Using USDA Crop Progress Data for the Evaluation of Greenup Onset Date Calculated from MODIS 250-Meter Data

Brian D. Wardlow, Jude H. Kastens, and Stephen L. Egbert

Abstract

Identification of the onset of vegetation greenup is a key factor in characterizing and monitoring vegetation dynamics over large areas. However, the relationship between greenup onset dates estimated from satellite imagery and the actual growth stage of vegetation is often unclear. Herein, we present an approach for comparing pixel-level onset dates to regional planting and emergence information for agricultural crops, with the goal of drawing reliable conclusions regarding the physical growth stage of the vegetation of interest at the time of greenup onset. To accomplish this, we calculated onset of greenup using MODIS 250 m, 16-day composite NDVI time series data for Kansas for 2001 and a recently proposed methodology for greenup detection. We then evaluated the estimated greenup dates using the locations of 1,417 large field sites that were planted to corn, soybeans, or sorghum in 2001, in conjunction with United States Department of Agriculture (USDA) weekly crop progress reports containing crop planting and emergence percentage estimates.

Average greenup onset dates calculated for the three summer crops showed that the dates were consistent with the relative planting order of corn, sorghum, and soybeans across the state. However, the influence of pre-crop vegetation (weeds and "volunteer" crops) introduced an early bias for the greenup onset dates calculated for many field sites. This pre-crop vegetation signal was most pronounced for the later planted summer crops (soybeans and sorghum) and in areas of Kansas that receive higher annual precipitation. The most reliable results were obtained for corn in semi-arid western Kansas, where pre-crop vegetation had considerably less influence on the greenup onset date calculations. The greenup onset date calculated for corn in western Kansas was found to occur 23 days after 50 percent of the crop had emerged. Corn's greenup onset was detected, on average, at the agronomic stage where plants are 15 to 45 cm (6 to 18 inches) tall and the crop begins its rapid growth.

Introduction

Remote sensing of vegetation phenology for large geographic areas is needed to characterize vegetation dynamics in support of global environmental change research. Time-series vegetation index (VI) data derived from satellite-based sensors such as the Advanced Very High Resolution Radiometer (AVHRR), with a near-daily global repeat coverage, have been widely used to monitor vegetation phenology at regional to global scales over the past decade (Lloyd, 1990; Reed *et al.*, 1994; Moulin *et al.*, 1997; Schwartz *et al.*, 2002; Yu *et al.*, 2004). VI data are well suited for phenology studies, given their correlation with biophysical parameters such as green leaf area (LAI) and green biomass (Asrar *et al.*, 1989; Baret and Guyot, 1991).

Changes in VI data over the growing season reflect the seasonal biophysical changes of vegetation (structural and physiological), from which a suite of vegetation phenological metrics (VPMs) (e.g., greenup onset, dormancy onset, and length of growing season) can be estimated. Numerous approaches have been applied to time-series VI data to identify VPMs (Lloyd, 1990; Reed *et al.*, 1994; Moulin *et al.*, 1997; White *et al.*, 1997; Jonsson and Eklundh, 2002; Zhang *et al.*, 2003; Yu *et al.*, 2004). However, few studies have provided a thorough evaluation of the VPM results, which remains a key issue in remote sensing-based, large area phenology research (Schwartz and Reed, 1999; Zhang *et al.*, 2003).

Detailed evaluation of VPMs is difficult when using coarse resolution remotely sensed data. AVHRR normalized difference vegetation index (NDVI) data, with a nominal spatial resolution of 1 km (local area coverage) or 8 km (global area coverage), have been the primary data used for most large area phenology studies. At AVHRR's coarse spatial resolution, the majority of pixels are *mixed* in the sense that they correspond to heterogeneous landscape mosaics of multiple land-cover or vegetation types that can have different phenological characteristics (Reed *et al.*, 1994; Zhang *et al.*, 2003). As a result, the time-series NDVI signal detected at the pixel-level is an integrated response of diverse vegetation types rather than a single type, confounding attempts at detailed evaluation. However, the Moderate Resolution Imaging Spectroradiometer (MODIS) launched in December, 1999, offers substantial potential for improved estimation and evaluation of VPMs. Time-series VI data from MODIS are produced at a higher spatial resolution (250 m) than AVHRR, which should result in a larger proportion of pixels corresponding to relatively homogeneous land cover types compared to pixels at the 1 km and 8 km resolutions. MODIS has a temporal resolution (16-day composite period) that allows the major phenological events traditionally calculated from remotely sensed data to be detected. Also, the MODIS VI data are of higher overall quality due to higher radiometric resolution (12-bit) and improved geometric registration, atmospheric correction, and cloud screening (Huete *et al.*, 2002; Vermote *et al.*, 2002; Wolfe *et al.*,

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2002). As a result, the time-series MODIS 250 m VI data provide an opportunity for better estimation and more detailed evaluation of vegetation phenology measures.

Scale differences between ground-based and remote sensing-derived phenology measures have also limited the evaluation of VPMs. Field programs have been implemented to monitor ground-based phenology, but they are typically species- or land-cover-specific and conducted at smaller, localized scales (Schwartz, 1999). Also, the specific physiological growth events that are observed at the ground level (e.g., first leaf or bud burst) cannot be directly related to the more generalized phenology events that are detectable in coarse-resolution satellite imagery. Reed *et al*. (2004) suggested that future ground surveys be designed to collect phenology information over heterogeneous areas to be consistent with remotely sensed VPMs but acknowledged such an effort would be logistically difficult and expensive. There is a clear need to utilize existing and readily available information that monitors vegetation growth and development to evaluate VPMs until such ground surveys can be conducted.

The various approaches for estimating specific VPMs from remotely sensed data have been found to identify fundamentally different phenomena related to a specific phenological event (Schwartz *et al*., 2002), which further confounds the evaluation of VPM results. For example, in a study of different approaches for estimating the greenup onset metric (or start of growing season), Reed *et al*. (2004) found that some appeared to be measuring environmental conditions directly preceding the growing season, while others appeared to measure progressive greenup stages.

In this research, we present and apply an approach for comparing pixel-level onset dates to regional planting and emergence information for agricultural crops, with the goal of drawing reliable conclusions regarding the physical state of the vegetation of interest at the time of calculated onset. Specifically, we illustrate the use of United States Department of Agriculture (USDA) Agricultural Statistics District (ASD)-level weekly crop progress report information for the state-level evaluation of greenup onset dates calculated for summer crops (corn, grain sorghum, and soybeans) in Kansas (Figure 1) from time-series MODIS 250 m NDVI data using the approach described in Zhang *et al*. (2003). Our evaluation relied upon readily available USDA crop information that was available at no cost, which made the approach both time and cost efficient at the state- to regional-scale.

