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A Comparative Analysis of Phenological Curves for Major Crops in Kansas

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Abstract: The goal of this research was to conduct an initial investigation into whether a time-series NDVI reference curve library for crops over a growing season for one year could be used to map crops for a different year. Time-series NDVI libraries of curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 dataset could be used to map crops for 2005. The 2005 16-day composite MODIS 250 m NDVI data were used to extract NDVI values from 1,615 field sites representing alfalfa, corn, sorghum, soybeans, and winter wheat. A *k*-means cluster analysis of NDVI values from the field sites was performed to identify validation sites with time-series NDVI spectral profiles characteristic of the major crop types grown in Kansas. After completing the field site refinement process, there were 1,254 field sites retained for further analysis, referred to as "final" field sites. The methods employed to evaluate whether the MODIS-based NDVI profiles for major crops in Kansas are stable from year-to-year involved both graphical and statistical analyses. First, the time-series NDVI values for 2005 from the final field sites were aggregated by crop type and the crop NDVI profiles were then visually assessed and compared to the profiles of 2001 to ascertain if each crop's unique phenological pattern was consistent between the two years. Second, separability within each crop class in the time-series NDVI data between 2001 and 2005 was investigated numerically using the Jeffries-Matusita (JM) distance statistic. The results seem to suggest that time-series NDVI response curves for crops over a growing period for one year of valid ground reference data may be useful for mapping crops for a different year when minor temporal shifts in the NDVI values (resulting from inter-annual climate variations or changes in agricultural management practices) are taken into account.

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INTRODUCTION

Mapping land use and land cover (LULC) patterns at regional, state, and global scales on a repetitive basis has been recognized (Turner et al., 1995; NRC, 2001; NASA, 2002) as a way of providing "up-to-date" LULC information and characterizing major human–environmental interactions. Crop mapping on an annual basis, therefore, can provide improved estimates of near real time changes in crop production and can greatly benefit strategic planning in agro-ecosystems.

Remote sensing techniques have been extensively used in crop mapping during the past several decades (Ehrlich et al., 1994; Maxwell and Hoffer, 1996; Congalton et al., 1998; Oetter et al., 2001; Maxwell et al., 2004; Xiao et al., 2006), providing timely assessments of conditions, changes in growth, and development of agricultural crops. In all these mapping efforts, the availability of high-quality ground reference datasets has been crucial. Hüni et al. (2007) and Lillesand et al. (1998) pointed out that most reference datasets are collected for purposes of training computer algorithms to recognize various land cover categories latent in the satellite imagery and assessing the categorical accuracy of the resulting classification. Different ground reference data collection methods are employed, depending on the application, the availability of primary sources of reference data, and the adequacy of interpretation and field staff (e.g., Khorram et al., 2001; Allen et al., 2002; Wickham et al., 2004; Wardlow et al., 2007).

Although reference data are vital in remote sensing–based research projects, in many cases and for various reasons, the data are of poor quality. There are several issues that impact the availability of high-quality reference data. First, the collection of reference data is an expensive process and adequate financial resources are often lacking to support this activity (Bronsveld et al., 1994). This problem is particularly common in Third World countries with inadequate resources at their disposal. Second, reference datasets, especially those related to plant phenomena that change over time, are often few in number and limited in their spatial and temporal validity (Bronsveld et al., 1994). Lillesand et al. (1998) acknowledged this constraint, by pointing out that ground reference data generally cannot be collected for large portions of an entire project area, or even for multiple time periods. Finally, in some instances the reference data are inadvertently inaccurate, outdated, unobtainable due to legal restrictions (e.g., inaccessibility to land parcels), or the locations are not easily accessible.

Although different reference data collection methods are available, most are time consuming, require substantial financial resources, and/or may not be undertaken on an annual basis. Dynamic agro-ecosystems, such as the ones found in the U.S. Great Plains, create a demand for collecting crop-related reference information and crop-related mapping activities on a regular basis. The present paper therefore serves as an initial investigation into whether a time-series NDVI reference curve library for crops over a one-year growing season can be used to map the same crops for a different year in the same location. In this case, time-series NDVI libraries of curves for 2001 and 2005 were investigated to ascertain whether or not the 2001 dataset could be used to map crops for 2005. An extensive, valid ground reference dataset is available for the state of Kansas, which was created for several MODIS-based crop mapping and monitoring projects conducted for 2001 (Wardlow et al., 2006, 2007; Wardlow and Egbert, 2008). Due to the rigorous process of selecting the field sites and curve refinement against field truth information, the 2001 Kansas profiles used in the series of these projects were considered to be a valid standard with which to compare. A 2005 Kansas Common Land Unit (CLU) data layer from the USDA Farm Service Agency (FSA) was available for use. The CLUs are polygons that correspond to individual field parcels for which the specific crop types grown are reported on annual basis by farmers and attributed to each polygon. Separate databases for five major crops (alfalfa, corn, sorghum, soybeans, and winter wheat) were created using GIS operations to select non-irrigated fields larger than 32.4 ha (80 acres, approximately five 250 m MODIS pixels) from the CLU data layer. The time-series NDVI values from 2005 MODIS were extracted using center points of the selected CLU polygons and refined using a *k*-means cluster analysis of NDVI values. The 2001 and 2005 sets of MODIS-based spectral profiles were subsequently compared visually as well as statistically using the Jeffries-Matusita (JM) distance statistic (Richards and Jia, 1999).

