (Fourier) analysis permits a complex curve to be expressed as the sum of a series of cosine waves (terms) and an additive term (Davis, 1986; Rayner, 1971). Each wave is defined by a unique amplitude and a phase angle, where the amplitude value is half the height of a wave, and the phase angle (or simply, phase) defines the offset between the origin and the peak of the wave over the range 0 to 2π (Figure 1a). Each term designates the number of complete cycles completed by a wave over the defined interval (e.g., the second term completes two cycles) (Figure 1b). Successive harmonic terms are added to produce a complex curve (Figure 1c), and each component curve, or term, accounts for a percentage of the total variance in the original time-series data set. Images of the additive term, and amplitude and phase angle for each term to the seventh harmonic were produced on a per-pixel basis for each year of data (26 periods) in the nine-year NDVI data set, using the procedures described by Jakubauskas et al (2000), modified from Davis, 1986).

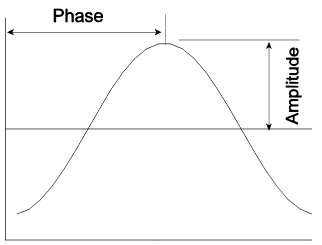

Figure 1a. Simple cosine curve representative of the first harmonic.

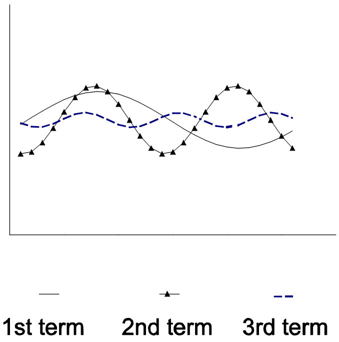

Figure 1b. Curves for harmonic terms 1, 2, and 3.

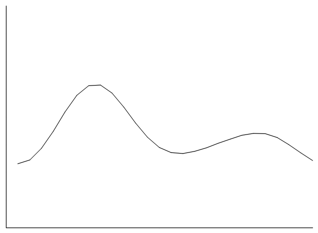

Figure 1c. Curve produced from addition of curves in Figure 1b.

2.4 Analysis of inter-annual variability

A derivative measure of inter-annual variability was derived from the phase values produced by the harmonic analysis. Because phase angles are directional, circular variance was calculated as a measure of variation (Davis, 1986). Circular variance in each image is calculated by first calculating the length of the vector resultant:

$$R = \sqrt{X_r^2 + Y_r^2}$$

where X_r and Y_r are equal to the sum of the cosines and sines, respectively, of the individual vectors. To calculate dispersion in the data, the resultant length, R is subtracted from the number of observations, n and then divided by the number of observations, $(s^2_o = (n - R)/n)$ (Davis, 1986). High circular variance indicates that phase values are closely clustered together (e.g., occur within 1-2 periods, indicating a consistent timing of phase during a year), while low circular variance indicates that phase values occur in multiple dispersed periods.

3 RESULTS AND DISCUSSION

3.1 Harmonic characteristics of Southern Great Plains land use/land cover

Land use and land cover types in the study area were characterized by amplitude and phase values derived from the NDVI biweekly composites. The additive term is equivalent to the mean NDVI over the 26 biweekly periods and indicates overall greenness of the vegetation. Grasslands and shrublands have lower additive term values than dryland and irrigated agriculture. Amplitude indicates the level of variation in temporal NDVI with high amplitudes indicating wide ranges of seasonal variation in NDVI. A high first-term amplitude indicates a unimodal greenness pattern while a high second-term amplitude indicates a bimodal greenness pattern. Phase angle indicates the periodicity at which the peak value for a term occurs and has a range of 0 to 2π. A phase angle close to π indicates a midsummer peak.

Irrigated corn and alfalfa in the Great Plains exhibit a strongly unimodal periodic pattern, with a high amplitude value in the first term and low amplitude values in successive terms (Figure 2). Row crops and grasslands have a first-term phase angle close to π, meaning that the peak greenness period is close to midsummer. The majority of the total variance in seasonal NDVI for corn is contained in the first harmonic term. Grassland and shrubland exhibit a unimodal phenological pattern similar to corn (Figure 3), with high first-term amplitude values and the majority of the variance (> 90%) in the first harmonic term. First-term phase values indicate that peak greenness for grasslands occurs during July, consistent with the warm-season nature of the grass species.