In this study, we focus on greenup onset, which is one of the most important vegetation phenological states to identify because it is when many land surface/atmosphere boundary exchanges (e.g., carbon assimilation) begin, and it is required for estimating other VPMs (e.g., length of growing season, rate of greenup, and accumulated greenness). However, greenup onset (and similarly, dormancy onset) is also one of the most challenging VPMs to meaningfully identify (Yu *et al*., 2004), which is demonstrated by the large number of methods developed for this purpose (Lloyd, 1990; Reed *et al*., 1994; White *et al*., 1997; Schwartz *et al*., 2002; Moulin *et al*., 1997; Zhang *et al*., 2003) and the various seasonal phenomena associated with greenup onset that these methods are meant to capture (Schwartz *et al*., 2002; Reed *et al*., 2004).

Study Area

The Kansas agricultural landscape is intensively cropped, with 10.7 million hectares (ha) (26.5 million acres) planted in a diverse mosaic of crop types. In addition to the state's best-known crop, winter wheat (*Triticum aestivum*), a substantial proportion of its cropland is planted to summer crops such as corn (*Zea mays*), sorghum (*Sorghum bicolor*), and soybeans (*Glycine max*). In 2001, 4.0 million ha (9.9 million acres), or 37 percent of the state's total cropland area, were planted to summer crops. Of this total, 1.5 million ha (3.8 million acres) were planted to sorghum, 1.3 million ha (3.3 million acres) to corn, and 1.1 million ha (2.8 million acres) to soybeans (Kansas Department of Agriculture, 2001).

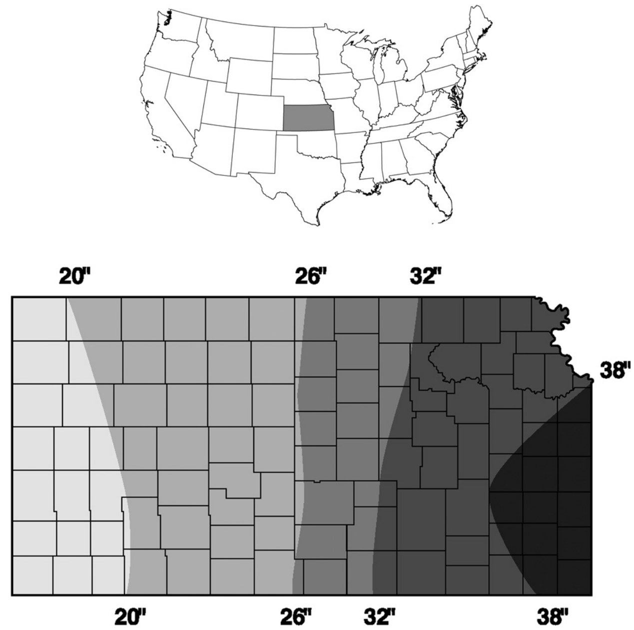

Figure 1. State of Kansas study area and the state's precipitation gradient map (inches/year) (Shroyer *et al*., 1998).

Each summer crop has a well-defined crop calendar, with subtle differences between the crops in terms of their specific planting times and the timing of their various growth stages (e.g., flowering and maturity). Corn is typically the earliest planted summer crop, with a recommended planting date range from 25 March to 10 May across Kansas (Hickman and Shroyer, 1994). Soybeans are usually the next crop planted with a planting date range from 10 May to 15 June (Kilgore and Fjell, 1997). Sorghum is the latest planted of the three crops, with its recommended dates ranging from 15 May to 25 June (Roozeboom and Fjell, 1998).

In general, there is a southeast-to-northwest planting date gradient across the state for each summer crop. Planting dates can vary by more than one month between southeast Kansas (earliest planting time) and northwest Kansas (latest planting time) for each summer crop. For example, planting times for corn in northwest Kansas (01 May to 20 May) are typically two to six weeks later than in southeast Kansas (25 March to 01 May) (Hickman and Shroyer, 1994).

The state has a pronounced east-west precipitation gradient (Figure 1). Precipitation ranges from more than 1016 millimeters (40 inches) per year in temperate eastern Kansas to less than 508 millimeters (20 inches) per year in semi-arid western Kansas. ASD-level monthly precipitation reported by the USDA for Kansas showed that the precipitation patterns were characteristic of this gradient in 2001, with most ASDs' monthly totals during the pre-planting to mid-season time frame deviating by less than 25.4 to 50.8 mm (1 to 2 inches) from the 10-year average. Precipitation and available soil moisture influence the length of growing season and the rates of emergence and initial plant growth, which in turn influence greenup onset detection. Irrigation is a widespread crop management practice in central and western Kansas that mitigates some of the effects of the semi-arid climate.

Focusing on summer crops in Kansas for evaluation of greenup onset using large-area, coarse-resolution satellite imagery is desirable for many reasons. These crops presumably embody an idealized *single species, bare soil to vegetation* scenario for studying greenup, and distinct events (in particular, planting and emergence) associated with their greenup phase are recorded at the ASD spatial scale by the USDA. Compared to natural cover types, these crops are highly managed. They are characterized by maximally efficient seeding rates, standardized plant spacing practices, soil fertility management, and regular maintenance of the soil surface before and after planting. In theory, such field sites should resemble what one would expect to see in a controlled laboratory experiment.

Data Description and Preprocessing

Time-Series MODIS 250 m NDVI Data

A 12 month (January to December 2001) time series of 16-day composite MODIS 250 m NDVI data (MOD13Q1 collection 4) for Kansas was analyzed in this study. The original format of the data was signed 16-bit integer (NDVI values scaled by 10,000), but for analysis purposes the data were rescaled to their native range of −1.0 to +1.0 as determined by the NDVI formula (NIR − RED)/(NIR + RED). The time series consisted of 23 consecutive 16-day NDVI composite images, which had a minimal standard spatial registration error of 0.20 pixels (50 m) at nadir among the images (Wolfe *et al*., 2002). The data were also projected from the original Sinusoidal projection to the Lambert Azimuthal Equal Area projection prior to analysis.

The MODIS NDVI composite images were generated using a constrained view maximum value compositing (MVC) technique (Huete *et al*., 2002). Since this study is concerned with only the initial greenup periods of the crops, there will be a tendency for composited maximum-value NDVI measurements during this part of the growth cycle to have been selected from the latter part of each compositing period due to within-period crop growth. Taking this idea to the extreme (and approximating the ideal, daily overpass, cloud-free case), calculations performed in this research involving daily interpolations assumed that NDVI values were always obtained from the final day of the compositing period.