This research was initiated out of the recognition that reference datasets are often difficult and/or expensive to collect and therefore may not be available on an annual basis, even though it is often desirable to map land cover (especially crops) yearly. Hence the following key research question regarding this work in Kansas was addressed: Are MODIS-based NDVI spectral profiles of major crops (alfalfa, corn, sorghum, soybeans, and winter wheat) different between 2001 and 2005? The assumption was that the MODIS-based NDVI profiles of major crops in Kansas would be stable from year to year, with minor variations resulting from inter-annual climatic differences (both in precipitation and temperature). If this scenario were found to be true, it would be possible to use a multi-temporal NDVI curve library for crops over a growing season for one year, created from a high-quality and complete reference dataset, to map crops for a different year without any curve adjustments. To address the key research question, two sets of MODIS 250 m NDVI spectral profiles from different years were visually compared and statistically evaluated using the Jeffries-Matusita (JM) distance statistic (Richards and Jia, 1999) to determine their level of similarity.

STUDY AREA

This study was conducted in the state of Kansas (area 21.3 million ha [82,282 square miles]) of the U.S. Central Great Plains. The state has a mid-continental temperate climate with a pronounced east–west precipitation gradient that strongly influences vegetation types, cropping patterns, and associated agricultural management practices. On average, western Kansas receives 460–510 millimeters (mm) of precipitation per year, central Kansas 900 mm, and eastern Kansas 890–1020 mm. Seasonal temperatures are highly variable, with mean low temperatures of –6° C in January and mean high temperatures of 32° C in July. The majority of the precipitation falls during the growing season from April through September.

Extensive grasslands dominate the Kansas natural vegetation landscape. In the west, sparse rainfall gives rise to shortgrass prairie, while increased rainfall in the central part of the state generates mixed-grass prairie. In the east, adequate precipitation occurs to support tallgrass prairie that intermingles with oak–hickory deciduous forest in the far eastern part of the state. It has been observed that most of the remaining grasslands in the western two-thirds of the state are native, having never been plowed, and are primarily used for grazing domestic livestock, while in the tallgrass prairie region, grazing is also prevalent, but many grasslands (both introduced and native) are managed for hay production (Egbert et al., 1998).

A larger portion of the state's total area is intensively cropped with alfalfa (*Medicago sativa*), corn (*Zea mays*), sorghum (*Sorghum bicolor*), soybeans (*Glycine max*), and winter wheat (*Triticum aestivum*). Eastern Kansas generally receives adequate precipitation to support mainly corn and soybean production without irrigation and fallow is nonexistent. In semi-arid western Kansas, alfalfa, corn, and soybeans are grown under irrigation because of limited precipitation. High crop production levels are maintained due to extensive irrigation from primarily groundwater sources and dryland farming techniques (e.g., crop-fallow rotations and non-till farming). The non-irrigated areas of western Kansas are planted to dryland crops such as sorghum or winter wheat or remain fallow to conserve soil moisture for crop production the following year. The variability in the NDVI signals for a specific crop exhibited across the state is a confirmation of regional variations in climate and management practices (Wardlow et al., 2006). It has further been noted that Kansas also contains large acreages of former cropland that are now covered with native and non-native grasses as part of the USDA Conservation Reserve Program (CRP) (Egbert et al., 1998).

DATA AND METHODS

A 12-month time series of 16-day composite MODIS 250 m NDVI data for 2005 for field sites of five cover types—alfalfa, corn, sorghum, soybeans, and winter wheat—across Kansas was analyzed. A total of 1,254 field sites representing each of the five crop types under investigation were used as the basis for aggregating extracted time-series NDVI values and creating NDVI phenological curves. The 2001 curves were then compared to those from 2005. A brief discussion of the data and methods used is provided below.

Time-Series MODIS VI Data

In recent years, the application of MODIS data has become widespread among LULC research scientists. More literature is becoming available on crop condition and yield prediction (Doraiswamy et al., 2004; Muratova et al., 2005; Reeves et al., 2005; Xu et al., 2005) and crop classification and mapping (Doraiswamy et al., 2003; Xavier et al., 2006; Xiao et al., 2006; Wardlow and Egbert, 2008). The MODIS Land Science Team provides a suite of standard MODIS data products to users, which include the 16-day NDVI and enhanced vegetation index (EVI) composites. The MODIS NDVI serves as a "continuity index" to the existing AVHRR NDVI record (Lindsey and Herring, 2002). The procedure for generating composited, MODIS VI products is the "constrained view angle" maximum value compositing (CV-MVC) method, in which the highest NDVI value from a series of multitemporal georeferenced images within a specified range of view angles from nadir is retained for each pixel location in order to minimize cloud and atmospheric contamination and standardize sun/view angles (Huete et al., 1999, 2002; Van Leeuwen et al., 1999). MODIS is an improved instrument due to its better design (e.g., solar diffuser, solar diffuser stability monitor, spectro-radiometric assembly, and high level of geolocational accuracy) (Guenther et al., 2002; Wolfe et al., 2002). MODIS offers a unique and improved combination of spectral (36 bands), temporal (daily global coverage), spatial (0.25 to 1 km), and radiometric (12 bits) attributes, compared to previous sensors (Lindsey and Herring, 2002). Other desirable attributes include cost-free status and rapid availability of various products

The 16-day composite MODIS 250 m NDVI data (MOD13Q1 Version 004) spanning the period from January 1 to December 19, 2005 were acquired from the NASA Earth Observation System Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The MODIS dataset comprised 874 tiles (38 per composite period) for North America. For each composite period, the MODIS NDVI data were extracted for each tile and the data were mosaicked and reprojected from the Sinusoidal to the Albers Conical Equal Area projection. The reprojected mosaics, 23 in total, were then sequentially stacked by composite period and subset to the Kansas state boundary to produce the final time-series datasets of Kansas.