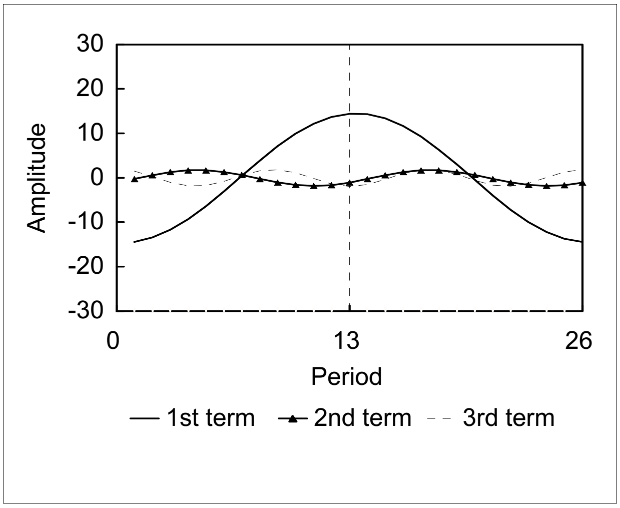

Figure 2. First three harmonic curves for corn.

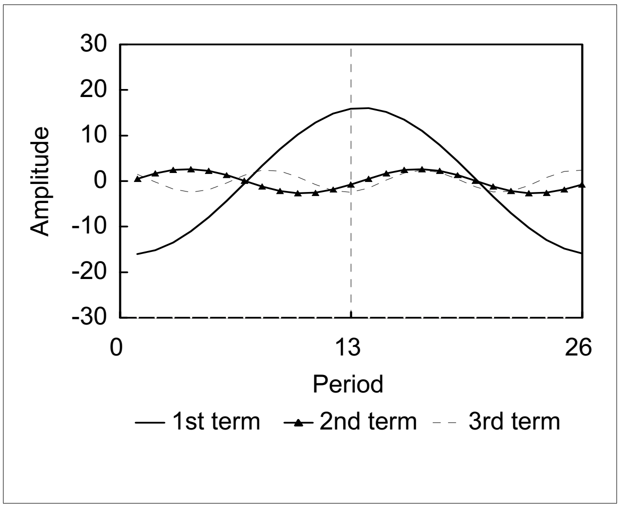

Figure 3. First three harmonic curves for grasslands

Alfalfa, although it also exhibits a strong summer-peak greenness pattern (Figure 4), differs from the strongly unimodal pattern of corn and grass in that it has relatively high second- and third-term amplitudes resulting from cultivation practices. Alfalfa is harvested repeatedly during the summer, producing a secondary and tertiary periodicity in greenness with the growth-cutting-growth-cutting-growth cycle during the summer. Irrigated alfalfa is typically harvested four times in western Kansas during a typical growing season, beginning in May and extending until July-September.

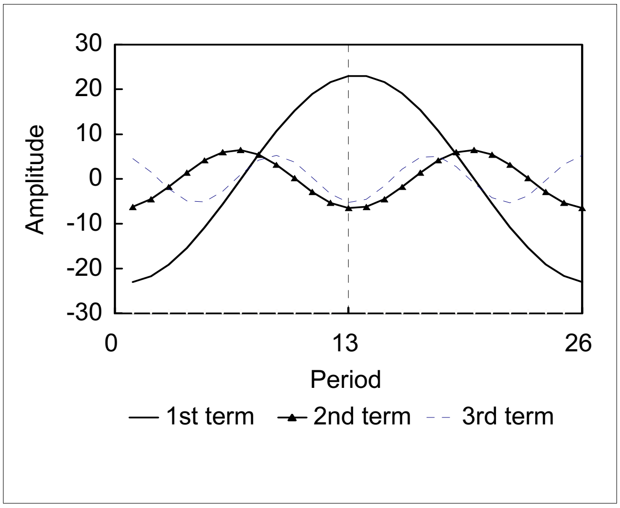

Figure 4. First three harmonic curves for alfalfa.