FSA Field Site Database

A database of 1,417 field site locations throughout Kansas planted to the three summer crops in 2001 was created using information from annotated aerial photographs provided by the USDA Farm Service Agency (FSA). FSA annotations for each field included the crop type, an irrigated/non-irrigated designation, acreage, a highlighted field boundary, and Public Land Survey System (PLSS) information. The individual field sites were typically 40.5 hectares or larger to ensure that fields would be detectable in the 250 m (6.25 hectares/pixel) imagery. However, some fields as small as 24.3 hectares were used in eastern Kansas (which typically has smaller average field sizes than the rest of the state) to increase the number of samples available in this region. Each field was located using a combination of MODIS 250 m imagery, Landsat ETM+ imagery, and a PLSS vector coverage that were georeferenced to the Lambert Azimuthal Equal Area projection. Once the field was located, a single 250 m pixel completely within the field's boundaries was selected to represent the site, and the corresponding time-series NDVI values for the pixel were extracted and entered into the database.

USDA Crop Progress Data

Crop progress data were acquired for each ASD from the weekly 2001 Crop Progress reports produced by the USDA National Agricultural Statistics Service (NASS) for Kansas. (These reports are publicly available at **http://usda.mannlib.cornell.edu/reports/nassr/field/weather/2001**/.) Information used for USDA estimates is based on survey data describing farmers' activities and roadside assessments of crop progress and development. (Details of the specific USDA methods can be found in the section titled "Crop Progress and Condition Survey and Estimating Procedures" located near the end of any of the Crop Progress reports beginning in 2002.) Percent planted and percent emerged information was extracted from each weekly report from 16 April (first week of reported planting for summer crops) to 02 July (first week following 100 percent reported emergence of all summer crops). USDA designates a field as *emerged* when the plants are visible for 50 percent or more of the field (**http://www.usda.gov/nass/pubs/cwterms.htm**), which is largely consistent with the plant-level definition of emergence that takes place when the coleoptile penetrates the soil surface.

One concern was whether or not our field site sampling corresponds to the sampling that was used for determination of the USDA crop progress estimates. Figure 2 shows three maps of Kansas, one for each of the three crops in the study. All three maps show county and ASD boundaries. For a

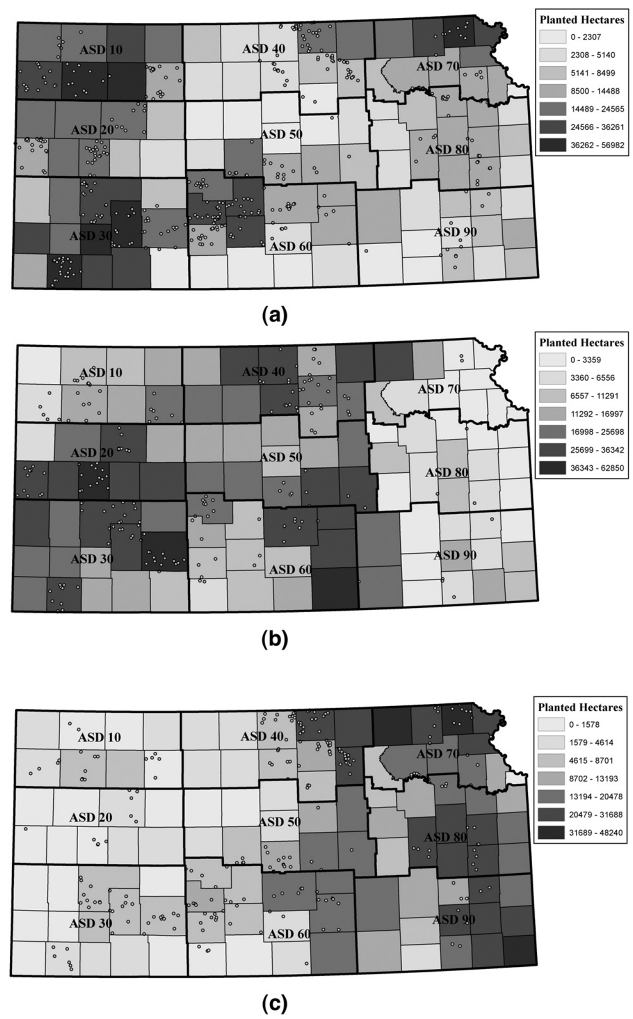

Figure 2. Point locations for the corn (a), sorghum (b), and soybeans (c) field sites used in the analysis. USDA estimated planted acreage (1 hectare = 2.47 acres) is shown by county with ASD boundaries shown using thick lines.

given crop, the maps show the locations of the point samples used in the analysis, and the counties have been color-coded to illustrate the 2001 planted acreage concentrations as reported by USDA NASS. Although visual correspondence appears to be positive, we do not have enough information to conclusively assess the level of statistical correspondence between our field site samples and the sampling used in the generation of the USDA crop progress estimates.

Another potential bias in our data may arise from field size. Our site samples were extracted from fields that are generally greater than 40.5 ha, and thus they may inherit any biases associated with this class of fields. All things considered, our field site database is not free from uncertainties such as those just described. However, the database is substantial and accurate, and if used cautiously, we believe it is appropriate for the present analysis. Also, statistical sampling concerns affecting some of the crops and ASDs are partially mitigated through result aggregation.

Point Screening

It was necessary that the analysis be restricted to points yielding onset dates that actually corresponded to the crop that was planted on the field. Pre-crop field conditions can deviate from the ideal, bare-ground scenario due to the presence of weeds or volunteer crops (i.e., plants sprouting from seeds left in the field from past crops), which can result in a vegetation signal from the field prior to the planting of summer crops. Points contaminated with pre-crop NDVI signals would thus give rise to an unwanted, early bias in regionally aggregated onset dates. As a result, we attempted to eliminate pixels exhibiting a strong, pre-crop NDVI signal from the analysis, presuming such signals resulted from the presence of weeds or volunteer crops on the field sites. To this end, we screened our point dataset, which resulted in the elimination of 567 of 1417 points from the analysis, leaving 850 points to use for evaluation. See Figure 3 for a comparison of regionally averaged, crop-specific NDVI time series calculated using the 850 retained points and time series using the 567 pixels excluded from the analysis.

