Analysis of MODIS 250 m NDVI Using Different Time-Series Data for Crop Type Separability

By

Eunmok Lee

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Chairperson Dr. Stephen L. Egbert

Dr. Jude Kastens

Dr. Kelly Kindscher

Dr. Xingong Li

Dr. Terry Slocum

Date Defended: July 21, 2014

The Dissertation Committee for Eunmok Lee

certifies that this is the approved version of the following dissertation:

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Chairperson Dr. Stephen L. Egbert

Date approved: July 21, 2014

ABSTRACT

The primary objectives of this research were to: (1) investigate the use of different compositing periods of NDVI values of time-series MODIS 250 m data for distinguishing major crop types on the central Great Plains of the U.S. and (2) analyze collection 5 versus collection 4 time-series MODIS 250 m NDVI data to separate crop types.

NDVI profiles extracted from different compositing periods for 2001 and 2005 were analyzed to see whether 8-day (and dual-8-day) composited NDVI data, as compared to 16-day composited NDVI data, would show finer scale spectral-temporal variability that would result in improved crop separability. NDVI value profiles were also extracted from different collection versions (4 and 5) for 2001 and 2005 (collection 5 only). Phenological curves for all crops and all datasets were created and visually inspected and JM distance statistical analysis was performed to compare separability of the crops for both the compositing period analysis and the collection version analysis.

Major conclusions and findings for the compositing period analysis include: (1) there are statistical differences among the different compositing period datasets, (2) time-series data that have shorter compositing periods are more effective in separating crop types, and (3) any observed differences should be interpreted with care and in the context of variations in environmental conditions for a given growing season. For the collection version analysis the major finding was that, contrary to expectations, the most recent version of time-series MODIS 250 m data (version 5) was inferior to version 4 in terms of crop separability; however the analysis did not suggest reasons for the outcome. As a result of this research, it is tentatively recommended (subject to further research) that MODIS NDVI data (a) from a shorter 8-day compositing period and (b) from collection 4 should be used where possible for crop-type mapping in the study region.

Keywords: MODIS; Vegetation index; Land use/land cover classifications; Crop separability

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In Korean, for my parents, family: 기억할 이름.

이종찬, 최윤선, 혜숙, 혜정, 은택.

한상철, 한영주.

한민경, 해나, 세라.

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1. Introduction

1.1. Problem Statement

Increasing demand from both the public and the private sectors for land use/land cover (LULC) information at a wider range of scales, from regional to global, along with the expectation of expanded and increasingly detailed results, drove this research. There are growing requirements for new LULC data sets that are more timely, accurate, and detailed (Cihlar, 2000; DeFries and Belward, 2000). Researchers in the remote sensing field are aware of a growing need for mapping LULC patterns on a routine basis for large geographic areas in order both to provide the most up-to-date LULC information and help us understand important human-environment interactions (Turner *et al*., 1995; NRC 2001; NASA 2009). In particular, LULC mapping for agricultural land cover needs to be conducted on a repetitive basis in order to describe present LULC patterns and trace common changes in the LULC patterns due to dynamic alterations caused by intensive and continuous human activities (Wardlow *et al.*, 2007). Despite considerable improvements over the last few decades in LULC classifications at various spatial scales (Eve and Merchant, 1998; Vogelmann *et al*., 2001; Homer *et al*., 2004) and global scales (DeFries and Townshend, 1994; DeFries *et al*., 1998; Loveland *et al*., 1999; Hansen *et al*., 2000; Bartholome and Belward, 2005), greater effort is needed in mapping detailed crop-related LULC patterns, particularly on the annual time step necessary to reflect common LULC changes that occur from year-to-year (Wardlow *et al.*, 2007).

1.1.1. Sensing LULC changes remotely – data choices

In spite of (or perhaps because of) many advances in remote sensing, it is not an easy task to find the best data and methodology for a given research question, particularly in land cover mapping. Thus rises the question – and this is a long-standing issue – what compromises should be made when faced with choices among spatial resolution, temporal frequency, and cost? Low spatial resolution images are generally restricted to broad land cover mapping associated with natural systems and often are not suitable for individual crop classification because of the high spatial variability and complexity of most agricultural systems (Turner *et al*., 1995). Many land cover data sets derived from multi-temporal, coarse-resolution (1-km or 8-km) AVHRR (Advanced Very High Resolution Radiometer) data (DeFries and Townshend, 1994; DeFries *et al*., 1998; Loveland *et al*., 1999; Hansen et al., 2000) and SPOT VEGETATION 1 km data (Bartholome and Belward, 2005) have focused on identifying broad-scale land cover patterns and natural vegetation classes from which a variety of biophysical parameters can be derived to better inform global environmental models. In contrast, comparatively higher resolution sensors, such as Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and SPOT (HRV) have provided valuable data sets for detailed LULC classification. Their uses, however, generally are limited for large-area applications due to their incomplete spatial coverage, relatively infrequent temporal coverage, cloud contamination problems, and the considerable costs and time required to acquire and process the large data volumes (DeFries and Belward, 2000).

1.1.2. Sensing LULC changes with MODIS

In an effort to study the feasibility of using time-series data for detailed, regional-scale crop-related LULC characterization in the U.S. Central Great Plains, Wardlow *et al*. (2007) demonstrated new possibilities using Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m Vegetation Index (VI) data tested in the state of Kansas. One of the key conclusions of their research states “a time series of the 16-day composite MODIS 250 m VI data had sufficient spectral, temporal, and radiometric resolutions to discriminate the region’s major crop types and crop-related land use practices (Wardlow *et al*., 2007, p. 307).” By using MODIS 250 m VI data, they were able to obtain meaningful results in detecting unique multi-temporal VI signatures for each crop class and for evaluating the crop classes’ average multi-temporal response patterns. In other words, the researchers illustrated the potential of MODIS 250 m vegetation index data for crop mapping, balanced against other factors such as cost, availability of resources, and time constraints. In their view, science-quality imagery from MODIS with global coverage, high temporal resolution (1-2 day repeat coverage), moderate to coarse spatial resolution (250 m, 500 m, and 1 km), and distribution free of charge provides major advantages compared to other sources used for regional to global scale LULC mapping.

1.1.3. Previous research

Early research suggested that multi-temporal remote sensing datasets are useful for identifying key crop developmental stages (Badhwar, 1984; Bauer, 1985; Henderson and Badhwar, 1984) as well as for crop classification (Badhwar and Austin, 1982), and that the phenological variability measured from satellite imagery is effective in both land cover mapping and phenological interpretation (Reed *et al*., 1994). Since then, among the diverse satellite-based remote sensing systems available, MODIS data have successfully been used for crop type classification (Chang *et al*., 2007; Wardlow and Egbert, 2008; Xavier *et al*., 2006), crop management practice discrimination (Galford *et al*., 2008; Ozdogan and Gutman, 2008; Sakamoto *et al*., 2006; Wardlow and Egbert, 2008; Wardlow *et al*., 2007; Wardlow *et al*., 2006), and crop phenology monitoring (Islam and Bala, 2008; Sakamoto *et al*., 2005; Wardlow *et al*., 2006). MODIS thus offers new opportunities for detailed crop-related LULC characterization in large areas.

Zhan *et al.* (2000) argue that there is still a good deal of specific LULC information that can be derived at the 250 m resolution level. Based on encouraging research showing that MODIS 250 m imagery is effective in detecting land cover change driven by both human and natural forces (Zhan *et al.*, 2002; Hansen *et al.*, 2002), Wardlow *et al.* (2007), as previously noted, showed that MODIS 250 m data were suitable for crop mapping in the U.S. Central Plains, given the significance of the area as a major crop producing region in the U.S. and its relatively large average field sizes. The research succeeded in providing initial results in the development of a MODIS-based mapping and monitoring protocol for large-area crop characterization. This ground-breaking research can be expanded still further to improve the classification of crop classes by examining other variables and using the higher temporal resolution (8-day) MODIS datasets now available, as well as the most recent version of reprocessed data (version 5).

1.2. Research Objectives/Questions

The overarching goal of this research was to broaden our understanding of two aspects of time-series MODIS 250 m VI data in characterizing crop-related LULC patterns for large areas such as in the U.S. Central Great Plains. More specifically, it was my goal to further investigate differences in Normalized Difference Vegetation Index (NDVI) and crop phenological characteristics using two aspects of time-series MODIS 250 m composite[1] data for distinguishing among 5 major crops (alfalfa, *Medicago sativa*; corn, *Zea mays*; sorghum, *Sorghum bicolor*;

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[1] MODIS products that were used for this research are MOD09Q1 and MOD13Q1. The former product provides bands 1 and 2 at 250 m spatial resolution and its composite period is 8-day. The latter product is provided every 16 days at the same spatial resolution as the former one. More detailed information about the products is discussed in the following chapter.

soybeans, *Glycine max*, and winter wheat, *Triticum aestivum*) grown in Kansas. Data from 2001 and 2005 were used in this study because ground reference data of good quality are available for these years at the Kansas Applied Remote Sensing Program (KARS). With the 2001 data, I also examined the impact of differences between NDVI values from MODIS collections[2] 4 and 5.

This research had two primary objectives, which are initially briefly presented here and then followed by more detailed descriptions. The first was, to investigate the NDVI values between different compositing periods of time-series MODIS 250 m data for distinctive separability of crop types. This is based on the hypothesis that 8-day (and dual-8-day) composited NDVI, compared to 16-day composited NDVI, may show finer scale spectral-temporal variability that would facilitate improved crop separability and, ultimately, crop mapping. If evidence could be found to support this working hypothesis, it would improve our understanding of the behavior of crop development over a growing season that could lead us to better classification of crop classes using finer temporal resolution data; The second object was to investigate the differences in NDVI values between collections 4 and 5 of time-series MODIS 250 m data, again for distinctive separability of crop types. The working hypothesis was that collection 5 data, produced by an improved reprocessing algorithm, would provide greater intercrop separability and likely more accurate mapping of crop types. Further, if the results showed significant differences between the two collections/versions and the reasons for these differences could be identified, this would contribute to an understanding of how the vegetation index (VI) processing and compositing techniques between the two collections may affect LULC classification limitations ascribable to calibration and instrument characteristics, clouds and cloud shadows, atmospheric effects, etc.

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[2] A collection is a MODIS data archive that has been reprocessed in order to incorporate better data value calibration and compositing algorithm refinements.

To summarize:

***<u>Research Issue 1</u>*: Investigating the use of NDVI values to separate crop types using different compositing periods of time-series MODIS 250 m data**

This issue concerns testing the hypothesis that higher temporal resolution may show improved separability for crop identification. Several questions were considered in examining this issue:

1. Are there meaningful statistical differences among the different composite period datasets?
2. Are the 8-day or dual-8-day time-series datasets (i.e., the datasets with finer temporal resolution) more effective in separating crop types than the 16-day time-series dataset?
3. What are the reasons for any observed differences?

***<u>Research Issue 2</u>*: Investigating the use of NDVI values to separate crop types using collections 4 and 5 time-series MODIS 250m data**

This issue involves an analysis of NDVI profiles using collections 4 and 5 of the MODIS 250 m vegetation index data. The producers of MODIS have reprocessed the data several times since the composite data stream was initiated in 2001. Reprocessing refers to employing the latest version of the scientific algorithm (described in Algorithm Theoretical Basis Documents)[3] to process the data using the best available calibration and geolocation information (Didan and Huete, 2006). To see whether collection 5 represents a potential improvement over collection 4 for crop separability, several questions were examined:

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[3] The refinements designed to improve the spatial and temporal characteristics such as compositing method, dealing with clouds, aerosol filtering, etc.