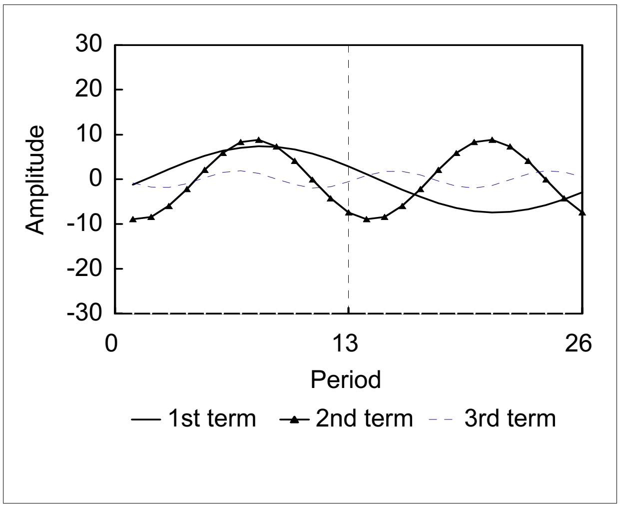

Figure 5. First three harmonic curves for winter wheat

Winter wheat has a strikingly different phenological patterns in comparison to other crop types described above in that it exhibits a bimodal temporal NDVI curve. The second harmonic term has the highest amplitude and contains the majority of the variance (Figure 5). Winter wheat is planted in the fall (late September/early October), sprouts, and goes dormant over winter and may be covered by snow. In the spring, the wheat greens up and is harvested by May, followed by plowing or fallow.

3.2 Interannual Variability

Year-to-year changes in the amplitude and phase values of a harmonic term are indicative of change in land use or land cover. Changes in the amplitude of a given term, with the phase value for that term remaining constant, may indicate changes in land use/land cover type or degradation in vegetation condition resulting from drought, flooding, or overgrazing. Interannual variations in the phase values of a term, with the amplitude remaining unchanged, may indicate climatologically-driven variations in the time of onset of greenness or maximum greenness.

3.21 Multi-year changes in first-term amplitude. An area within the study region that has undergone a significant increase in first-term amplitude values during the nine-year period occurred in southeastern Colorado. This area represents a major human-induced directional change in land cover and land use. In the late 1980s, over 50,000 hectares of former winter wheat-producing land in this area was enrolled into the United State Department of Agriculture Conservation Reserve Program (CRP). In 1989, the first year in the time series data set, CRP vegetation (a mixture of cool- and warm-season grasses) had just been established. As the vegetation cover became more established, a more pronounced greenness pattern developed, producing progressively higher first-term amplitude values (Figures 6 and 7).

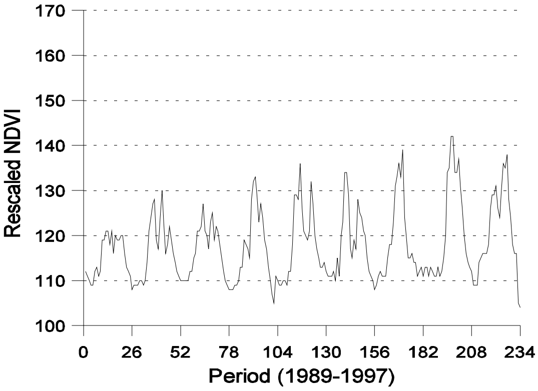

Figure 6. Nine years of biweekly NDVI values (26 periods per year, 234 periods total) for winter wheat cropland converted to grassland, showing progressive increase in seasonal amplitude of NDVI values.

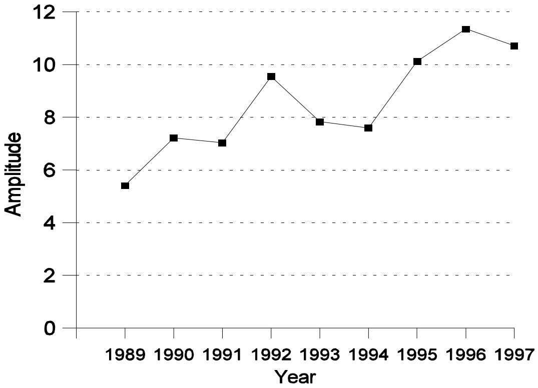

Figure 7. Nine-year increase in first-term harmonic amplitude for winter wheat cropland converted to warm- and cool-season grasslands under the Conservation Reserve Program.