The point screening technique relied on two pieces of information. First, we identified the latest MODIS period that could be posited to occur before any significant regional plantings. By considering only NDVI up to this point in time, the likelihood of eliminating pixels with legitimate, early,

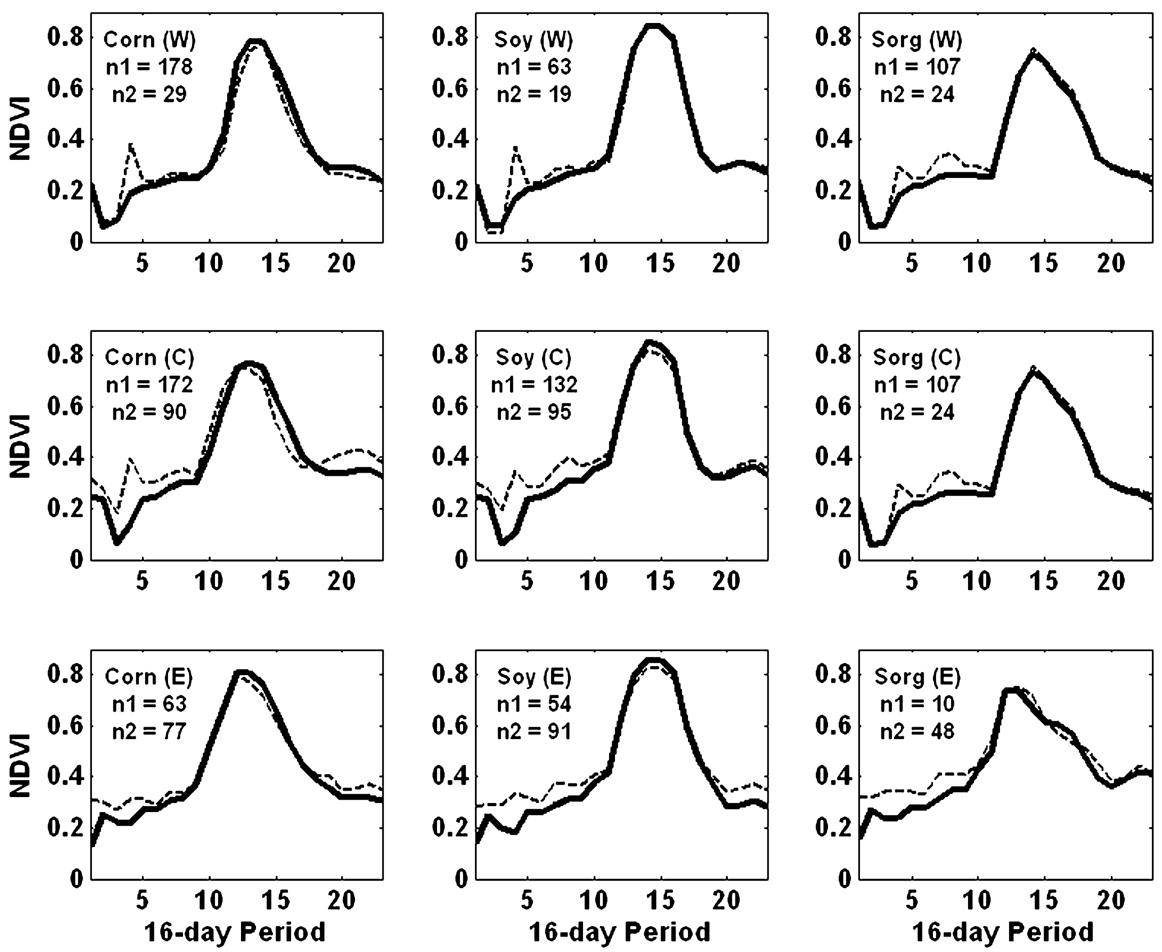

Figure 3. Unsmoothed, average NDVI time series (solid lines) obtained from the 850 pixels used in the analysis, along with unsmoothed, average NDVI time series (dashed lines) obtained from the 567 pixels excluded from the analysis using the point screening procedure described in the text. Information included in the plots describes the crop type, region (W = west, C = central, and E = East), and corresponding sample sizes (n1 = number of retained field sites, n2 = number of excluded field sites).

crop-induced NDVI response was minimized. To obtain the latest such period in a crop- and district-specific fashion, we used USDA percent planted data to identify the week (specifically, the Julian day at the end of the week) just prior to the first reported plantings. If a positive percent was given in the first weekly USDA release of this information, then the Julian day at the end of the week just prior to the initial report date was selected. The Julian day was divided by 16 and conservatively rounded down to obtain a MODIS period number. The point screening then used MODIS time series values up to and including this latest estimated pre-planting period.

The second piece of information that was needed for the point screening was an NDVI threshold reflective of the typical response produced when a considerable amount of non-crop vegetation (i.e., weeds and volunteer crop) is present on an unplanted field site. For this purpose, we used data from fallow fields, which are fields that are not planted to a crop during an annual cropping cycle to facilitate soil moisture build-up on the field site. Using NDVI time-series data from 73 fallow field sites in Kansas, the average fallow time series was calculated, along with a standard deviation time series. In the core growing season (April through August), the maximum NDVI value obtained when adding the one standard deviation curve to the average curve was 0.35. This value was taken to correspond to a typical condition where a field is partially covered by non-crop vegetation. Any pixels that exceeded this value in at least one period up to and including the threshold period (i.e., the period just prior to presumed planting) were removed from the evaluation set.

It should be noted that all but two of the 73 fallow sites were located in the western districts, with each of the remaining two points located near the western border of a central district. This reflects a farmland management bias induced by the east-west precipitation gradient, as fallowing is uncommon in the wetter central and eastern districts. Thus, to perform more spatially specific point screening, an alternative method would be required due to the lack of fallow field reference sites in central and eastern ASDs in Kansas.

Data Smoothing

Because of the effects of signal noise and viewing and ground conditions (such as clouds and snow), there are many temporally localized oscillations in the pixel-level NDVI time series in our dataset, possibly warranting smoothing. In the context of onset date determination, the effects of time series smoothing can be summarized with two observations. Too much smoothing, and identified onset dates can lose precision. Too little smoothing, and high frequency variation in the data can lead to spurious results. We devised a simple smoothing algorithm in an attempt to balance these issues. As can be inferred from the following description, some aspects of the smoothing algorithm were selected specifically for the context of this study and may not be appropriate in other situations.

The smoothing algorithm employed in this study involves two steps. In the first step, the time series tails are vigorously smoothed, as variation occurring in these segments is of no use (regardless of its source) in the determination of onset dates for summer crops in Kansas. In the second step, local minimum points in the NDVI time series interior are subjected to a simple smoothing procedure.

For the tail treatment (the first step), a relevant threshold background NDVI was needed to screen pixels with undesirably suppressed values. Through visual inspection of hundreds of pixel-level time-series graphs, we determined that a minimum latent (i.e., background) value of 0.15 NDVI existed throughout the study region. When observed, values below this level resided almost exclusively near the tails of the time series (i.e., in wintertime). Looking at the 15 composite periods we designated as the time series interior (periods 6 to 20, spanning 22 March to 16 November), only three of the 850 retained pixels possessed an NDVI value less than 0.15. Two of these three pixels had one such date, and the third one had two such dates. Thus, 0.15 is a conservative background NDVI cutoff.