1. Are there meaningful statistical differences between the collections?
2. Does collection 5 of the time-series MODIS 250 m dataset have better ability to discriminate the study area's major crop types (alfalfa, corn, sorghum, soybeans, and winter wheat) compared to collection 4?
3. What are the potential causes of the differences?

1.3. Study Area and Major Crops to be Studied

For this research, I focused on the state of Kansas. There are several reasons why the state of Kansas is an appropriate area for this research. For this discussion, I adopt the rationale Wardlow suggested (2005, pp. 24 - 25), followed by supplementary information to add context and justification.

First, the state's "general cropping practices and patterns are representative of the larger Central Great Plains region."

The Central Great Plains is one of the most important crop producing regions in the U.S. Current critical issues in the region such as climate change and groundwater availability are challenges that Kansas faces in common with the entire region. Also, Kansas is agriculturally typical of the region, especially considering long-running historical cropping practices combined with irrigation and dryland farming techniques that have been used to maintain high crop production. According to Kansas Farm Facts 2011, Kansas ranked in the top 10 states nationally for several major U.S. crops and livestock. The principal crops that will be under investigation for this research include alfalfa (*Medicago sativa*; rank #11 U.S. production[4]), corn (*Zea mays*;

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[4] Rank #6 according to Kansas Farm Facts 2010

rank #8), sorghum (*Sorghum bicolor*; rank #1), soybeans (*Glycine max*; rank #10), and winter wheat (*Triticum aestivum*; rank #1).

Second, "the state has a range of environmental conditions, general landscape patterns, and crop management practices across which to evaluate the utility of the MODIS VI data for crop mapping."

Winter wheat is the major cash crop cultivated predominantly on dryland farm fields over the region. Alfalfa, corn, sorghum, and soybeans are also major crops grown on both non-irrigated and irrigated land depending on the environmental conditions of the area. The state's unique precipitation gradient (higher east and lower west, Figure 3) plays a crucial role in the study area's cropping patterns and associated management practices, as does the availability of ground-water. The temperature variation that increases from northwest (Mean Annual Temperature < 11 °C) to southeast (Mean Annual Temperature > 15 °C) also affects temporal and spatial patterns of crop cultivation and conditions, and hence NDVI in the study area (Wang *et al*., 2001).

Third, "there have been a number of LULC (Whistler et al., 1995; Egbert et al., 2001) and crop-specific mapping efforts (Price et al., 1997; Jakubauskas et al., 2002) conducted within Kansas that provide insight into effective classification strategies for this area and a general understanding of the state's LULC/cropping patterns."

Although most earlier mapping research was done using remotely sensed imagery other than MODIS (such as Landsat TM and AVHRR), most of the results were derived from multiyear projects with extensive efforts and subsequently became available for numerous state and federal agencies that used them for management and planning purposes.

Finally, "a number of data sources were available for Kansas to evaluate and validate the results of this research."

Well-documented information and maps on cropping patterns and practices of the state are available from public agencies including the USDA (United States Department of Agriculture), the Kansas Data Access and Support Center (DASC - the state GIS data center), and KARS. In particular, the broad variety of digital maps and available data from DASC and KARS was a valuable resource for this research.

1.4. Data

Table 1.1 shows the data used for this research. Special attention was paid to the MODIS dataset, as it had gone through several pre-processing steps before the NDVI values were analyzed, such as mosaicking, re-projection, extracting NDVI values, and Maximum Value Compositing (MVC) procedures.

Table 1.1 List of data

Data	Source	Description
MODIS 250 m NDVI Data	• Available from the Land Processes Distributed Active Archive Center (LP DAAC) at no cost : https://lpdaac.usgs.gov/	• 12-month time series of MODIS 250 m NDVI data (products MOD09Q1 & MOD13Q1, collection 005) spanning from January to December, 2001 and 2005 were the two data sets analyzed in this research. • The data from 3 MODIS tiles (h09v05, h10v05, h10v04) are required for complete spatial coverage of Kansas.
USDA Crop Acreage Data	• United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) : http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp	• From USDA NASS, planted crop acreage data was collected. The data set contains land use practice information for each crop type as well as acreage information. • The acreage data were used as a measurement of relative area for classified crops to evaluate the MODIS-derived results' consistency with the state's reported crop area.
Other Satellite Imagery and Geospatial Data Sets	• Kansas Applied Remote Sensing (KARS) Products	• The KARS Program maintains a collection of aerial photography/imagery[5], and satellite map products along with geospatial data sets. Some of these were used as a visual reference while creating the field site database and for evaluating the classified crop patterns of the MODIS map.

The research began by extracting NDVI values from the various MODIS 250 m datasets based on both composite period (8-day, dual-8-day, and 16-day) and collection version

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[5] Field site training and validation database were created based on the Kansas Farm Service Agency's annotated aerial photos (Wardlow, 2008).

(collection 4 and 5). The NDVI values were initially explored primarily by descriptive and visual analysis to see how different the NDVI characteristics appeared to be by crop type (alfalfa, corn, sorghum, soybeans, and winter wheat), land use practice (irrigated versus non-irrigated), and agricultural region, i.e., using the four corners of the state's nine Agricultural Statistics Districts (ASD 10/30/70/90). The four corner ASDs were selected for comparison as they represent the extremes of the state's precipitation, temperature, and planting time gradients, which are assumed to be the key drivers of regional variations in the crop-specific VI responses (Wardlow *et al*., 2007).

1.5. Dissertation Organization

This dissertation includes two research chapters, in addition to this introductory chapter and a summary and conclusions chapter. Each research chapter has a complete discussion of each of the two research questions outlined earlier in the research objectives section.

Chapter 2 investigates the NDVI values between different compositing periods of time-series data for distinctive separability of crop types. The hypothesis is that 8-day (and dual-8-day) composited NDVI compared to 16-day composited NDVI may show finer scale spectral-temporal variability that would facilitate improved crop separability and, ultimately, crop mapping. Two different types of MODIS products - MOD09Q1 and MOD13Q1 – were used, representing 8-day and 16-day compositing periods, respectively.

Chapter 3 discusses whether collection 5 of the time-series MODIS 250 m dataset has better ability to discriminate Kansas' major crop types compared to collection 4. MODIS products have been reprocessed several times since the launch of the sensor to apply the latest science algorithm; each succeeding dataset is referred to as a version or collection of MODLAND (i.e., MODIS Land) products.

The final chapter presents a brief summary of the results of each of the research questions and the conclusions of the research. Further research questions and suggestions are discussed as well. To avoid redundancy of information that would result from information regarding similar background, research area, and data for each chapter, the references for both research chapters are combined and placed at the end of the final chapter.

2. Analysis of MODIS 250m NDVI Using Different Compositing Periods of Time-Series Data for Crop Type Separability

2.1. Introduction

There have been increasing requirements for new land use/land cover (LULC) data sets that are more timely, accurate, and detailed (Cihlar, 2000; DeFries and Belward, 2000). These needs, emanating from both the public and the private sectors, are called for at a wider range of scales, from regional to global. Researchers in the field are aware of a growing need for mapping LULC patterns on a routine basis in order to both provide the most recent LULC information and help us understand important human-environment interactions (Turner *et al*., 1995; NRC 2001; NASA 2009). In particular, LULC mapping for agricultural land cover needs to be conducted on a repetitive basis in order not only to describe present LULC patterns but to trace dynamic changes in the LULC patterns caused by intensive and continuous human activities (Wardlow *et al*., 2007).

Remarkable advances in remote sensing have made it practical to monitor and collect data related to agricultural LULC changes, especially over the past a few decades. Despite the usefulness of remotely sensed data in characterizing agricultural LULC patterns, it is still not a routine task to find the most appropriate sensor and methodology for a given research question. Researchers are required to make decisions on what compromises to make among spatial resolution, temporal frequency, and, sometimes, cost. It appears, though, that there has been a transition, in general, from lower spatial and temporal resolution of remotely sensed data to moderate spatial and high temporal resolution for LULC mapping.

Low spatial resolution images (pixels of 1 km or larger) are generally restricted to broad land cover type mapping associated with natural systems and often are not suitable for crop classification because of the high spatial variability and complexity of agricultural systems (Turner *et al.*, 1995). Many land cover data sets derived from multi-temporal, coarse-resolution (1-km or 8-km) Advanced Very High Resolution Radiometer (AVHRR) data (DeFries and Townshend, 1994; DeFries *et al.*, 1998; Loveland *et al.*, 1999; Hansen *et al.*, 2000) and SPOT VEGETATION 1 km data (Bartholome and Belward, 2005) have focused on identifying broad-scale land cover patterns and natural vegetation classes from which a variety of biophysical parameters can be derived to better inform global environmental models. In contrast, comparatively higher resolution sensors, such as Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and SPOT have provided valuable data sets for detailed LULC classification. Their uses, however, generally are limited for regional applications due to their incomplete spatial coverage, relatively infrequent temporal coverage, cloud contamination problems, and the considerable costs and time required to acquire and process the large data volumes (DeFries and Belward, 2000).

2.1.1. MODIS time-series data

Among the diverse satellite-based remote sensing systems available, Moderate Resolution Imaging Spectroradiometer (MODIS) data have successfully been used for crop type classification (Chang *et al*., 2007; Wardlow and Egbert, 2008; Xavier *et al*., 2006), crop management practice discrimination (Galford *et al*., 2008; Ozdogan and Gutman, 2008; Sakamoto *et al*., 2006; Wardlow and Egbert, 2008; Wardlow *et al*., 2007; Wardlow *et al*., 2006), and crop phenology monitoring (Islam and Bala, 2008; Sakamoto *et al*., 2005; Wardlow *et al*., 2006). In other words, these researchers have illustrated the usefulness of MODIS 250 m Vegetation Index (VI) data for crop mapping, balanced against other factors such as cost, availability of resources, and time constraints. In their observations, what MODIS provides - global coverage of science-quality imagery with high temporal resolution (1-2 day repeat coverage), moderate to coarse spatial resolution (250 m, 500 m, and 1 km), and no data cost (Table 2.1) - are major advances compared to other sources used for regional to global scale LULC mapping.

Table 2.1 MODIS Technical Specifications

Orbit: 705 km (sun-synchronous, near polar, circular)[6]
Swath Dimensions: 2,330 km (across track) by 10 km (along track at nadir)

Key Use	Band[1]	Bandwidth	Spatial Resolution (m)
Land/Cloud Boundaries[2]	1 2	620 – 670 (red) 841 – 876 (NIR)	250
Land/Cloud Properties	3 4 5 6 7	459 – 479 (blue) 545 – 565 (green) 1230 – 1250 1628 – 1652 2105 – 2155	500

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[6] MODIS is on both Terra and Aqua satellites. Differences between MODIS data retrieved from these platforms result from their orbits. Terra's local equatorial crossing time is approximately 10:30 a.m. and Aqua crosses the equatorial line at approximately 1:30 p.m. The differences in Terra's and Aqua's orbits lead to different viewing times and cloud cover.

Ocean color/ Phytoplankton/ Biogeochemistry	8	405 – 420	1000
	9	438 – 448	
	10	483 – 493	
	11	526 – 536	
	12	546 – 556	
	13	662 – 672	
	14	673 – 683	
	15	743 – 753	
	16	862 – 877	
Atmospheric Water Vapor	17	890 – 920	1000
	18	931 – 941	
	19	915 – 965	
Surface/Cloud Temperature	20	3.660 – 3.840	1000
	21	3.929 – 3.989	
	22	3.929 – 3.989	
	23	4.020 – 4.080	
Atmospheric Temperature	24	4.433 – 4.498	1000
	25	4.482 – 4.549	
Cirrus Clouds	26	1.360 – 1.390	1000
Water Vapor	27	6.535 – 6.895	1000
	28	7.175 – 7.475	
	29	8.400 – 8.700	
Ozone	30	9.580 – 9.880	1000
Surface/Cloud Temperature	31	10.780 – 11.280	1000
	32	11.770 – 12.270	
Cloud Top Altitude	33	13.185 – 13.485	1000
	34	13.485 – 13.785	
	35	13.785 – 14.085	
	36	14.085 – 14.385	

[1] Bands 1 to 19, nm; Bands 20 to 36, µm

[2] Bands in the shaded cells were used for this research.