Common Land Unit (CLU) and Field Site Database for 2005

The USDA FSA has long been involved in the acquisition, use, and distribution of large-print aerial photography (photomaps) to achieve their farm program management tasks (Gabbott, 2003). The main purpose of the aerial photography enlargements was to provide an accurate geospatial record of farm tracts and field boundaries (Gabbott, 2003; Williams, 2004). The tract and farm field boundaries, known as Common Land Units (CLUs) were delineated on the aerial photography enlargements by FSA staff as a means to provide a visual representation of farm fields, thus allowing a common, intuitive way for staff and farmers to interact and record planted acreages (Williams, 2004). The USDA-FSA defines a CLU as an individual contiguous farming parcel, which is the smallest unit of land that has a permanent contiguous boundary, common land cover and management, and a common owner and/or common producer association (FSA, 2001, 2007).

According to Gabbott (2003), millions of aerial photography enlargements have been produced since the 1930s and many of them are still in use. Over the past years, however, the photo enlargements have changed as a result of the source imagery. Source imagery was flown at various scales including 1:20,000 during the period 1938–1979, high-altitude scales of 1:60,000 and 1:80,000 during 1980–1987, and 1:40,000 scale during the period 1987 to present. When FSA began implementing GIS in 1999 to better manage farm records and geospatial data and to enhance program delivery, National Digital Orthophoto Program (NDOP) imagery was used to delineate CLU boundaries with aerial photographic enlargements as a reference. As a result of the need to meet FSA's evolving requirements for imagery, the National Agricultural Program (NAIP) was established in 2003. The NAIP provides FSA with 9" × 9" large-format color digital imagery at 1:40,000 scale for the annual compliance program every year, and also supplies USDA Service Center agencies with current replacement orthophotography base imagery on a five-year cycle (Williams, 2004). The NAIP imagery is used to maintain CLU data continuously in the USDA county-based field service centers.

The USDA-FSA has outlined some of the many uses for CLUs (FSA, 2001, 2007). Although the potential uses for CLUs are many, most work is focused on replacing current paper maps with digital images, and using GIS to achieve greater accuracy

Table 1. Kansas Non-irrigated Crop Types and Sample Size for 2001 and 2005

Crop type	2001 sites after refinement	2005 sites before refinement	2005 sites after refinement
Alfalfa	119	149	138
Corn	279	348	290
Grain sorghum	319	398	268
Soybeans	219	274	230
Winter wheat	356	445	327
Total	1,292	1,615	1,254

in acreage calculations (FSA, 2001, 2007). CLUs are also used to generate agricultural training and validation data used in producing the USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (Allen et al., 2002). Since CLUs have the potential of providing up-to-date farm records, it is therefore a valuable resource for generating ground reference datasets for remote sensing–based applications.

A 2005 Kansas CLU data layer was available from the USDA FSA. However, only 64 counties had the necessary attributed data. Due to limited time, only non-irrigated fields were considered for this study. Separate databases for the five major crops were created by selecting non-irrigated fields larger than 32.4 ha (80 acres approximately five 250-m MODIS pixels) from the CLU data layer using GIS operations. Point-labeling all CLUs created center points for each crop polygon. The total number of initial samples for 2005 was 1,615 and the final sample size was 1, 254 (Table 1), after the initial reference dataset was subjected to cluster analysis (Romesburg, 2004), using *k*-means clustering, as explained in the methods section below.

Kansas Average NDVI Profiles for 2001

A total of 2,800 (i.e., non-irrigated = 1,292; irrigated = 1,508) verified field sites in Kansas were used by Wardlow et al. (2007) to extract time-series NDVI values from 2001 MODIS data. Average NDVI profiles were created for the five major crops of alfalfa, corn, sorghum, soybeans, and winter wheat. To refine the curves of these crop types, the profiles were visually evaluated to verify that their spectral characteristics were consistent with the phenology of the crop type reported by the FSA. Each refined curve was considered a standard NDVI profile for the respective crop type in Kansas. Due to the rigorous process of selecting the field sites and curve refinement against field truth, the 2001 Kansas profiles were considered to be a valid standard with which to compare the 2005 profiles. Although slight curve time-shifts were anticipated between 2001 and 2005 because of variation in precipitation management practices, and regional shifts in a crop's NDVI curve that were found across Kansas in 2001 (Wardlow et al., 2007), it was expected that the curve patterns would be the same.

Methods

A total of 1,615 initial field sites for 2005 (Table 1), representing the five crop types under investigation, were used as a basis for extracting time-series NDVI values. The extracted NDVI data from the initial field sites for each crop type were subjected to Cluster Analysis (Romesburg, 2004), using *k*-means clustering, as a way of evaluating variability among field sites within each crop type, and to identify and eliminate outliers. Several cluster sizes were tried and in each case profiles were plotted and visually examined. Because some larger cluster sizes did not have members, the maximum cluster size of 10 was assumed adequate, and subsequently 10 clusters were retained for each crop. The 2005 NDVI cluster profiles were visually compared to the 2001 MODIS-based profiles for the same crops in Kansas. Each crop's NDVI cluster profiles that were consistent with the spectral-temporal profiles of the same crop in Kansas were aggregated to represent crop-specific state-level multi-temporal NDVI profiles. Outliers and sites atypical of Kansas's crop phenology (361 in total) were identified and removed. The final field sites, totaling 1,254 (Table 1) whose average NDVI profiles appeared to be consistent with the known crop profiles, constituted the crop reference dataset for Kansas in 2005. The 2005 sites, like for 2001, were appropriately distributed across the state (Fig. 1) and thus were considered to be a good representation of the crop distribution pattern in 2005.