Looking at the eight tail periods (1 to 5 and 21 to 23), 710 of the 850 pixels possess at least one NDVI value below 0.15; 240 pixels had one such occurrence in the tails, 372 had two occurrences, 95 pixels had three, two pixels had four, and one pixel had five. Given the virtual non-occurrence of such low values in our time series interior (which contained numerous and varied background NDVI values), these values undoubtedly correspond to some factor whose variational effects we would like to reduce.

To smooth the front tail of the time series, the first five points of each pixel-level time series were subjected to the following treatment. The fifth period (spanning 06 to 21 March) was chosen as the cutoff for the front tail because NDVI values below 0.15 occurred with high frequency (relative to occurrence in the interior) up to this period, but no summer crop planting had occurred anywhere in the state by this point in time. Considering just the first five points, values below 0.15 were ignored, and the median was calculated from the remaining points. Values for the first five periods were then replaced with this statistic. The end of the time series was subjected to symmetric treatment, except that only the last three points were smoothed. This choice was due primarily to the longer duration of wintertime conditions (and the associated NDVI problems) at the beginning of a year than at the end of a year.

After treatment of the time-series tails, the second step of the smoothing procedure involved smoothing the interior of each time series in a simple, conservative fashion. First, all local minima were identified. These are the NDVI values x_k (where k denotes the time period) such that $x_{k-1} > x_k < x_{k+1}$. Since a constrained view maximum value compositing technique was used to generate the NDVI used in this research (Huete *et al.*, 1999), and we were looking at NDVI responses from vegetation presumed to have a unimodal growth-senescence annual cycle, responses at local minima were presumed to be artificially low. Consequently, all such local minima x_k were replaced with the minimum value of x_{k-1} and x_{k+1}. We are essentially looking at only the initial monotonic greenup segment of each NDVI curve, where no legitimate, substantial, local NDVI minima should occur (in theory), which provides some justification for the interior smoothing. See Figure 4 for an example of a pixel-level NDVI time series before and after smoothing.

Analytical Methods

Onset Method

The onset date identification method presented in Zhang *et al.* (2003) was used in this study (hereafter, this technique will be referred to as the *Zhang method*). The foundations of the Zhang method rely on two mathematical exercises. First, an algorithm is used to identify the end of the first monotonic segment of a VI time series. Ideally, this segment should comprise the complete greenup portion of the crop growth cycle present in the time series. The technique involves computing sequential, five-point running slope values. In the idealized NDVI time series, these slope values will be non-negative throughout the initial greenup growth cycle. The earliest instance (assigned to the midpoint of the five-point window) when this slope value becomes negative is designated as the end of the initial greenup growth cycle.

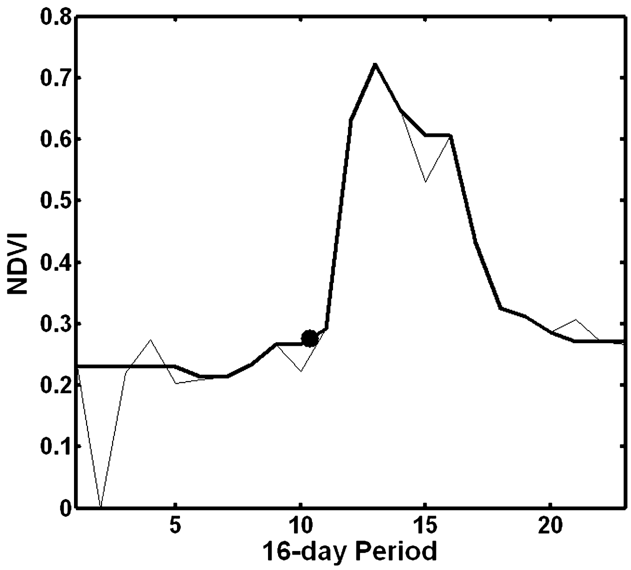

Figure 4. Smoothed (thick line) and unsmoothed (thin line) NDVI time series from a single pixel in the analysis set. The indicated point represents the point of greenup onset obtained from the smoothed curve by applying the method described in the study.

In our application of the five-point running slope method, all points in a pixel-level NDVI time series were identified where the five-point running slope changed sign from positive to negative. These points became candidate end points for the first segment. Of these dates, the one selected was the earliest point on the candidate list whose corresponding segment contained at least one NDVI value greater than 0.35 (to be consistent with the previously described point screening method).

The second component of the Zhang method involves fitting a logistic curve to the identified segment corresponding to the initial greenup growth cycle. The functional form of the logistic curve is given by $y(t) = \frac{c}{1 + e^{a+bt}} + d$, where t is time and a, b, c, and d are free parameters to be estimated. There is no closed-form solution for obtaining parameters yielding the best-fit logistic function for a given time series, so numerical optimization is required. In our analysis, MATLAB® software was used to perform this optimization. Specifically, the *fminsearch* function was employed, which uses the Nelder-Mead simplex (direct search) method. Separate optimizations were performed using a carefully constructed family of 30 pairs of initial conditions for *a* and *b*, with initializations for asymptote-defining parameters *c* and *d* determined from the particular time series in question. From these independent optimizations, the one yielding the lowest fitting error (quantified by sum of squared errors) was used for further analysis.

The functional form of the fitted logistic curve is such that the derivative of the function's curvature can be calculated explicitly. As described in Zhang *et al.* (2003), there are theoretical reasons for assigning an onset date to the first point of maximum increase in curvature of the fitted logistic curve (there are two such points on each fitted logistic function). Further, given the continuity of the fitted logistic function, the point of onset can be resolved with as much temporal detail as desired. On the other hand, the compositing process may preclude the significance of this detail below the length of the compositing period (16-day). Given the large number of pixel-level time series used in this study and our aggregation approach to the analysis, we calculated the onset date to the day in an attempt to discern subtle differences in timings of onset events. As mentioned earlier, NDVI values were presumed to have been collected on the final day of each compositing period. See Figure 4 for an example NDVI time series and its point of greenup onset calculated using the Zhang method.

Result Aggregation

All aggregations of onset date values reported in this paper were performed using sample-size weighting schemes so that each point had exactly the same influence on results as every other point. To be consistent, USDA ASD numbers used for comparison were aggregated in the same manner, using district-level field site sample sizes for weighting all such aggregations. However, there is a drawback to this method. Because linear interpolations are used to arrive at particular planted/emerged percentages from Julian dates and vice versa, in conjunction with the fact that the percent measure as a function of time is generally nonlinear and saturates at both extremes (0 percent and 100 percent), it is possible that aggregations done in this fashion can exhibit logical inconsistencies. In an effort to minimize possible negative impacts of the linear interpolation methods used, differences between onset date and date of 50 percent planted/emerged were relied on rather than percent planted/emerged at onset. We believe that interpolations used in the former approach are likely more reliable than those used in the latter, since changes in percent planted/emerged should typically be more linear around 50 percent than away from 50 percent if we assume these series exhibit typical "S" curve behavior.