In an effort to study the feasibility of using time-series data for detailed, regional-scale crop-related LULC characterization in the U.S. Central Great Plains, Wardlow *et al*. (2007) showed new possibilities with MODIS 250 m VI data tested in the state of Kansas. One of the key conclusions of their research states "a time series of the 16-day composite MODIS 250 m VI data had sufficient spectral, temporal, and radiometric resolutions to discriminate the region's major crop types and crop-related land use practices (Wardlow *et al*., 2007, p. 307)."

2.2. Problem Statement

The general goal of this research was to widen the applicability of time-series MODIS 250 m VI data in characterizing crop-related LULC patterns for large areas such as in the U.S. Central Great Plains. More specifically, the objective of this study was to investigate differences in Normalized Difference Vegetation Index (NDVI) and phenological characteristics between different compositing periods of time-series MODIS 250 m data. Close investigations of 8-day, dual-8-day, and 16-day time-series MODIS 250 m composite[7] data were made for distinguishing among 5 major crops (alfalfa, corn, sorghum, soybeans, and winter wheat) grown in Kansas. Data from 2001 and 2005 were used in this study since ground reference data of good quality are available for these years at the Kansas Applied Remote Sensing Program (KARS).

The primary objective of the research was to investigate the NDVI values between different compositing periods of time-series MODIS 250 m data for distinctive separability of crop types. This is based on the hypothesis that 8-day (and dual-8-day) composited NDVI compared to 16-day composited NDVI may show finer scale spectral-temporal variability that would facilitate improved

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[7] MODIS products used for this research are MOD09Q1 and MOD13Q1. The former product provides bands 1 and 2 at 250 m spatial resolution and its composite period is 8-day. The latter product is provided every 16 days at the same spatial resolution as the former one. More detailed information about the products will be discussed in the later section.

crop separability and, ultimately, crop mapping. If evidence can be found to support the hypothesis, this may improve our understanding of the seasonal behavior of vegetation that can lead to better classification of crop classes.

Research Issue: Investigating the use of NDVI values to separate crop types using different compositing periods of time-series MODIS 250 m data

This issue tested the hypothesis that higher temporal resolution may show higher distinctive separability in crop identification. Several questions have been considered in examining this issue:

1. Are there meaningful statistical differences among the different composite period datasets?

2. Are the 8-day or dual-8-day time-series datasets more effective in separating crop types than the 16-day time-series dataset?

3. What are the reasons for any observed differences?

2.3. Study Area

Kansas is one of the most important crop-producing states in the U.S. According to Kansas Farm Facts 2011 (Kansas Field Office, 2011), Kansas ranked in the top 10 states nationally for several major U.S. crops and livestock. The principal crops that were under investigation for this research include alfalfa (*Medicago sativa*; national rank #11), corn (*Zea mays*; rank #8), sorghum (*Sorghum bicolor*; rank #1), soybeans (*Glycine max*; rank #10), and winter wheat (*Triticum aestivum*; rank #1). Also, Kansas is agriculturally typical of the Central

Great Plains (Wardlow *et al*., 2007), especially considering long-running historical cropping practices combined with irrigation and dryland farming techniques that have been used to maintain high crop production.

Current critical issues in the region such as climate change and groundwater availability are the challenges that Kansas faces in common with the entire region. According to the National Climatic Data Center's (NCDC) *2012 State of the Climate* report (Blunden *et al*., 2013), for example, 2012 was among the 10 warmest years on record. The report indicated that the nationally-averaged temperature for the months of June, July and August was 2.3 °F above the 20th-century average (74.4 °F). In particular, July was the hottest month on record in the U.S. and August was the 16th-warmest August since 1895. The weekly Crop Progress and Condition Report of the National Agricultural Statistics Services (NASS), Kansas Field Office provides evidence of how the environmental conditions can affect crop management practices in the state (Table 2.2) from year to year. In mid-September 2012, Kansas saw higher temperatures and lower precipitation compared to the previous year, so Kansas farmers had already harvested more than 50 % of corn at the time, as Table 2.2 shows. The NASS report of the week (Sep. 17, 2012) says that farmers "were busy harvesting corn and have started harvesting their other crops along with preparing wheat fields for planting." (NASS, 2012, p. 2)

Table 2.2 Crop progress comparison in 2012, an example for Corn

Corn	Week Ending (mid-September)		
	Sep. 16, 2012	Previous Year	5-Year Average
Mature	86%	68%	63%
Harvested	51%	29%	22%

Winter wheat is the major cash crop cultivated predominantly on dryland farm fields over the Central Great Plains region. Alfalfa, corn, sorghum, and soybeans are also major crops grown on both non-irrigated and irrigated land depending on the environmental conditions of the area. The state's unique precipitation gradient (higher east and lower west, Figure 2.1) plays a crucial role in the study area's cropping patterns and associated management practices, as does the availability of ground water. The temperature variation that increases from northwest (mean annual temperature < 11 °C) to southeast (mean annual temperature > 15 °C) also affects temporal and spatial patterns of crop development, and hence NDVI in the study area (Wang *et al*., 2001).

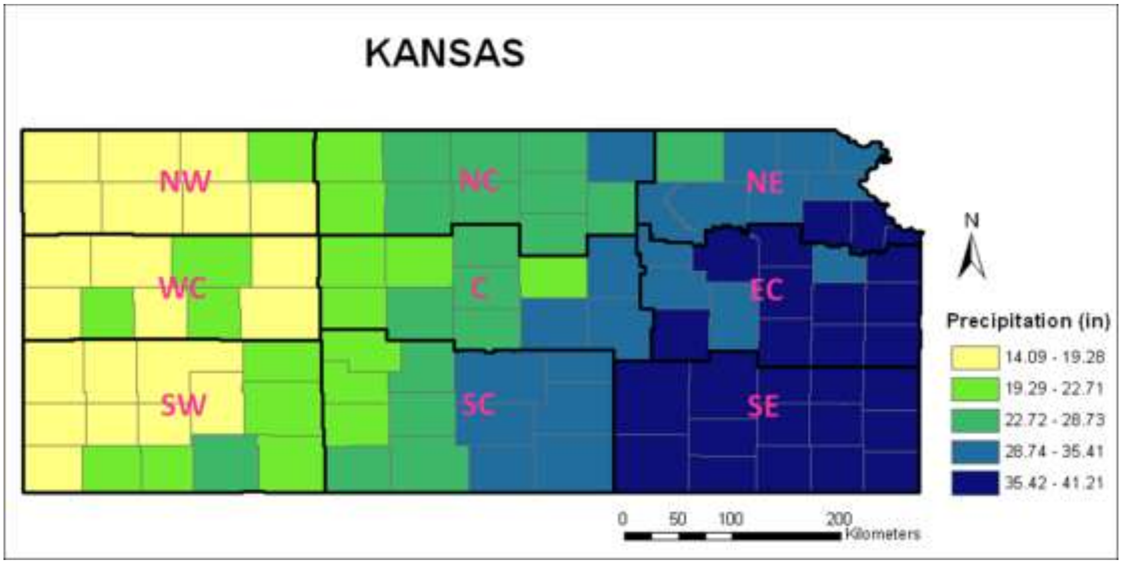

Figure 2.1 Kansas precipitation (2001-2005 average) map divided into nine Agricultural Statistics Districts [source: Weather Data Library, http://www.ksre.ksu.edu/wdl/]

Kansas is divided into nine Agricultural Statistics Districts[8] (ASDs) that are subgroups of counties defined by geography, climate or cropping practices for convenience in managing agricultural statistical information. The county boundaries are represented with the lighter gray lines in the Figure 2.1. Due to the precipitation and temperature differentials between eastern and western Kansas, distinctive VI profiles are expected based on the cropping practices and the ASDs for each crop.

2.4. Data Description and Processing

2.4.1. Time series MODIS VI data

MODIS has numerous standard data products that are used by scientists for research in a variety of disciplines such as oceanography, biology, and atmospheric science. MOD09Q1 is one of the surface reflectance products generated from the first two bands of the corresponding full 36 band scenes (Table 1.1). The product file is a composite using eight consecutive daily 250 m images. Selecting the best[9] observation for every cell in the image during each eight day period helps reduce clouds[10] and other undesirable artifacts from a scene. The file contains one additional band for quality control.

There are also several composite MODIS vegetation products. Vegetation Indices (VIs) are calculated from spectral information derived from two or more bands designed to characterize vegetation properties and provide reliable spatial and temporal inter-comparisons

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[8] Agricultural Statistics Districts are defined groupings of counties in each state, by geography, climate, and cropping practices for convenience in compiling and presenting statistical information on crops and livestock. Kansas is divided into nine ASDs.

[9] The third layer of the product lists quality assurance parameters including atmospheric correction performed, band data quality, cloud state, etc.

[10] The cloud state has four categories of ‘clear’, ‘cloudy’, ‘mixed’, and ‘not set; assumed clear.’

(Huete *et al.*, 2002). MOD13Q1 is the 250 m VI[11] product that gathers information on a per-pixel basis through multiple observations over a sixteen day period. Blue, red, and near-infrared bands are used to determine daily vegetation indices. Due to the lack of a 250 m blue band which is essential for computing the Enhanced Vegetation Index (EVI), the EVI algorithm uses the 500 m blue band.

2.4.2. Different time series datasets

Three different composite sets (8-day, 16-day, and dual-8-day composite period) of 12-month time series MODIS 250m NDVI data spanning from January to December for both 2001 and 2005 were created for this research. For complete spatial coverage of Kansas, three MODIS tiles (h09v05, h10v05, and h10v04) are required (Figure 2.2). To cover one growing season, MOD09Q1 data consisting of 46 8-day composite periods (45 for 2001, as the June 18th period of the year was not available due to system failure) and MOD13Q1 consisting of 23 16-day composite periods of the MODIS data were assembled. Subsequently, 23 dual-8-day composite periods also were created from the 8-day and 16-day composite data by using the Maximum Value Composite (MVC) method (Figure 2.4). Table 2.3 summarizes the imagery that was used in this study.

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[11] MOD13Q1 includes both NDVI and EVI layers.

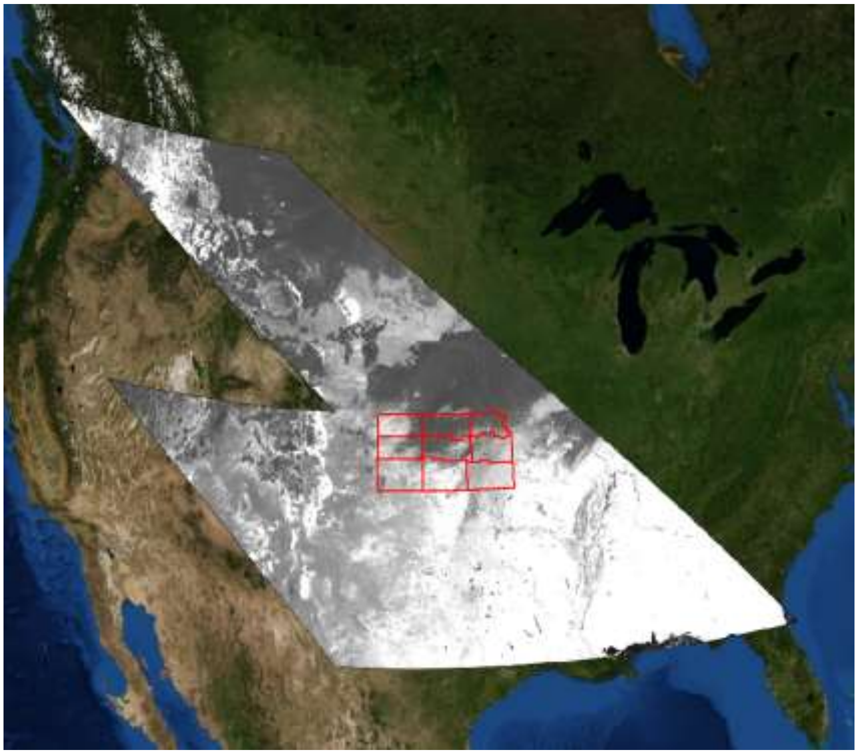

Figure 2.2 A mosaicked image with three MOD09Q1 scenes taken in January 1, 2005. The red line defines the boundary of Kansas with its nine ASDs.