The methodology employed in this study to evaluate whether the MODIS-based NDVI profiles for major crops in Kansas are stable from year to year involved both graphical and statistical analyses. First, the time-series NDVI values for 2005 for the final field sites were aggregated by crop type and the crop NDVI profiles were then visually assessed and compared to the profiles of 2001 to ascertain if each crop's phenological pattern (as represented in NDVI response curves) was consistent between the two years. Second, separability within each crop class in the time-series NDVI data between the two study years was investigated numerically using the Jeffries-Matusita (JM) distance statistic (Richards and Jia, 1999). JM distance has been affirmed in previous research work to be an effective measure for class separability (Van Niel et al., 2005; Wardlow et al., 2007). Under normality assumptions, the JM distance between classes *i* and *j* is given by

$$JM_{ij} = 2(1 - e^{-a}),$$

$$\text{where } a = \frac{1}{8}(\mu_i - \mu_j)^T\left(\frac{\Sigma_i + \Sigma_j}{2}\right)^{-1}(\mu_i - \mu_j) + \frac{1}{2}ln\left(\frac{\left|\frac{\Sigma_i + \Sigma_j}{2}\right|}{|\Sigma_i|^{1/2}|\Sigma_j|^{1/2}}\right).$$

In this study, μ_i and μ_j are the class-specific mean NDVI values at a particular time period (or, more generally, vectors of mean values for a span of time periods), and $\sum_i$ and $\sum_j$ are unbiased estimates for the class-specific variance at the time period (or, more generally, covariance matrices for a span of time periods). JM distance values range between 0 and 2. A maximum JM distance of 2 between two classes means that the class-specific distributions are perfectly distinguishable from each other,

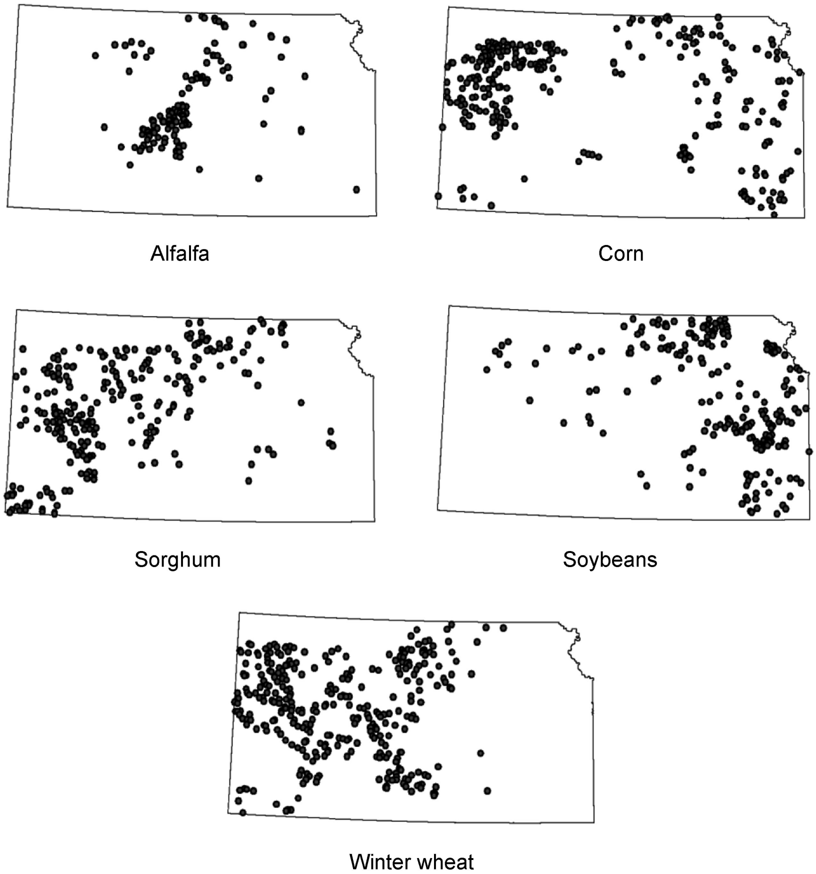

Fig. 1. Retained field site locations by crop type for the 2005 dataset.

whereas a minimum JM distance of 0 indicates that two class-specific distributions are indistinguishable.

RESULTS AND DISCUSSION

Time-Series NDVI Profiles and Crop Phenological Characteristics

The multi-temporal NDVI profiles for each crop type presented in Figure 2A show that each crop type had a unique and well-defined profile in 2005, as a result of differences in the timing of green-up, peak greenness, and senescence. Distinct spectral-temporal differences were discernible between NDVI profiles of summer crops (corn, sorghum, soybeans) and both alfalfa and winter wheat in the spring periods when summer crops were yet to be planted. There was clear mid-summer separability between alfalfa and winter wheat, as alfalfa continued to experience “grow and cut” cycles while winter wheat maintained low NDVI values after harvest. The timing of green-up for alfalfa and winter wheat occurred in early spring (i.e., late March), which was