Results and Discussion

An evaluation of the state-level, average greenup onset dates identified for specific summer crops showed that the dates were consistent with the relative planting order of corn, sorghum, and soybeans in Kansas. Corn had the earliest detected greenup onset on 24 May (144 Julian date), the earliest 50 percent planted date (28 April, or 118), and the earliest 50 percent emerged date (09 May, or 129) among the summer crops. Soybeans had an intermediate greenup onset date (27 May, or 147), 50 percent planted date (17 May, or 137), and 50 percent emerged date (27 May, or 147). Sorghum had the latest greenup onset date (03 June, or 154), 50 percent planted date (24 May, or 144), and 50 percent emerged date (06 June, or 157).

Median greenup onset and 50 percent emerged dates were correlated across the nine ASDs to further evaluate the relationship between these dates, under the assumption that the emergence event and greenup onset should be related. Corn had the highest correlation ($r = 0.75$, $r^2 = 0.56$), then soybeans ($r = 0.54$, $r^2 = 0.29$), and the lowest correlation was observed when sorghum was considered ($r = 0.23$, $r^2 = 0.05$). These unexpectedly low correlations suggested that there were some unwanted inconsistencies in the results, particularly for soybeans and sorghum. A closer evaluation of each crop found the greenup onset dates of sorghum and soybeans tended to occur earlier than corn relative to the USDA percent values for each respective crop. This earlier tendency for sorghum and soybeans is demonstrated by the lack of a lag between their respective 50 percent emerged and greenup onset dates (see Table 1). In comparison, corn had a 15-day lag between the greenup and 50 percent emerged dates when aggregating results across all nine districts. Vanderlip (1998) stated that sorghum's early season growth is slow compared to corn and soybeans, which have

Table 1. Onset Results and Agricultural Reporting Data

Crop	Region	Number of Field Sites	Onset Date*	Percent Planted at Onset	Percent Emerged at Onset	50% Planted Date*	50% Emerged Date*	Lag**
Corn	ASD 10	53	155	100	100	125	133	22
	ASD 20	50	161	100	100	127	138	23
	ASD 30	75	153	100	100	116	129	24
	ASD 40	59	128	67	31	124	131	−3
	ASD 50	20	132	98	84	113	125	7
	ASD 60	93	144	100	99	112	126	18
	ASD 70	27	129	92	61	120	126	3
	ASD 80	24	136	99	88	114	121	15
	ASD 90	12	123	99	84	100	117	6
Soybeans	ASD 10	18	158	85	65	144	154	4
	ASD 20	10	159	81	44	146	161	−2
	ASD 30	35	159	90	73	135	146	13
	ASD 40	67	152	86	54	138	149	3
	ASD 50	21	123	11	0	131	141	−18
	ASD 60	44	144	78	61	133	139	5
	ASD 70	26	143	88	41	136	146	−3
	ASD 80	19	140	46	23	141	146	−6
	ASD 90	9	128	32	5	140	150	−22
Sorghum	ASD 10	26	166	88	72	146	158	8
	ASD 20	35	176	97	93	148	165	11
	ASD 30	46	171	96	87	144	158	13
	ASD 40	36	110	0	0	146	161	−51
	ASD 50	9	123	4	0	141	155	−32
	ASD 60	26	164	85	77	139	145	19
	ASD 70	2	135	31	13	141	148	−13
	ASD 80	3	140	53	34	139	144	−4
	ASD 90	5	135	64	46	129	137	−2
Corn	State	413	144	95	85	118	129	15
Soybeans	State	249	147	74	48	137	146	1
Sorghum	State	188	154	69	61	144	157	−3
All 3 crops	State	850	147	83	69	129	140	7
Corn	West	178	156	100	100	122	133	23
Corn	Central	172	137	88	74	116	128	9
Corn	East	63	131	96	76	114	122	9
Soybeans	West	63	159	87	66	139	151	8
Soybeans	Central	132	145	71	48	135	144	1
Soybeans	East	54	139	64	29	138	147	−8
Sorghum	West	107	171	94	85	146	160	11
Sorghum	Central	71	131	32	28	143	154	−23
Sorghum	East	10	137	54	36	134	141	−4

*Dates are in terms of Julian days.
**Lag = (Onset Date) – (50% Emerged Date).

similar growth rates during the initial greenup stage of the growing season. Therefore, sorghum and soybeans would both be expected to have a similar or longer lag between their respective greenup and 50 percent emerged dates than corn. A few examples illustrating specific cases with inconsistent results are described below. See Figure 5 for a scatter plot showing onset date versus the 50 percent emerged date at the district level for all three crops under investigation.

Case Specific Issues

The influence of sample size was an issue that warranted consideration during the evaluation of the case-specific results, particularly after implementation of the point screening procedure reduced sample sizes across the board. Generally speaking, the smaller the sample, the lower the confidence in statistics obtained from the sample. Of the 27 district-crop combinations under investigation, six had sample sizes of 10 or fewer, five had sample sizes between 11 and 20, six had sample sizes between 21 and 30, and the remaining ten cases had sample sizes greater than 30. These tallies reflect the counts given in Table 1.

Regardless of sample size concerns, inconsistent results obtained from some cases were explainable. For instance, in southeast Kansas (ASD-90), the USDA information reported for soybeans included both single-crop and double-crop management practices and was therefore not representative of the single-crop soybean sites used in this study. Local agricultural extension agents reported that typically 30 percent to 50 percent of soybeans in ASD-90 are planted in a double cropping rotation (winter wheat immediately followed by soybeans in the same year), with double-crop soybeans typically planted two to six weeks later than single-crop soybeans (Kilgore and Fjell, 1997). The USDA makes no distinction between single- and double-crop soybeans in their planted and emerged percentages. Our small sample (n = 9) of soybean fields in ASD-90 reflected single-crop soybeans, and the early-biased ASD-90 soybean results may have simply underscored the lack of double-crop soybean samples in our study sites for the district.