After mosaicking and re-projecting from the Sinusoidal to the Lambert Azimuthal Equal Area projection, NDVI values were extracted for each composite period to be analyzed using sample field sites of the five major crop types in Kansas. This research employed NDVI values since the blue band necessary for calculating the Enhanced Vegetation Index (EVI) is not available in 8-day time series MODIS data. Although both VIs are thought to complement each other for vegetation studies (Huete et al., 2002), they are not significantly different in general. Huete *et al*. (2002) evaluated multi-temporal NDVI and EVI profiles using time-series MODIS 500 m and 1 km data over several biome types such as forest, grassland, and shrub-land. They found that both signatures satisfactorily represented the seasonal behavior of each biome type. Wardlow *et al*. (2007) also found that both MODIS NDVI and EVI illustrated similar phenological variations and were highly correlated for the same crops that were studied in this research.

Table 2.3 Summary of 8-day and 16-day time series MODIS 250m datasets

Product name	MOD09Q1		MOD13Q1	
Spatial resolution	250 m		250 m	
Composite period	8-day		16-day	
Year	2001	2005	2001	2005
# of dates	45[1]	46	23	23
# of scenes[2]	135	138	69	69

[1] Due to system failure, June 18, 2001 is not available.

[2] Three scenes (h09v05, h10v05, and h10v04) are needed to cover the area encompassed by Kansas.

2.4.3. Field site database

For the 2001 field site dataset, I used the same data that Wardlow *et al*. (2007) used in their research. The information from annotated aerial photos provided by the United States Department of Agriculture (USDA) Farm Service Agency (FSA) was used to create a database of field site locations. The important point in acquiring field sites is to secure an adequate number of field sites from widely distributed fields for each crop class that are representative of the spatial and spectral characteristics of the crops. In this research, the field sites were selected from up to 48 counties from a total of 105 counties in the state. A minimum field size was limited to 32.4 ha which covers approximately five pixels in the 250-m scene so that each site would be represented well enough by multiple pixels (Wardlow *et al*., 2007).

The field site locations for 2005, however, were different from those of 2001 due to the unavailability of the same dataset for 2005. To minimize any spatial gaps, I selected the nearest sites to 2001 dataset by using a proximity analysis function in ArcGIS tools[12]. The function can find the nearest field site by calculating the distance from each point in the input layer (2001 field sites) to the nearest point in the second layer (i.e., the 2005 field sites). Figure 2.3 illustrates the geographic locations of each dataset and selected nearest points. Table 2.4 shows the number of field sites by crop type.

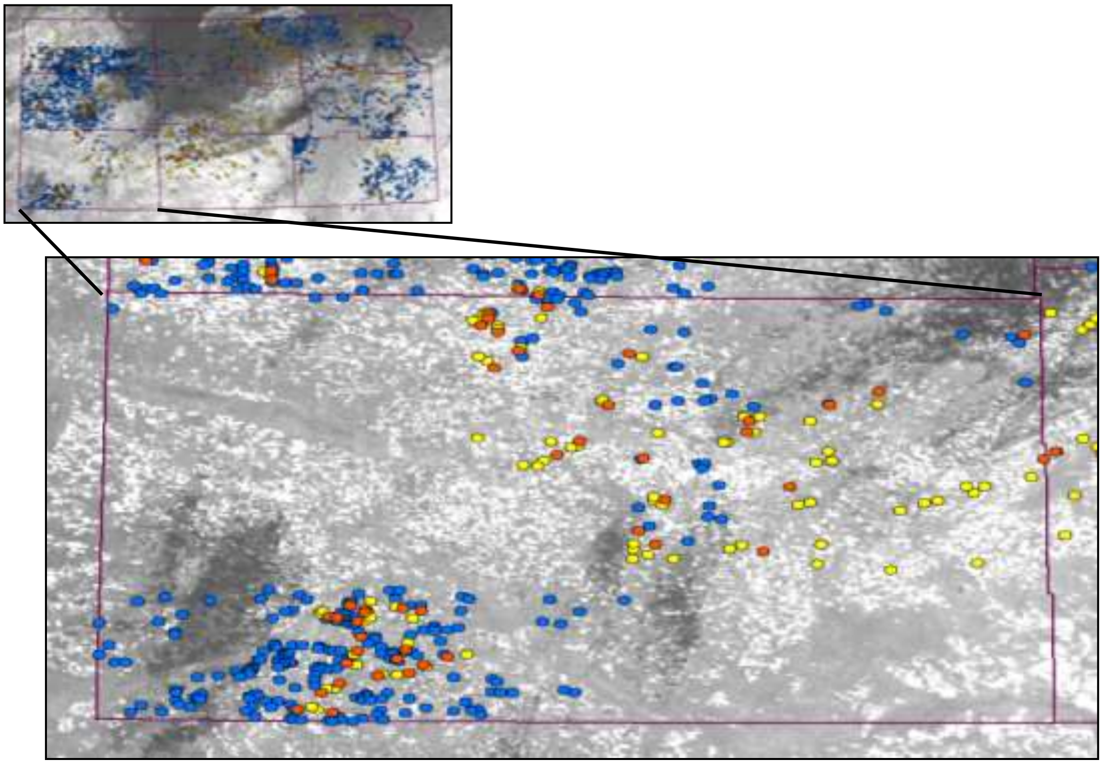

Figure 2.3 Field site locations of corn for 2001 (yellow) and 2005 (blue) datasets zoomed in ASD 30. Red circles show the selected nearest points of 2005 dataset.

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[12] ArcToolbox > Analysis Tools > Proximity > Near

Table 2.4 Number of field sites by crop type

Crop	2001					2005 selected				
	Total : NI[1] : I[2]	ASD 10	ASD 30	ASD 70	ASD 90	Total[3] (out of)	ASD 10	ASD 30	ASD 70	ASD 90
Alfalfa	243 : 119 : 124	25	37	3	-	109 (528)	4	8	1	1
Corn	609 : 279 : 330	72	80	44	36	349 (3524)	62	44	24	21
Sorghum	354 : 319 : 35	39	55	5	37	239 (4393)	31	42	2	19
Soybeans	454 : 219 : 235	32	39	48	36	217 (2581)	16	7	22	28
Winter wheat	446 : 356 : 90	56	75	8	27	356 (20481)	52	57	5	20
Total	2106	224	286	108	136	1270 (31507)	165	158	54	89

[1] Non-Irrigated
[2] Irrigated
[3] Selected out of whole filed sites through **Near** function in ArcGIS, all Non-Irrigated

2.5. Methods

2.5.1. Compositing different time-series of NDVI values

NDVI is computed using a normalized ratio of the near infrared and visible red bands:

$$\text{NDVI} = (\rho_{NIR} - \rho_{red}) / (\rho_{NIR} + \rho_{red}) \tag{1}$$

where ρ_{NIR} and ρ_{red} are the near infrared and red spectral reflectance values, respectively, measured by the MODIS sensor. Through substantial preprocessing involving atmospheric and geometric correction along with spatial and temporal compositing, the standard 16-day composite dataset provides both NDVI and EVI (Enhanced Vegetation Index) data files. As for the dual-8-day composite dataset, however, NDVI values had to be calculated using Band 1 (Red, 0.62 – 0.67 µm) and Band 2 (NIR, 0.841 – 0.876 µm). In spite of the potential usefulness of using both NDVI and EVI together, this research was contained to using only NDVI values since the blue band necessary for calculating the EVI is not available in 8-day time-series MODIS reflectance data.

The Maximum Value Composite (MVC) is a procedure in which each NDVI value obtained for each date during the compositing period is examined on a pixel-by-pixel basis to secure only the highest NDVI value for each pixel location (Holben, 1986). To compare 8-day time-series NDVI values with those of 16-day time-series, the compositing period for 8-day time-series data needed to be extended to the same compositing period of the 16-day time-series. For example, the Julian date for the 8-day time-series data starts from 2001.01.01, 2001.01.09, 2001.01.17, 2001.01.25 until 2001.12.27 keeping 8 days of intervals. On the other hand, the 16-day time-series data maintains 16 days of intervals from 2001.01.01, 2001.01.17, 2001.02.02 to 2001.12.19. So the first two 8-day NDVI datasets (e.g. 2001.01.01 and 2001.01.09) were composited by using the MVC method and then a new dual-8-day time-series NDVI dataset was created to compare with the first 16-day NDVI dataset (i.e., 2001.01.01). In the same way, the next two 8-day NDVI datasets (e.g. 2001.01.17 and 2001.01.25) were chosen to match with the second 16-day NDVI dataset (i.e., 2001.01.17). Figure 2.4 describes the processes.