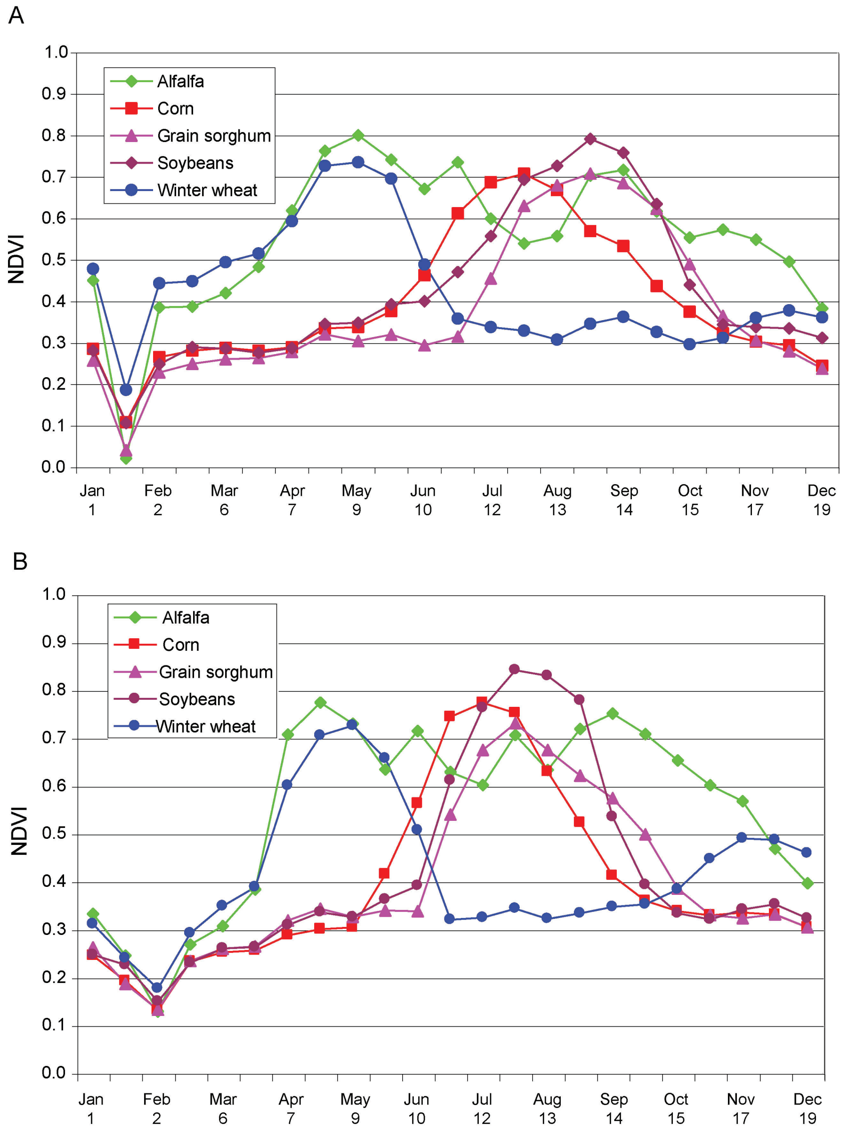

Fig. 2. Time-series NDVI profiles (State average) for major crops in Kansas in (A) 2005 and (B) 2001.

much earlier than that of summer crops (i.e., May and June). Peak NDVI values (i.e., peak greenness) for alfalfa and winter wheat were attained in mid-spring (i.e., May) compared to summer crops whose peak NDVI values were attained in mid-summer (i.e., late July and late August).

In Kansas, summer crops are planted at relatively different times. Corn is typically the earliest summer crop to be planted (April to mid-May), followed by soybeans (mid-May to mid-June) and sorghum (late-May to late-June) (Shroyer et al., 1996).

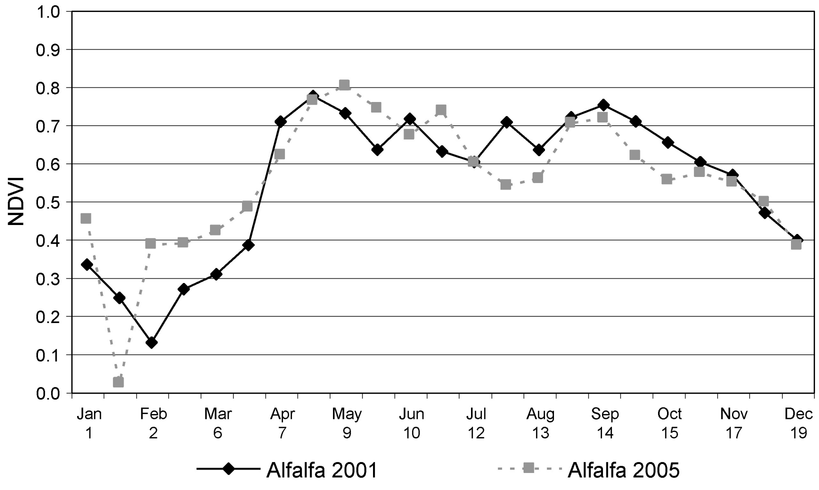

Fig. 3. Time-series NDVI profiles (state average) for alfalfa in Kansas.

The planting-date differences among crops during both growing seasons (2005 and 2001) were clearly reflected in the phased timings of green-up in Figures 2A and 2B. However, in 2005 the green-up time lag among summer crops was relatively longer compared to 2001. There were also differences in the timing and value of the peak NDVI among summer crops, with soybeans having the highest NDVI values during both growing seasons. Typically, the soybean canopy remains green until a very rapid drying occurs. The drying and leaf fall are more rapid than for corn and sorghum, which results in a more rapid NDVI decrease in late summer. The general crop spectral patterns observed for 2005 were similar to the 2001 NDVI profiles in Figure 2B.

Inter-annual Comparison of Crop NDVI Profiles

In this section, the assessment of separability between specific crop types in the time-series NDVI data was done by visual comparison of 2005 and 2001 multi-temporal NDVI profiles, and numerically using the JM distance statistic. In both cases state averages were used. A total of five graphs were visually evaluated to determine the extent of crop separability between the two reference years.

Alfalfa. In 2005, the crop's phenological characteristics and the "growth-and-cut" cycles were visible in the time-series NDVI data, as illustrated by the profile of the state average in Figure 3. The typical alfalfa curve characterized by a steep ascending phase resulting from the rapid increase in NDVI values during the early spring observed in 2001, seems to be somewhat subdued in 2005. In 2005, the first peak NDVI value of 0.80 attained by May 9 was relatively higher compared to 0.77 attained by April 23. According to Shroyer et al., (1998), alfalfa is typically cut three or four times per year in Kansas, with the first cutting in late May or early June. For instance, cuttings in 2005 occurred during June 10, July 12, and October 16 composite periods, while in 2001 occurred in May 25, June 26, and August 13 composite periods. Although readily discernible, the "growth-and-cut" cycles do not coincide because they took place at slightly different times of the growing season.