In central Kansas (ASD-50), a pronounced early bias was observed in the greenup onset dates calculated for both sorghum and soybeans. As in other districts, this early bias can be partially attributed to the extensive weed or volunteer crop cover that commonly precedes the planting of both sorghum and soybean crops in Kansas. Local agricultural extension agents acknowledged that pre-crop establishment of winter annual weed and volunteer crop cover

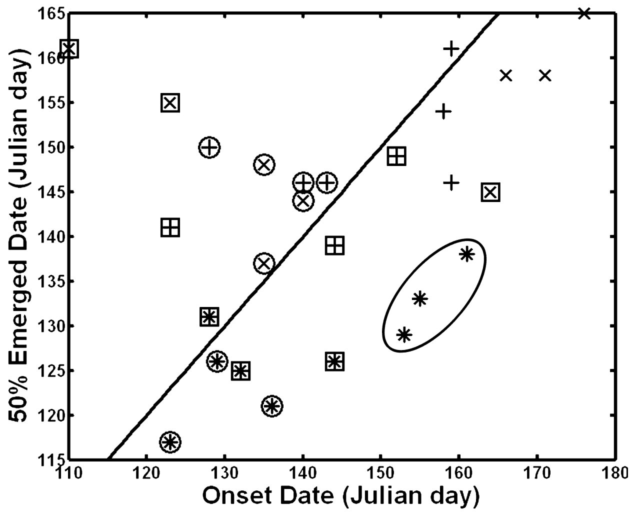

Figure 5. A scatterplot of onset dates and 50 percent emerged dates is shown. Points denoted with "*" are for corn, "+" is for soybeans, and "×" is for sorghum. Points from the western districts have no perimeter, whereas points from the central districts are framed in squares and points from the eastern districts are framed in circles. An oval is drawn around points for corn in the western districts, which produced the most reliable results. A one-to-one line is shown for reference.

has recently increased on fields planted to sorghum and soybeans in ASD-50. According to the agents we contacted, this is partially a consequence of the common winter wheat-sorghum and winter wheat-soybean rotations used more heavily in this district than the others and the widespread practice of no-till farming. The lack of tillage associated with no-till farming and the 10 to 11 month idle period between winter wheat harvest (late-June) and summer crop planting (mid-May to early-June of the following year) that occurs in the aforementioned rotations favors the germination and establishment of weeds and volunteer crops prior to summer crop plantings. Extension agents indicated that corn is much less likely to follow winter wheat in crop rotations in ASD-50, which may partially account for the less problematic onset results for corn compared to the other summer crops in this district. It should be noted that no-till farming is being increasingly implemented in other parts of Kansas, and thus may have also contributed to inconsistencies in other districts in the manner described above.

Pre-Crop Vegetation: Effects of the Precipitation Gradient and Planting Times

As previously mentioned, the most prominent issue related to the evaluation of the greenup onset metric was the presence of pre-crop vegetation on many fields prior to the planting of summer crops. Assuming that fields possess a non-vegetated surface (i.e., bare soil and possibly non-photosynthetic crop residue) prior to the planting of summer crops, the initial NDVI increase from each field should be associated with the greenup onset of the crop planted on the field. However, many fields had extensive pre-crop vegetation cover in the form of winter annual weeds such as henbit (*Lamium amplexicaule*) and chickweed (*Stellaria media*) and volunteer crops from the previous year (wheat in particular). This pre-crop vegetation produced a true vegetation-related NDVI increase prior to the planting of summer crops on these fields, which led to the identification of greenup onset that was earlier than expected. Numerous fields with a strong pre-crop vegetation signal were removed prior to the analysis using the point screening technique discussed earlier, but many fields with a more subtle pre-crop vegetation response in the time-series NDVI appear to have remained in the analysis set. The influence of pre-crop vegetation on greenup onset identification varied, as expected, with the pronounced east-west precipitation gradient across Kansas and with the relative planting times of the summer crops.

In general, the pre-crop vegetation influence increased from west to east, along the precipitation gradient across Kansas due to the increasing availability of soil moisture. Its influence was the least in semi-arid western Kansas and was the greatest in eastern Kansas. The number of fields with a strong pre-crop vegetation signal removed during the point screening discussed earlier clearly highlights the east-west correspondence between precipitation and pre-crop vegetation. A considerably larger proportion of fields were removed in the eastern districts (63 percent, or 216 of 343 fields) and central districts (43 percent, or 279 of 654 fields) than in the western districts (17 percent, or 72 of 420 fields).

Higher annual precipitation facilitates pre-crop weed establishment in two ways. First, it favors adequate soil moisture availability in the early spring (e.g., March and April) to initiate and support the growth of weed cover in unplanted fields. Second, soil moisture conservation is less of an issue in areas receiving greater amounts of precipitation, and consequently there is less incentive to remove the weed cover that appears before planting. As a result, the prevalence of pre-crop vegetation would be expected to increase in a west-to-east fashion in Kansas. This observation also suggests that in spite of our point-screening efforts, we should still expect to see an increasing prevalence of pre-crop NDVI response following a similar west-to-east pattern in the points that were retained for the analysis (i.e., retained pixels will have a greater likelihood of being contaminated as we move east).

The influence of pre-crop vegetation on greenup onset identification was also greater for the later planted summer crops (soybeans and sorghum). In 2001 the USDA reported that statewide, corn reached 50 percent planted 19 days earlier than soybeans and 25 days earlier than sorghum. Pre-crop vegetation would be expected to be more persistent on fields planted to either sorghum or soybeans than corn, given the additional time that weeds would have to become established on these field sites. The point screening results reflect this expectation, with a larger proportion of fields removed for sorghum (47 percent or 166 of 354 fields) and soybeans (45 percent or 205 of 454 fields) than corn (32 percent or 196 of 609 fields). The lower correlations and lack of a lag between 50 percent emerged and greenup onset dates (see Table 1) for soybeans and sorghum presented earlier also support the assertion that field sites from these crops experienced more pre-crop vegetation contamination than did corn field sites.

The prevalence of the pre-crop vegetation signal and other problems discussed above were unexpected, but highlight the difficulties associated with the evaluation of large area, satellite-derived phenology measures. To support our analysis, the greenup onset dates were further evaluated in light of these issues. The ASD-level results showed a consistent early bias for most summer crops in the east and central regions compared to the west region. With few exceptions, ASD-level results for sorghum and soybeans in the east and central regions rarely exhibited the expected lag between the greenup onset date and the 50 percent planted and 50 percent emerged dates. In comparison, the west region had more reasonable and consistent lags among the ASDs for these crops (see Table 1).

Due to the reduced influence of pre-crop vegetation on corn field sites described earlier, the ASD-level greenup onset dates for corn were generally more reliable than onset dates calculated for the other two crops. However, the range of lag times associated with corn was more variable among the ASDs for the east and central regions than in the west, suggesting that results were more consistent in the west (the same is true for the other two crops as well). On corn field sites, the lag between greenup onset and the 50 percent emerged date ranged from −3 to 18 days for the central region and 3 to 15 days for the east region. In contrast, the west region's ASDs had less variability among these dates, with a lag of 22 to 24 days between the greenup onset and the 50 percent emerged date.