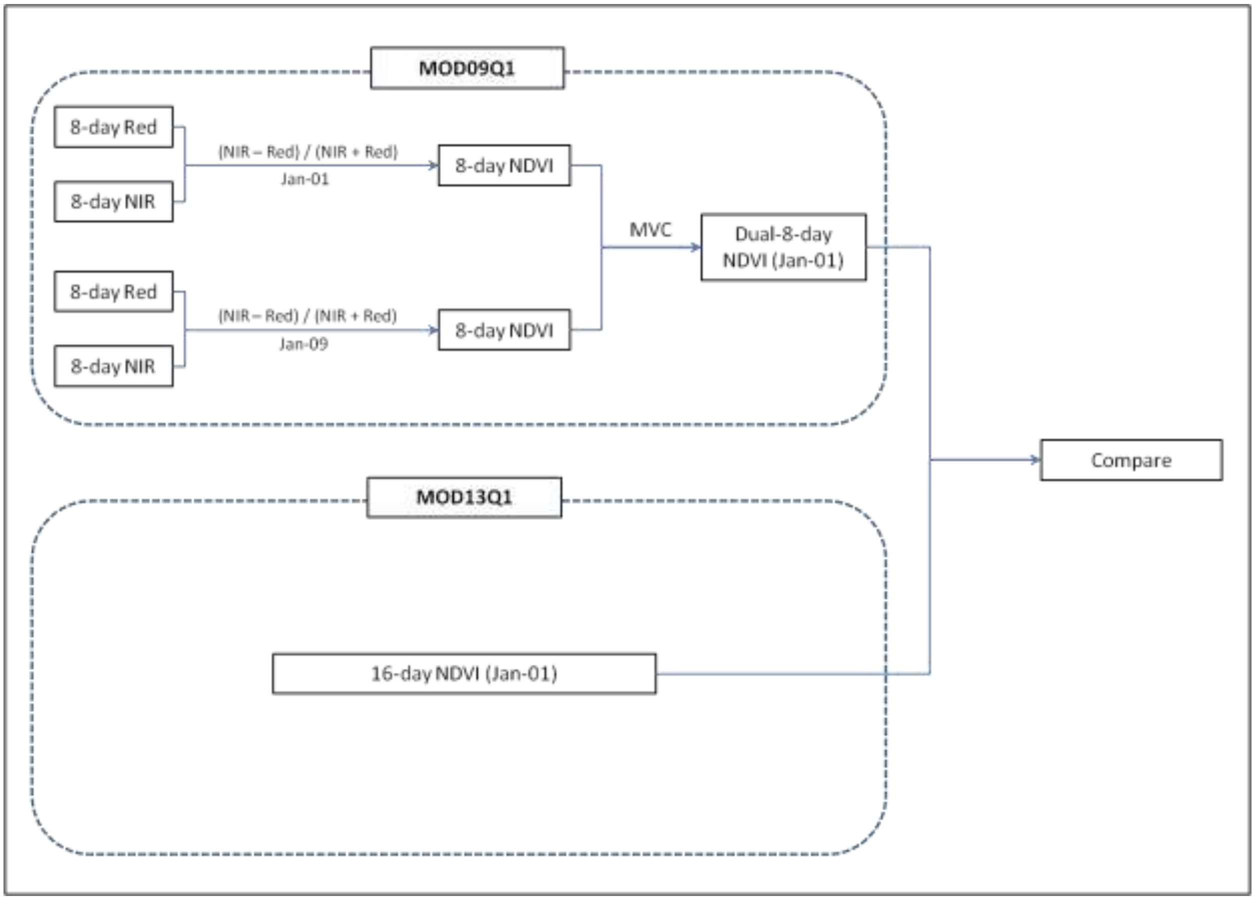

Figure 2.4 Comparison between different composite periods of NDVI time series

The mean multi-temporal NDVI profiles were calculated at the state level, and these NDVI profiles were first visually compared to their crop calendars. The NDVI profiles also were visually compared for irrigated and non-irrigated crops to explore possible separability between these two crop management practices based on spectral-temporal differences during the year. Field sites were grouped by western and eastern ASDs (e.g. ASD10 and ASD30, versus ASD70 and ASD90), and crop-specific NDVI profiles were calculated to estimate the regional variations of the profiles among crop classes across the study area. Three different time series (8-day, dual-8-day and 16-day) of MODIS 250 m datasets were examined to analyze the causes of any differences. Specifically, I examined the ranges of the NDVI values and the lengths of the phenological growth periods.

2.5.2. JM distance

To investigate the separability between specific crop types in the time-series datasets, the Jeffries-Matusita (JM) distance analysis was used, which several researchers have found to be a useful separability measure (Richards and Jia, 1999; Van Niel *et al*., 2005; Wardlow *et al*., 2007). The JM distance between a pair of class-specific probability functions is defined as

$$J_{ij} = \int_x \left[\sqrt{p_i(x)} - \sqrt{p_j(x)}\right]^2 dx \tag{2}$$

where $p_i(x)$ and $p_j(x)$ are two class probability density functions. When classes are normally distributed, equation (2) reduces to

$$J_{ij} = 2(1 - e^{-B}) \tag{3}$$

where

$$B = \frac{1}{8}D^2 + \frac{1}{2}\ln\left(\left|\frac{\Sigma_i + \Sigma_j}{2}\right| \Big/ \sqrt{|\Sigma_i||\Sigma_j|}\right) \tag{4}$$

and

$$D^2 = (\mu_i - \mu_j)^T \left(\frac{\Sigma_i + \Sigma_j}{2}\right)^{-1} (\mu_i - \mu_j) \tag{5}$$

In (5), μ_i indicates the mean value of the ith class and $\sum_i$ indicates the covariance of the same class. The JM distance provides a measure of distributional distinction between two classes that accounts for both differences in class means as well as the individual class spreads. In cases when the sample distributions are largely indistinguishable, JM will be near 0, and in cases where the sample distributions are highly distinct, JM will be near 2. In general, larger JM values imply greater separability than smaller JM values. Greater JM separability of land cover categories also suggests that the land cover classes will be able to be mapped successfully using statistical classification methods.

2.6. Results and Discussion

2.6.1. General crop types

The NDVI profiles for each crop type that were calculated from a 12-month (Jan – Dec, 2001) time series of 16-day composite (Collection 5) MODIS 250 m data across Kansas are shown in the Figure 2.5. The figure illustrates that each crop type has a unique and distinctive average profile from one another. First of all, there is clear spectral and temporal difference between the summer crops (corn, sorghum, and soybeans; so called because the crops grow during the summer) and the others. Peak NDVI values for the summer crops are observed in July and August, while the peak NDVI values of alfalfa and winter wheat are in late April and early May. The specific spectral-temporal characteristics of each crop are discussed in the following sections. Regional and inter-class comparisons are also made by looking at each crop’s NDVI profile and phenology.

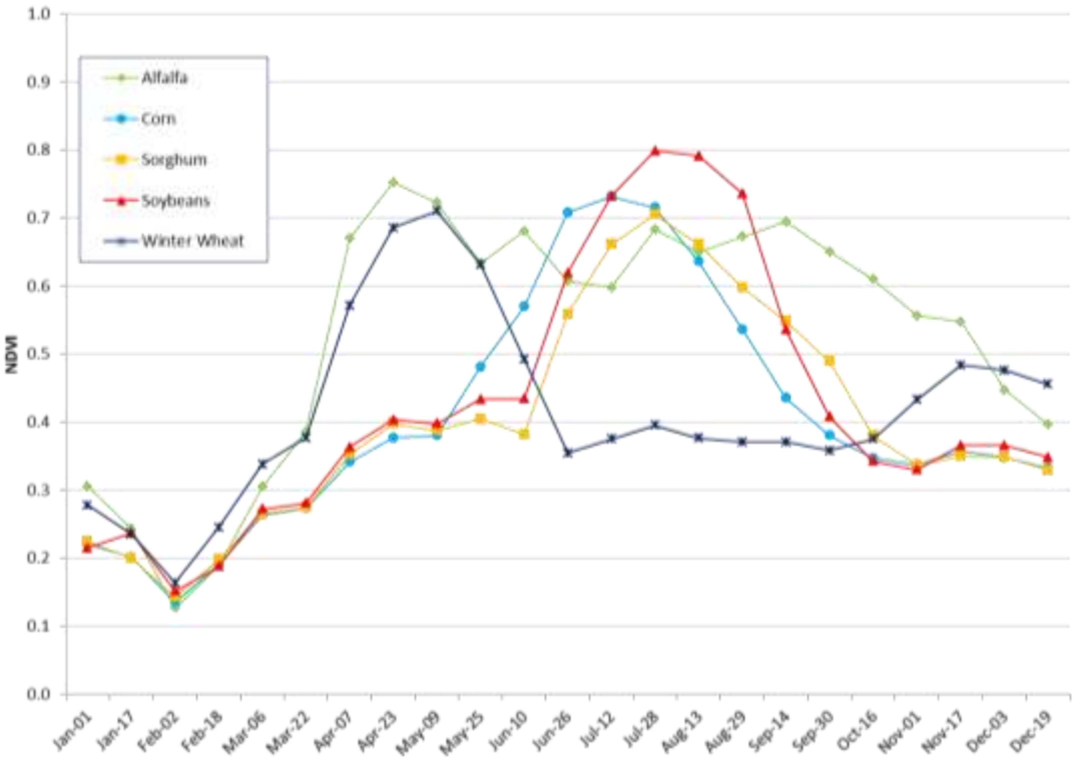

Figure 2.5 NDVI profiles (state average) for major crop types in Kansas. The NDVI values were extracted from 2001 MODIS product MOD13Q1 Collection 5.

2.6.2. Alfalfa

The major phenological pattern of alfalfa is multiple ‘growth and cut’ curves as the crop is normally harvested three or four times per year in Kansas (Shroyer *et al*., 1998). The curves were easily identified visually in Figures 2.5 and 2.6. Note that the NDVI profiles in Figure 2.5 were extracted from 2001/16-day composite using both non-irrigated and irrigated field sites data. The NDVI profiles shown in Figure 2.6 represent different year/time-series/crop management practices. The NDVI profiles represent the data for 2001/16-day (brown) vs. dual-8-day (blue)/non-irrigated in Figure 2.6.a; 2001/16-day (brown) vs. dual-8-day (blue)/irrigated in Figure 2.6.b; 2001/16-day (brown) vs. dual-8-day (blue)/combined non-irrigated and irrigated in

Figure 2.6.c; and 2005/16-day (brown) vs. dual-8-day (blue)/non-irrigated in Figure 2.6.d, respectively. The Collection version 5 was used for all the profiles in both figures.

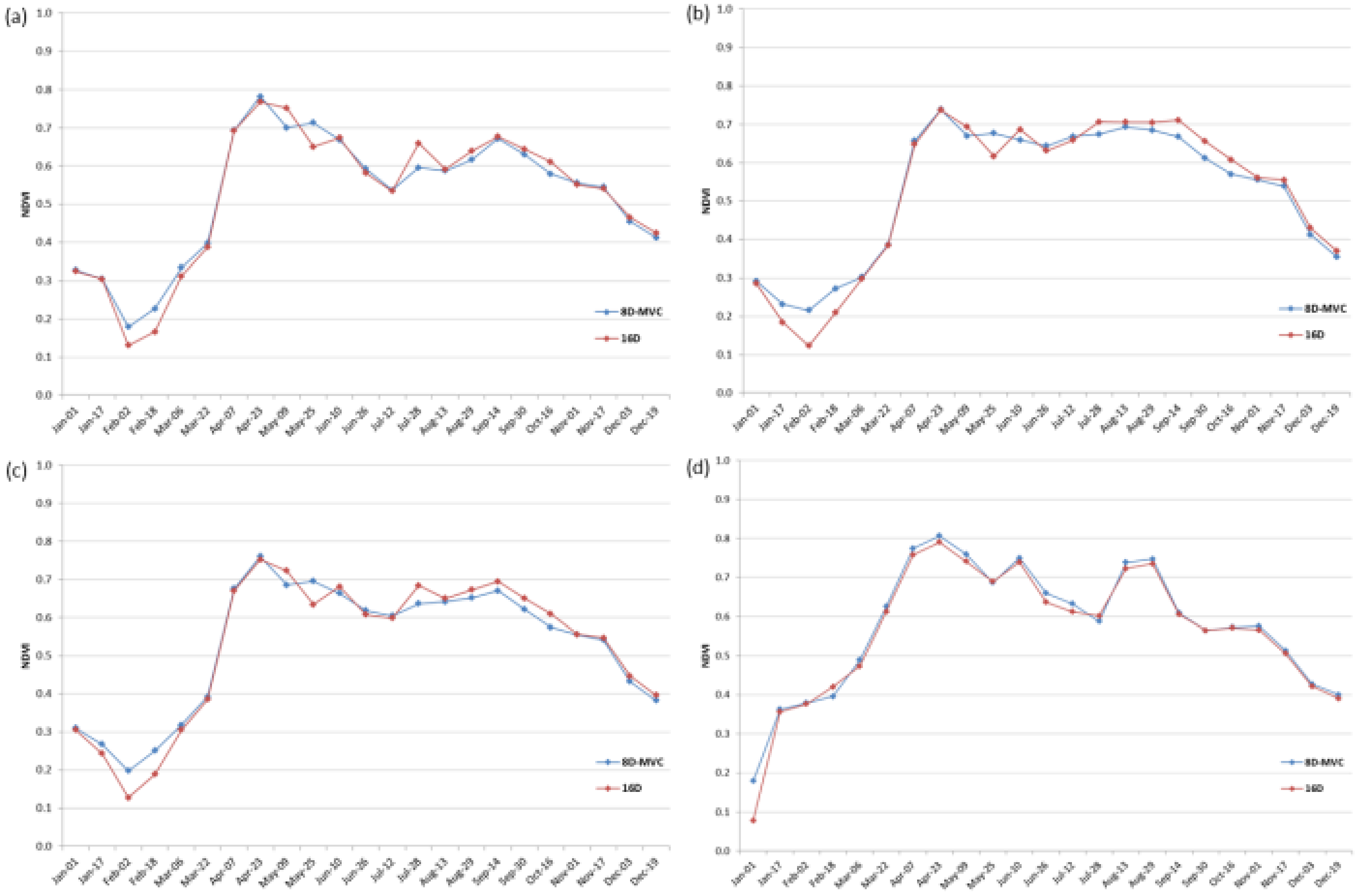

Figure 2.6 Alfalfa NDVI profiles comparisons; (a) 2001, 16-day (brown) vs. dual-8-day (blue), Non-Irrigated; (b) 2001, 16-day (brown) vs. dual-8-day (blue), Irrigated; (c) 2001, 16-day (brown) vs. dual-8-day (blue), average of Non-Irrigated and Irrigated; (d) 2005, 16-day (brown) vs. dual-8-day (blue), Non-Irrigated