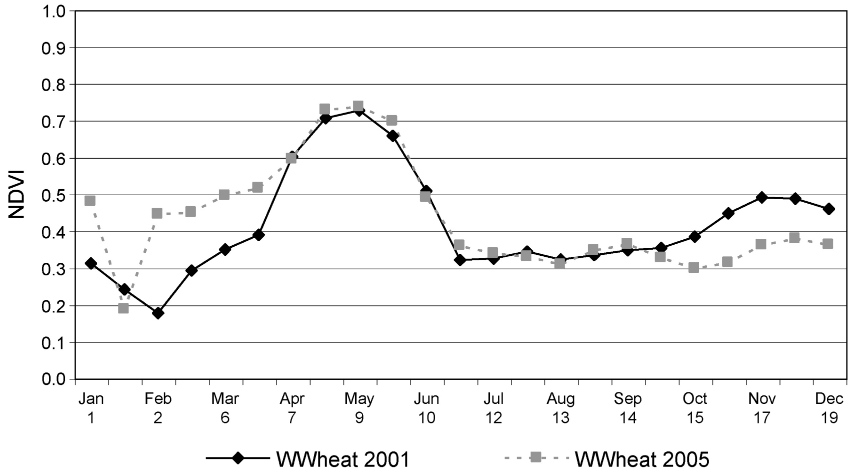

Fig. 4. Time-series NDVI profiles (state average) for winter wheat in Kansas.

Winter Wheat. Both the 2001 and 2005 state average winter wheat NDVI profile characteristics (Fig. 4) reflect the distinctive crop calendar of the crop planted and emerging in the fall (usually in September or October) when soil moisture is optimum for germination and plant emergence, crop dormancy over the winter, and breaking dormancy and reinitiating growth in early spring (March), followed by rapid growth and maturity in the spring (Paulsen et al., 1997). In both years, winter wheat grew rapidly, with the 2005 profile displaying slightly higher NDVI values from the April 23 to May 25 composite periods. Although both profiles displayed a second smaller NDVI peak in November and December, corresponding to the emergence and growth of the following year's crop, the 2001 peak was relatively higher.

Corn. In Kansas, the planting of corn for grain usually occurs between early April and late May (Shroyer et al., 1996). Seedling emergence usually occurs in 6 to 10 days, followed by a rapid development of vegetative material. When vegetative growth nears completion, the ear develops very rapidly, followed by flowering and grain filling (McWilliams et al., 1999). Crop growth usually requires about 130 to 150 days across the U.S. central Corn Belt (Neid and Newman, 1990), and harvesting is carried out between late September to early November (UDSA, 1997).

Figure 2 shows that corn had the earliest green-up, between May 9 and May 25, among summer crops. However, the 2005 profile (Fig. 5) had a relatively lower maximum peak NDVI value of 0.71 (reached by July 28) in comparison to 2001, which had a slightly earlier green-up and a peak value of 0.77 (reached by July 12), as well as a later senescence with the NDVI beginning to gently decrease by the August 29 composite period. The possible reason for the observed difference in the profiles between the two years is that in 2005, heavy showers were experienced throughout the state in the month of June. Hail damage and flooding were reported in some parts of the state, which reduced crop productivity and thus, slightly lowered NDVI values (NASS, 2005a).

Sorghum. The sorghum profiles (Fig. 6) show that the green-up and peak NDVI occurred at different times between the 2001 and 2005 growing seasons. In 2005, the

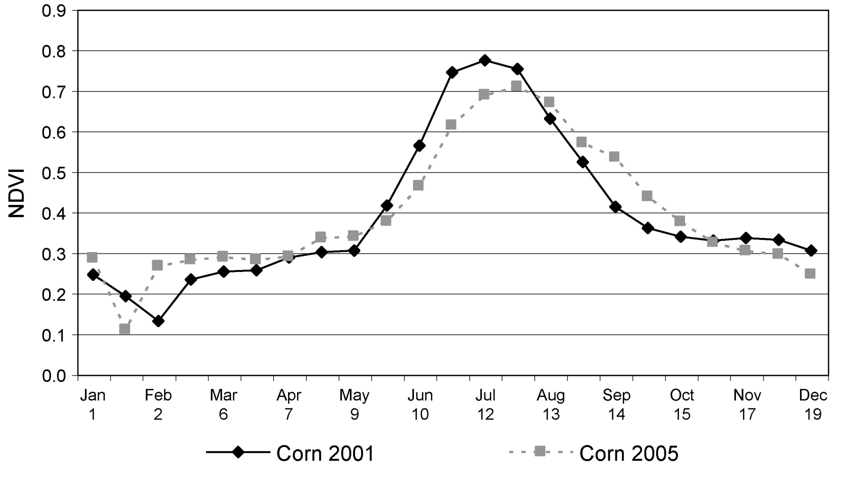

Fig. 5. Time-series NDVI profiles (state average) for corn in Kansas

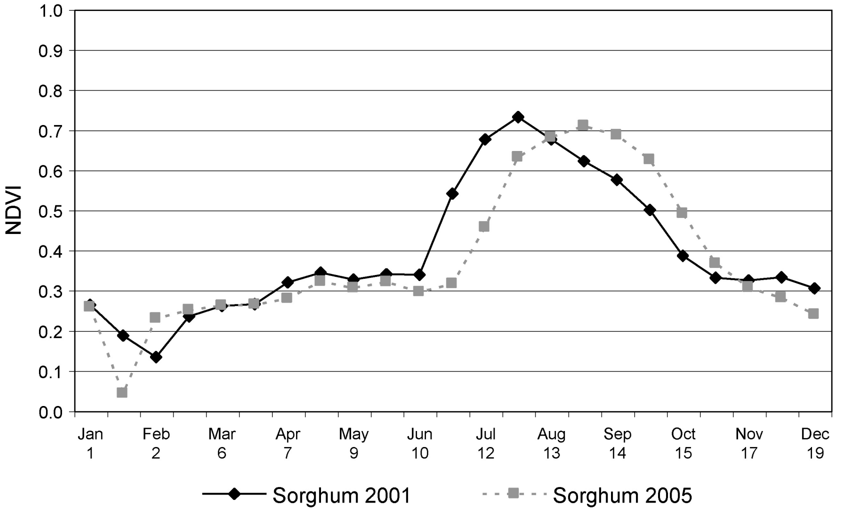

Fig. 6. Time-series NDVI profiles (state average) for sorghum in Kansas.