Corn in Western Kansas: Relating Onset Date to Agronomic Growth Stage

As demonstrated in the preceding discussion, the most reliable results in relating calculated onset date to USDA reports were for corn in western Kansas. Furthermore, the point sample fraction of irrigated field sites (66.3 percent) matched very closely with the corresponding planted acreage figure from the entire west region as reported by the USDA (66.2 percent), which supports the assertion that the field site sample reflects the region as a whole. Assuming our results to be accurate, we were able to speculate on phenological growth stage and other physical characteristics of this crop at time of onset. Conventional wisdom describes greenup onset as the time after emergence when "the plants really begin to take off." Though this is a very broad statement, our agronomic evaluation of corn in western Kansas supports this assertion with respect to the onset method of Zhang *et al.* (2003).

Our analysis using the Zhang method indicated that in 2001, greenup onset for corn in western Kansas occurred approximately 23 days after emergence. Feedback from western Kansas extension agents suggests that the corn plant typically ranges from 15 to 45 cm (6 to 18 inches) tall at this point, dependent on temperature and other growth limiting factors such as soil moisture. Dryland corn will likely be in the lower part of this range, whereas the upper part of the range is more reflective of corn in fields that are irrigated. The extension agents also indicated that at 23 days after emergence, corn would typically be between the 4-leaf stage (V4) and the 8-leaf stage (V8) in terms of its development, with dryland fields more likely near V4 and irrigated fields closer to V8.

It is known that the phenological development of corn in these early growth stages is more dependent on temperature than any other factor. According to Hardman and Gunsolus (2002), corn plants add one new leaf approximately every three days following emergence. This suggests that at day 23, corn is likely at stage V7 or V8. Alternatively, Weuthrich (1997) suggests that 85 growing degree units (GDUs) are required before a new leaf can be formed, with this linear relationship holding from emergence to the 10-leaf stage (V10). GDUs are calculated as a function of minimum and maximum daily temperature (Lauer, 1997). Using western Kansas temperature information collected by the National Weather Service and the GDU relationship identified in Weuthrich (1997), we calculated that the corn we were observing was likely between stages V4 and V5 at 23 days after emergence. Using a different model, Lauer, (1997) also provides a scale relating corn developmental stages to cumulative GDUs. His findings suggest that the corn we observed was between stages V6 and V7. In reality, we expect to observe somewhat broad ranges for plant height and growth stage in western Kansas due to different hybrids and management practices used in that region.

Now consider corn plant growth at stage V6, which is in the middle of the possible range of growth stages that likely characterized the corn crop in western Kansas in 2001 at time of greenup onset. At this stage, corn is approximately 30 to 35 cm (12 to 14 inches) tall. According to Ritchie *et al.* (1993), at V6 "the nodal root system is now the major functioning root system for the plant," and "the stalk is beginning a period of greatly increased elongation." Thus, with respect to corn in western Kansas, our findings suggest that the Zhang method is estimating onset to occur around the time that corn growth really is "starting to take off," which lends valuable theoretical insight into what event is captured when using the method in a controlled situation. Though the relevance of this conclusion is somewhat dependent on our decision to use the last day of the compositing period to represent the date of NDVI acquisition, backing this number off by several days will not nullify the results of this agronomic evaluation.

Conclusion

In this study, we have presented an example of how USDA crop phenology information (specifically, percent planted and percent emerged data) can be used to quantitatively examine results obtained from an onset date identification method. The use of higher resolution MODIS 250 m NDVI data coupled with the large field sizes (40.5 ha or larger) of individual field sites ensured that the pixel-level time-series NDVI signal analyzed for each site was representative of a single summer crop type (with the exception of weeds and other non-crop vegetation present in some fields) that had a well documented phenology for evaluation purposes.

The primary issue affecting the analysis was that many field sites deviated from the idealized agricultural field site scenario where the field consists of bare soil prior to crop emergence. A pre-crop NDVI signal was observed for numerous field sites, which had a negative impact (i.e., introduction of an early onset bias) on the quality of results we obtained from some of the study cases. The influence of pre-crop vegetation on the greenup onset results was unexpected, but illustrates the difficulty of evaluating large area VPMs, even for large extents of homogeneous vegetation. In general, the pre-crop vegetation influence on the onset results was the strongest for the later planted summer crops and for the ASDs that received higher annual precipitation. Both characteristics favor the establishment of pre-crop vegetative cover.

The strongest conclusion drawn from our study was for corn in western Kansas, which most closely matched the hypothetical "bare ground to crop" greenup scenario. The early planting date of corn and the semi-arid climate of western Kansas limited the presence of weed/volunteer crop cover on cornfield sites in this area and minimized the influence of a pre-crop vegetation signal on the greenup onset results. We found that onset date (determined using the method of Zhang *et al.*, 2003) for corn in western Kansas lagged approximately 23 days behind reported 50 percent emergence of the crop. At this point in time, the agronomy literature and communications with agronomists and western Kansas agricultural extension agents suggest that the western Kansas corn crop was approximately 15 to 45 cm (6 to 18 inches) tall and between the 4-leaf (V4) and 8-leaf (V8) developmental stage.

The onset date identification method described in Zhang *et al.* (2003) that we chose to investigate is classified by Reed *et al.* (2004) as an inflection point method. In their assessment, inflection point methods tend to provide the earliest measures of onset when compared to other families of methods. In light of the detailed results we obtained for corn in western Kansas, the plants were well into their growth cycle at time of onset calculated using the Zhang method. However, the onset points arguably appeared too early (specifically, before any noticeable increase in NDVI; see Figure 4) when performing a visual assessment, which raises questions about the sensitivity of the MODIS instrument in responding to early season crop growth. An obvious question that could be examined with further research using these or similar datasets is where in the growing season and crop development process do other methods identify greenup onset.

This research used remotely sensed data and crop development information that is readily available for large geographic areas at little or no cost. In general, the data processing, analysis, and evaluation methods were conducted in a relatively short time frame at a state to regional scale. The exception was the assembly of the field site database, which required an estimated 360 hours to complete. However, state-level GIS databases that delineate and characterize individual fields will be available in the near future (e.g., Kansas FSA). Such databases will have the potential to alleviate the burden of manually locating field sites and thus allow more widespread and thorough examinations similar to the one presented here. The use of such databases will allow larger samples of field sites to be rapidly collected using specific sampling schemes and criteria, which can be used in combination with the MODIS 250 m NDVI and USDA crop information implemented in this study for further evaluation of the greenup onset and other VPMs (e.g., time of peak greenness, dormancy onset, and length of growing season). Larger sample sizes will permit more refined analysis methods that may overcome some of the difficulties encountered in this research. This study is an initial step in moving the evaluation of large area remote sensing phenology results from qualitative to quantitative assessments that can provide some insight into the phenological growth stage that method-specific VPMs are detecting.

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