As previous researche discussed (Wardlow *et al.*, 2008; Wardlow *et al.*, 2007), a distinctive NDVI pattern was discovered for both non-irrigated and irrigated alfalfa in the time-series MODIS data. As would be expected slightly higher NDVI values were observed in the irrigated sites during the summer (Figure 2.6.a & 2.6.b). These observations accord closely with those of previous research. In Wardlow *et al.*'s research (2008; 2007), however, they found similar NDVI values for non-irrigated and irrigated sites in the spring, while I found higher NDVI values for non-irrigated sites in the spring. The reason for the difference is unclear.

The common pattern in the NDVI profiles is that 16-day time-series data have higher values from mid-June than dual-8-day time-series data except for the 2005 data (Figure 2.6.d). Another unique pattern in common is that 16-day time-series data show stronger seasonal variations except in Figure 2.6.d that shows relatively similar variations.

2.6.3. Corn

Although the summer crops show similar phenological curves, unique spectral-temporal responses representing subtle differences in their growth cycles are reflected in their NDVI profiles (see, e.g., Wardlow *et al.*, 2007) (Figure 2.5). Corn was one of the summer crops studied in this research and typically is the earliest planted summer crop (April to mid-May) followed by soybeans (mid-May to mid-June) and sorghum (late-May to late-June) (Shroyer *et al.*, 1996). In Figure 2.7, plot (a) illustrates the data for 2001/16-day (brown) vs. dual-8-day (blue)/non-irrigated, (b) illustrates the data for 2001/16-day (brown) vs. dual-8-day (blue)/irrigated, (c) illustrates the data for 2001/16-day (brown) vs. dual-8-day (blue)/combined non-irrigated and irrigated, and (d) illustrates the data for 2005/16-day (brown) vs. dual-8-day (blue)/non-irrigated, respectively. Collection 5 was used for all the profiles in the figure.

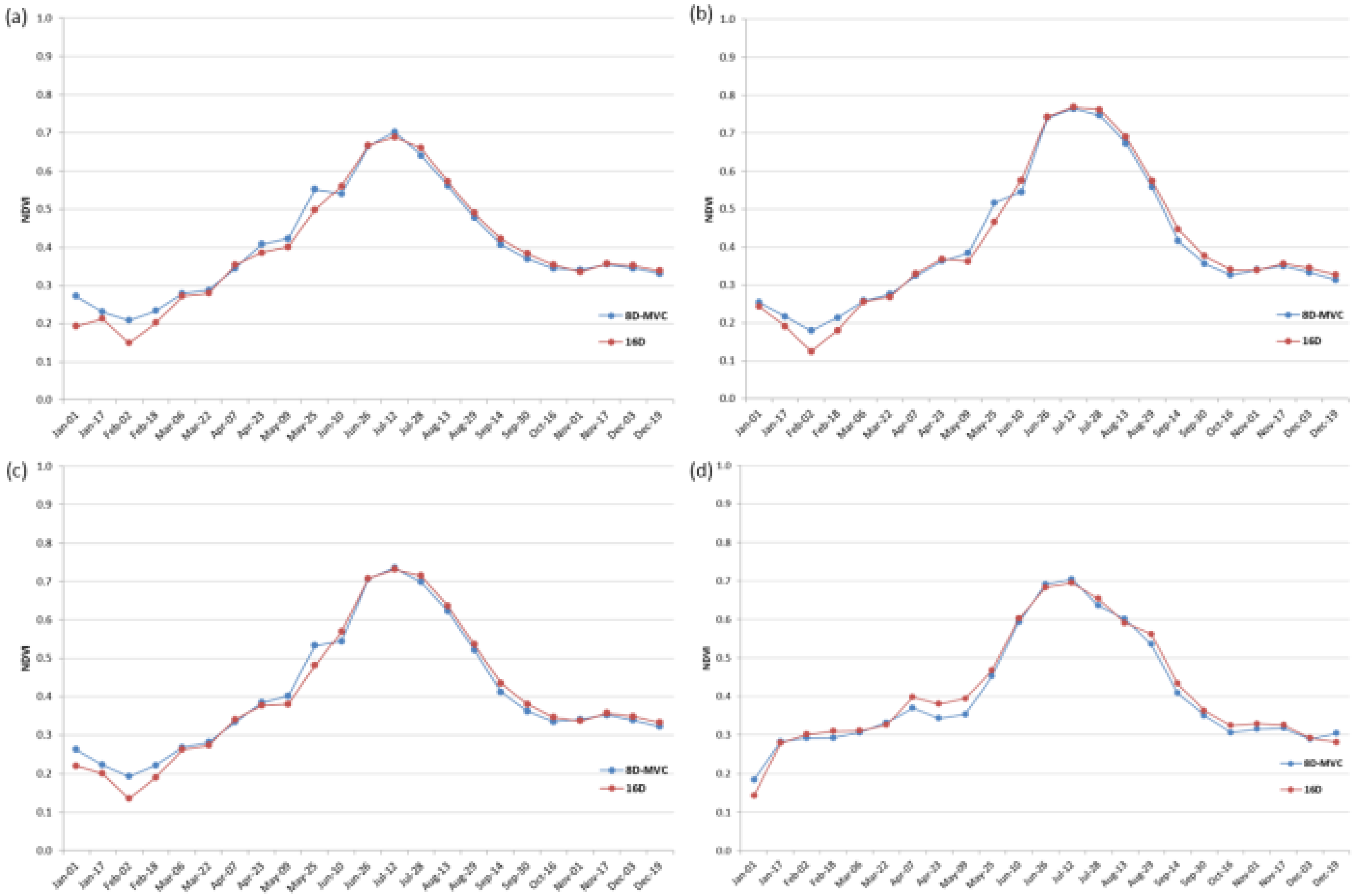

Figure 2.7 Corn NDVI profiles comparisons (a) 2001, 1616-day (brown) vs. dual-8-day (blue), Non-Irrigated, (b) 2001, 16-day (brown) vs. dual-8-day (blue), Irrigated, (c) 2001, 16-day (brown) vs. dual-8-day (blue), average of Non-Irrigated and Irrigated, (d) 2005, 16-day (brown) vs. dual-8-day (blue)

Irrigated corn (Figure 2.7.b) has slightly higher NDVI values than non-irrigated corn (Figure 2.7.a) during the peak greenness period (July 12) and the senescence phase (June 26 – September 14) for both 16-day and dual-8-day time-series data. In comparison, before the time of the peak greenness, 8-day time-series data show slightly higher NDVI values and dual-8-day time-series data show higher NDVI values after peak greenness (Figure 2.7.a, b, and c). In 2005

(Figure 2.7.d), except for the short period at peak greenness and during winter, 16-day time-series NDVI values remain higher throughout the year.

2.6.4. Sorghum

Figure 2.8 illustrates the data for (a) 2001/16-day (brown) vs. dual-8-day (blue)/non-irrigated, (b) 2001/16-day (brown) vs. dual-8-day (blue)/irrigated, (c) 2001/16-day (brown) vs. dual-8-day (blue)/combined non-irrigated and irrigated, and (d) 2005/16-day (brown) vs. dual-8-day (blue)/non-irrigated. For sorghum, the timing of peak greenness occurs during the July 28 period and the crop has the lowest overall NDVI values among the summer crops (Figure 2.5). Similar differences between non-irrigated and irrigated sorghum are found during the mid- to late-summer periods, but irrigated sorghum has slightly higher NDVI values (Figure 2.8.b) than non-irrigated sorghum (Figure 2.8.a) especially during the peak greenness phase in 2001.

In comparing 16-day and dual-8-day time-series data, the profiles of the crops rarely show distinct differences. Slight differences with lower 16-day time-series NDVI values during the dormancy from January 1 to March 6 periods are observed (Figure 2.8.a, b, and c). In 2005, the dual-8-day time-series has higher NDVI values during the peak greenness phase (Figure 2.8.d).

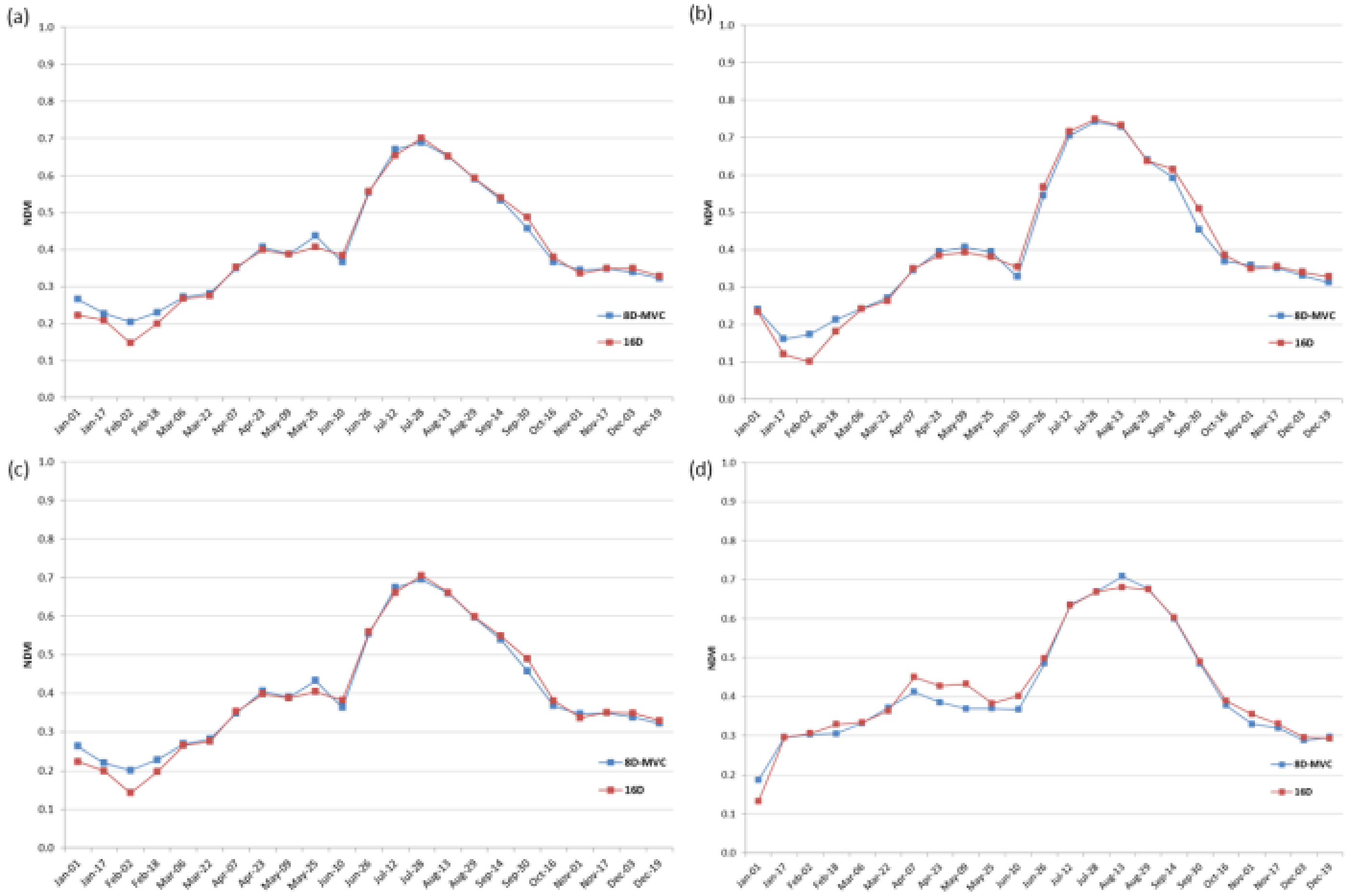

Figure 2.8 Sorghum NDVI profiles comparisons (a) 2001, 16-day (brown) vs. dual-8-day (blue), Non-Irrigated, (b) 2001, 16-day (brown) vs. dual-8-day (blue), Irrigated, (c) 2001, 16-day (brown) vs. dual-8-day (blue), average of Non-Irrigated and Irrigated, (d) 2005, 16-day (brown) vs. dual-8-day (blue)