green-up occurred between the June 10 and June 26 composite periods, while in 2001 it was between the May 25 and June 10 composite periods. Sorghum peaked in 2005 during the August 29 period with a relatively lower NDVI (0.71), while in 2001 the peak was during the July 28 period with an NDVI value of 0.73. One of the reasons for the observed difference in the profiles is possibly due to sorghum planting that progressed behind normal (by a week) nearly all spring (NASS, 2006; NASS, 2005b). The other reason could be the difference of the date when more than 50% of the crop had emerged. In 2005, most of the crop had emerged by June 13 (NASS, 2005a) in comparison to 2001, which was by June 6 (Wardlow et al., 2006). According to NASS (2006), the state of Kansas received only light showers throughout July and August.

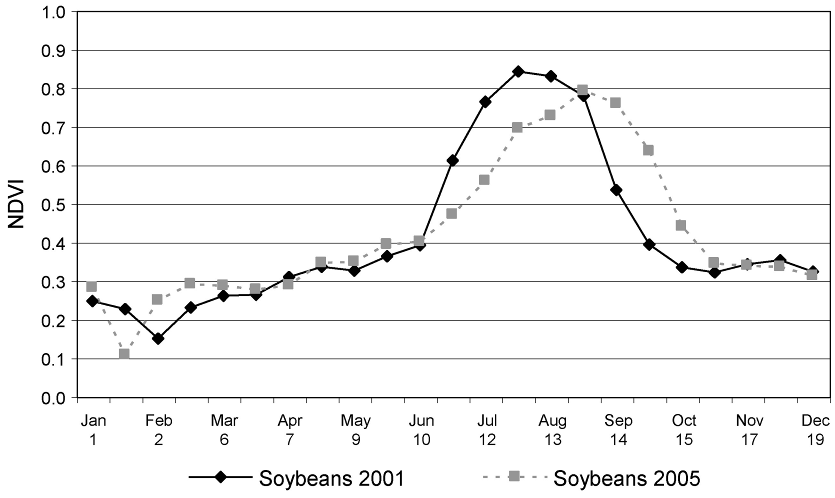

Fig. 7. Time-series NDVI profiles (state average) for sorghum in Kansas.

The dry weather gradually reduced crop condition so that by late August only 37% of the crop remained in good to excellent condition. The above trend in weather may be responsible for a relatively lower NDVI peak value in 2005.

Typically, the senescence behavior of sorghum exhibits a gradual decrease in NDVI, because the crop requires several weeks following physiological maturity to dry and reach harvest maturity (Vanderlip et al., 1998). However, the 2005 sorghum profile exhibited a slightly different senescence behavior in comparison to the 2001 profile, which exhibited a gradual NDVI decrease over a two-month period (July 28 to September 30). The reason for the contradictory senescence behavior observed above is not known.

Soybeans. Soybean planting takes place in mid-May to early June and harvesting is from late September to late October (USDA, 1997). Emergence normally takes 5 to 10 days after planting, followed by rapid vegetative and reproductive phases (McWilliams et al., 2004). When the crop attains full maturity, the green foliage changes color as it dries up and rapid leaf drop occurs after desiccation (Rogers, 1997), and subsequently the crop is harvested beginning around September 19.

The soybean profiles (Fig. 7) are consistent with the above crop calendar and indicate that the green-up during the 2001 and 2005 growing seasons occurred during the June 10 composite period, but that green-up was much more rapid in 2001. In 2005 soybeans experienced slow growth after the composite period of June 10, possibly because of slowed soybean planting resulting from locally heavy showers during the month of June (NASS, 2005b). According to NASS (2006), the progress of soybean planting was slightly above the five-year average for most of the spring. By mid-June, however, frequent rainfall throughout the state had slowed progress. In late July, dry weather prevailed across the Plains, with severe heat causing crop stress (NASS, 2005b). Soybeans peaked during the period of August 29 in 2005, one month later than 2001, having a relatively lower NDVI value (0.79) and a late senescence in comparison to 2001.

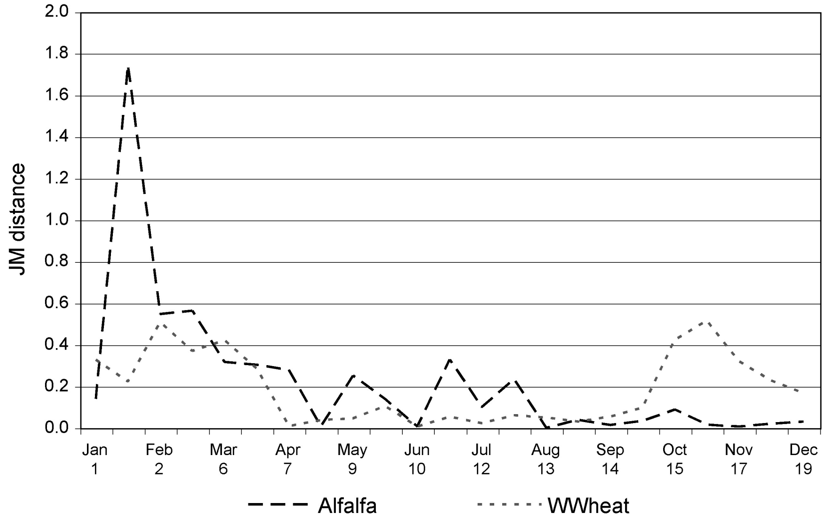

Fig. 8. JM distance values observed when comparing 2001 and 2005 field-site mean NDVI values for alfalfa and winter wheat.