3.22 Interannual changes in phase values. Row crops and grassland, whose phenology is driven by principally by seasonal climatic factors, tend to have strongly unimodal NDVI curves with the majority of the variance in the data captured by the first harmonic term. Inter-annual variation in the timing, peak, and duration of greenness for these strongly unimodal land cover types is minimal, producing low circular variance for the first-term phase, indicted by dark areas in Figure 8. This low first term circular variance indicates that the first term phase value does not vary greatly from year to year, and that the timing of vegetation peak greenness is seasonally consistent. Winter wheat has a bimodal greenness pattern, and a greater percentage of the overall variance in the original data is explained by the second harmonic term. Winter wheat has high circular variance in the first term phase (lighter tones in Figure 8), and low second-term circular variance (dark areas on Figure 9), indicating consistent phase, or seasonal time of peak greenness. Second-term circular variance for land cover types with unimodal phenological patterns, however, is high. Circular variance was not consistent for shrublands and grasslands, although shrublands in western Texas and grasslands in eastern Colorado and western Kansas tend to have moderate to high circular variance in the first-term phase.

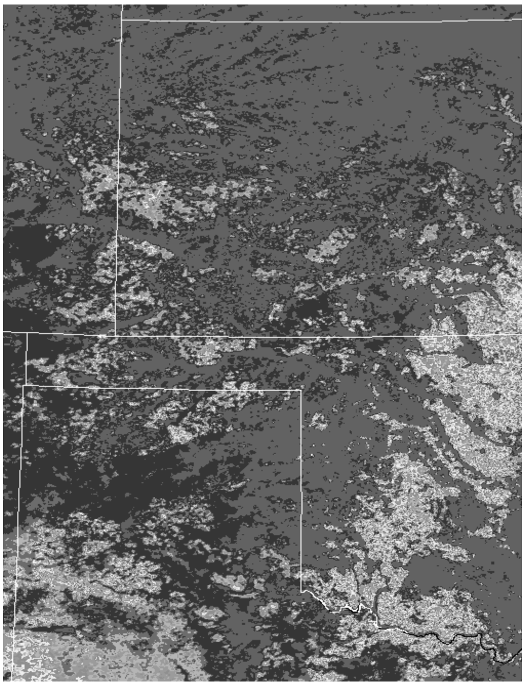

Figure 8. First term circular variance. Dark tones indicate low circular variance (consistent phase values), while lighter tones indicate high year-to-year variability in first-term phase.

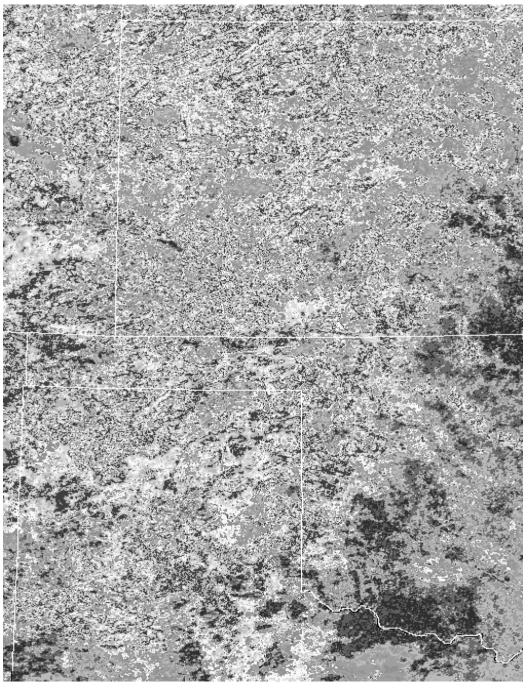

Figure 9. Second term circular variance. Dark tones indicate low circular variance (consistent phase values), while lighter tones indicate high year-to-year variability in second-term phase.

4 CONCLUSIONS

The objective of this study was to characterize seasonal and inter-annual variability of natural and managed land cover types in the southern Great Plains using harmonic analysis of a nine-year time series of NOAA AVHRR NDVI imagery. Seasonal, inter-annual, and directional change in land use/land cover condition were quantified as changes in phase and amplitude values in different terms of the harmonic analysis. Harmonic analysis of time-series data provides an unbiased, replicable method for assessing change and stability in sensitive landscapes, and offers considerable promise as a tool for monitoring directional landscape change.

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