2.6.5. Soybeans

Figure 2.9 illustrates the data for (a) 2001/16-day (brown) vs. dual-8-day (blue)/non-irrigated, (b) 2001/16-day (brown) vs. dual-8-day (blue)/irrigated, (c) 2001/16-day (brown) vs. dual-8-day (blue)/combined non-irrigated and irrigated, and (d) 2005/16-day (brown) vs. dual-8-day (blue)/non-irrigated. Soybeans have the highest NDVI values (0.78) among all the major crops studied and exhibit a rapid drop in NDVI values around the September 14 period (Figure

2.5). Like sorghum, similar differences between non-irrigated and irrigated soybeans are found during mid- to late-summer.

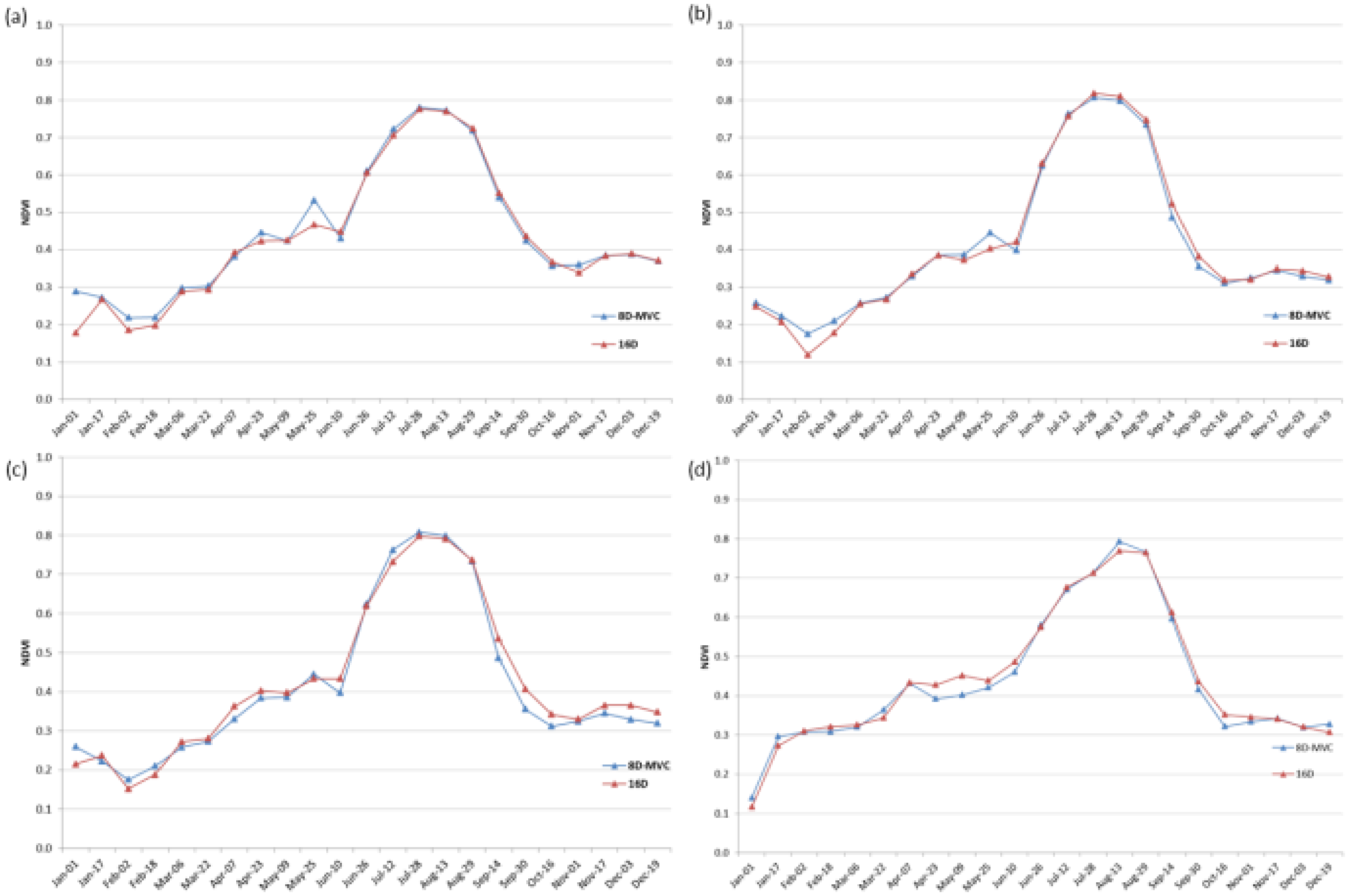

Figure 2.9 Soybeans NDVI profiles comparisons (a) 2001, 16-day (brown) vs. dual-8-day (blue), Non-Irrigated, (b) 2001, 16-day (brown) vs. dual-8-day (blue), Irrigated, (c) 2001, 16-day (brown) vs. dual-8-day (blue), average of Non-Irrigated and Irrigated, (d) 2005, 16-day (brown) vs. dual-8-day (blue)

It is difficult to find distinctive differences between 16-day and dual-8-day time-series data for soybeans, especially during the growing season in 2001 (Figure 2.9.a, b, and c). In 2005, the crop peaked during the August 13 period (Figure 2.9.d) and it was a late peak compared to the case in 2001 (July 28, Figure 2.9. c). Dual-8-day time-series data have slightly higher NDVI values during the peak greenness period (Figure 2.9.d) in 2005.

2.6.6. Winter Wheat

Figure 2. 10 illustrates the data for (a) 2001/16-day (brown) vs. dual-8-day (blue)/non-irrigated, (b) 2001/16-day (brown) vs. dual-8-day (blue)/irrigated, (c) 2001/16-day (brown) vs. dual-8-day (blue)/combined non-irrigated and irrigated, and (d) 2005/16-day (brown) vs. dual-8-day (blue)/non-irrigated. The winter wheat NDVI profile is characterized by its planting and emergence before winter dormancy and resumption of growth in the early spring (Paulsen *et al*., 1997). The results of the observed NDVI profiles showing differences between non-irrigated and irrigated sites (Figure 2.10.a and b) differ from those of the previous research of Wardlow *et al*., 2007 which showed higher NDVI values for irrigated sites.

Interestingly, both the 16-day and dual 8-day time-series datasets had different peak period in the Figure 2.10.a and c. During the most of growing season both in 2001 and 2005, the dual-8-day time-series show higher NDVI values in Figure 2.10.

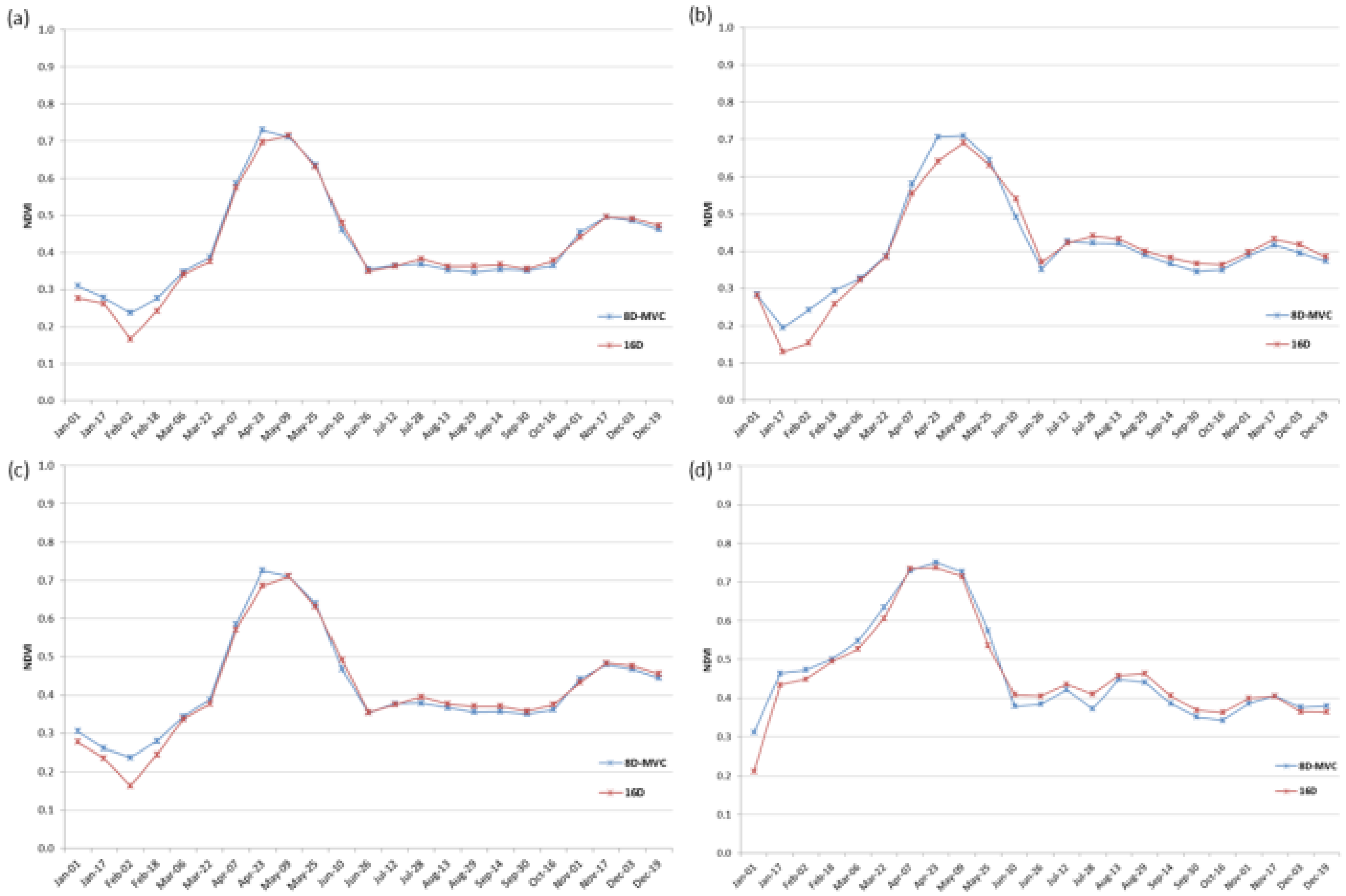

Figure 2.10 Winter Wheat NDVI profile comparisons (a) 2001, 16-day (brown) vs. dual-8-day (blue), Non-Irrigated, (b) 2001, 16-day (brown) vs. dual-8-day (blue), Irrigated, (c) 2001, 16-day (brown) vs. dual-8-day (blue), average of Non-Irrigated and Irrigated, (d) 2005, 16-day (brown) vs. dual-8-day (blue)

2.6.7. Regional intra-crop VI profiles

Wardlow *et al*. (2007) found regional variations within the NDVI seasonal patterns of each major crop that represented the range of climatic conditions that a crop is grown under across Kansas. In this section, NDVI profiles are presented for each of the five study crops for each of the four “corner ASDs for Kansas: ASD10 – northwest, ASD30 – southwest, ASD70 – northeast, and ASD90 – southeast.