JM Distance Statistic. After the JM distance statistic was calculated for the five crop pairs, the pair-wise JM distances were plotted in graph form. Alfalfa and winter crops (Fig. 8) were separated from the summer crops (Fig. 9) to avoid clutter in one graph. None of the crop-pair comparisons produced a perfect match (JM = 0) or indicated that the crops were completely different between the two years (JM = 2). However, the JM distance values for all crops, although above 0, were very low (<0.3) throughout all the crops' growing seasons.

The JM distance values for alfalfa, a perennial crop, were generally lower than 0.4 during the whole crop growing period (Fig. 8). There is a reduction in the JM distance value from 0.4 to 0.04 in March and April, which corresponds to the time period during which alfalfa breaks winter dormancy and begins photosynthetic activity/growth (Shroyer et al., 1998). The three noticeable spikes in the values by the composite periods of May 9 (JM = 0.25), June 26 (JM = 0.3), and July 28 (JM = 0.2) are as a result of the unsynchronized alfalfa cuttings patterns between 2001 and 2005 that has been explained earlier in this section.

During the winter wheat growing season, the JM distance values were below 0.1 (Fig. 8). These small values indicate that there was minimal winter wheat difference between NDVI observations from 2001 and 2005. The JM distance value decreased from 0.2 to 0.01 between late March and early April, the time period during which winter wheat breaks winter dormancy and resumes growth (Paulsen et al., 1997). The values remained low for the rest of the season until the months of October to November, when the peak value of 0.5 was reached between the 2001 and 2005, as was revealed in Figure 4. This high value may be due to differences in emergence and growth of the following year's crops, or a larger number of fields being idled and not planted in winter wheat during the fall.

During the summer crops' growing season, the JM distance for corn was below 0.2, suggesting low difference in the NDVI responses for corn between 2001 and 2005

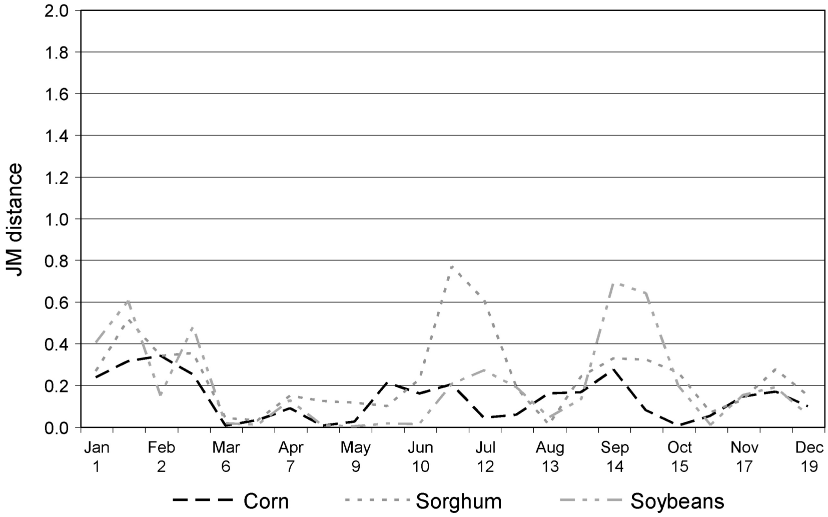

Fig. 9. JM distance values observed when comparing 2001 and 2005 field-site mean NDVI values for corn, sorghum, and soybeans.

(Fig. 9). However, during the composite periods of June and July, the values were closer to 0.2 because of variation in green-up, rate of growth, and maximum peak NDVI values between the months of June and July, as was evidenced in Figure 5. Sorghum had JM distance values of above 0.2 during the periods from June to July and September to October (Fig. 6). However, the maximum value of 0.7 was observed at the composite date of June 26, the time period which displayed differences in green-up and crop growth rate (Fig. 6). During the month of September, the values were around 0.3, mainly as a result of differences in senescence periods. Soybeans reached higher JM distance values during the composite periods in September, with the maximum value of approximately 7.0 reached by September 14, resulting from the delayed crop growth (and especially senescence) in 2005.

CONCLUSIONS

The goal of this research was to conduct an initial investigation into whether time-series NDVI response curves for crops over a growing season for one year might be used to map crops for a different year. In this case, time-series NDVI response curves for 2001 and 2005 were investigated to ascertain whether the 2001 dataset could be used to map crops for 2005 or any other later years. The results indicate that there was near-complete agreement between the winter wheat crop profiles but there were some minor differences in the crop profiles for alfalfa and summer crops between 2001 and 2005. The differences observed between the alfalfa profiles were mainly due to differences in "growth-and-cut" cycles that were not in synchrony. However, the profiles of summer crops—corn, grain sorghum, and soybeans—displayed a shift to the right by at least 1 composite date, indicative of late crop emergence and a delayed growth and senescence cycle. In 2005, heavy showers experienced throughout the month of June (accompanied by hail damage and flooding reported in some parts of the state) particularly affected crop growth. The results, especially for alfalfa and summer crops, seem to suggest that time-series NDVI response curves for crops over a growing period for one year of valid ground reference data may be useful for mapping crops for a different year when minor temporal shifts in the NDVI values resulting from inter-annual climate variations or changes in agricultural management practices are taken into account. This study was limited in that only non-irrigated crops at the state level were investigated and not more than two years were considered.

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