Alfalfa

The alfalfa NDVI profiles in Figure 2.11 present regional differences in the timing of the crop’s phenological phases among the four corner USDA ASDs in which ASD10 (northwest) is represented in yellow, ASD30 (southwest) in red, ASD70 (northeast) in green, and ASD90 (southeast) in blue. ASD90 has the earliest greenup in 2005 (Figure 2.11.c and d), while it is difficult to find distinctive regional differences in time of greenup for 2001 (Figure 2.11.a and b). Note that there are no field sites in the ASD90 region for 2001 data.

Figure 2.11 Alfalfa NDVI profiles comparisons by ASDs (a) 2001, 16-day, (b) 2001, dual-8-day, (c) 2005, 16-day, (d) 2005, dual-8-day

Comparing 16-day and dual-8-day time-series data, the 2005 data show stronger variations and the variations that occurred in ASD70 are noteworthy. Although it appears that the winter dormancy of the crop was broken at a similar time across the state, ASD70 has the lowest NDVI values for 16-day time-series data in 2005 (Figure 2.11.c).

Corn

Figure 2.12 represents the regional differences in NDVI profiles for corn. In general, the eastern ASDs (70 and 90) start growing earlier in spring than the western ASDs (10 and 30) due to the earlier planting dates in eastern Kansas. These regional greenup differences are clear in the NDVI profiles for all summer crops (Figure 2.12, 2.13, and 2.14). In contrast, alfalfa and winter wheat have their initial greenup around the same time (Figure 2.11 and 2.15). In Figure 2.12, considerably lower NDVI values are observed in the western ASDs in 2005 compared to those in 2001. Heavy showers throughout the state were seen in June of the year (NASS, 2005) and shortages of topsoil moisture started from mid-July until mid-August (Kansas Field Office, 2006). The observed difference might be explained by these fluctuations in precipitation. ASD90 has the most unique variation and shows the highest NDVIS values with dual-8-day time-series data in 2005.

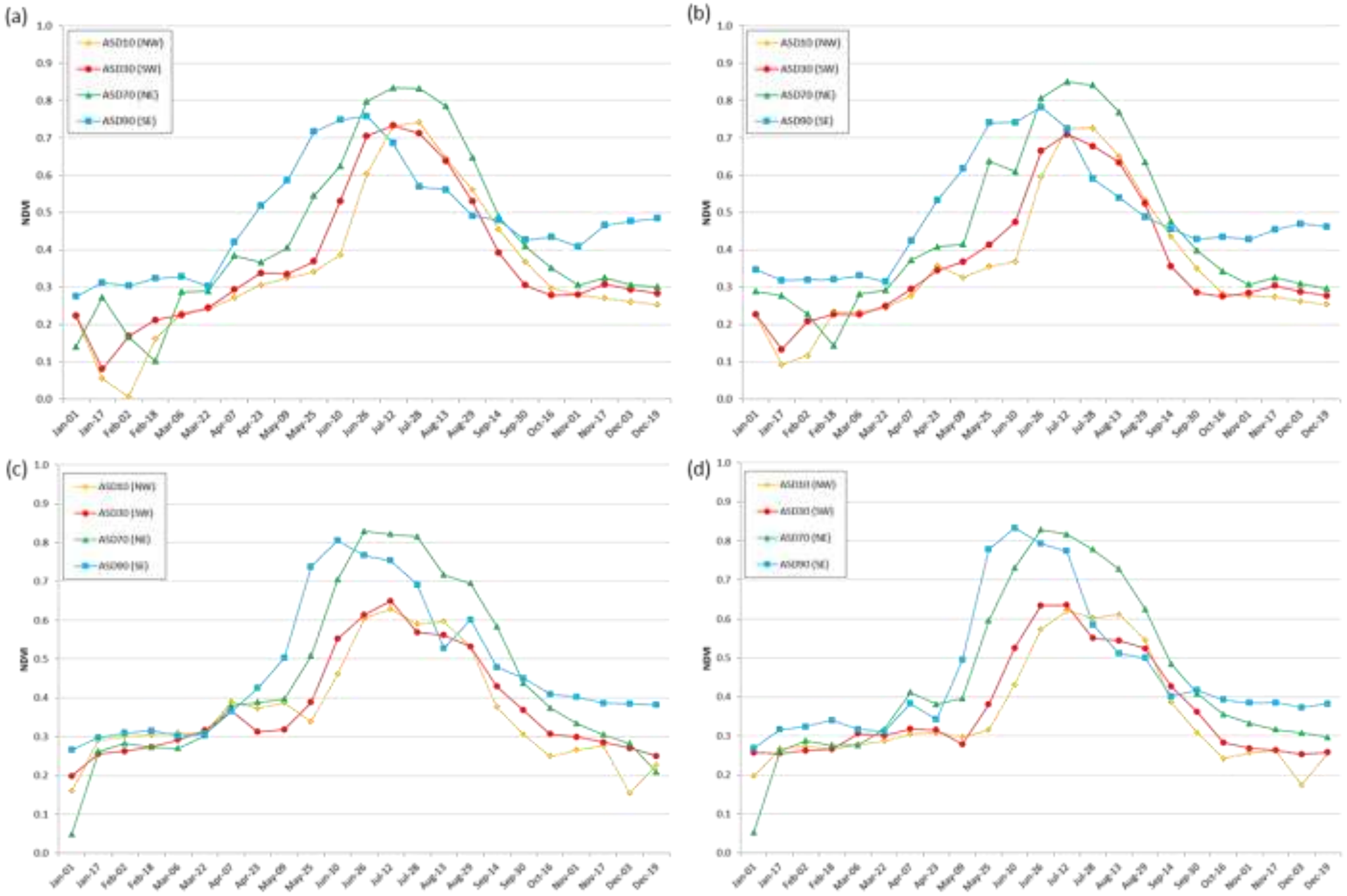

Figure 2.12 Corn NDVI profiles comparisons by ASDs (a) 2001, 16-day, (b) 2001, dual-8-day, (c) 2005, 16-day, (d) 2005, dual-8-day

Sorghum

Figure 2.13 illustrates the regional intra-crop NDVI profiles for sorghum and also shows similar temporal offsets from western to eastern Kansas for those of corn (Figure 2.12). In 2005, the time lag gets longer between the eastern and western ASDs and a dip is observed in ASD70 at the peak of its profile.

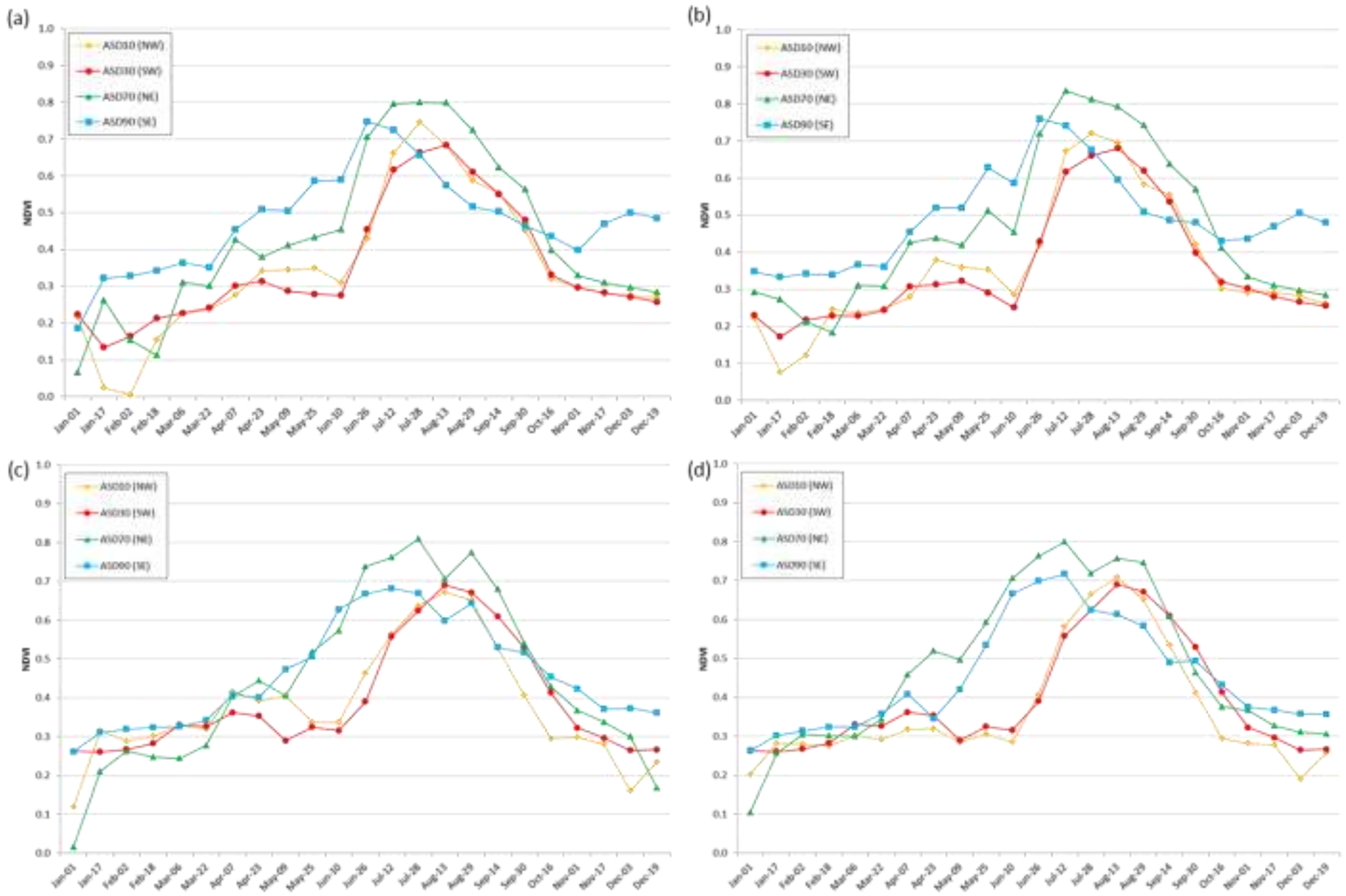

Figure 2.13 Sorghum NDVI profiles comparisons by ASDs (a) 2001, 16-day, (b) 2001, dual-8-day, (c) 2005, 16-day, (d) 2005, dual-8-day

Soybeans

Figure 2.14 illustrates the regional NDVI profiles for soybeans and they are in accordance with the crop’s phenological calendar. In general, it appears that greenup starts at the same time (June 10) during 2001 and 2005, but that greenup proceeds much more slowly in 2005, especially in ASDs 10, 30, and 90 (Figure 2.14.c and d).

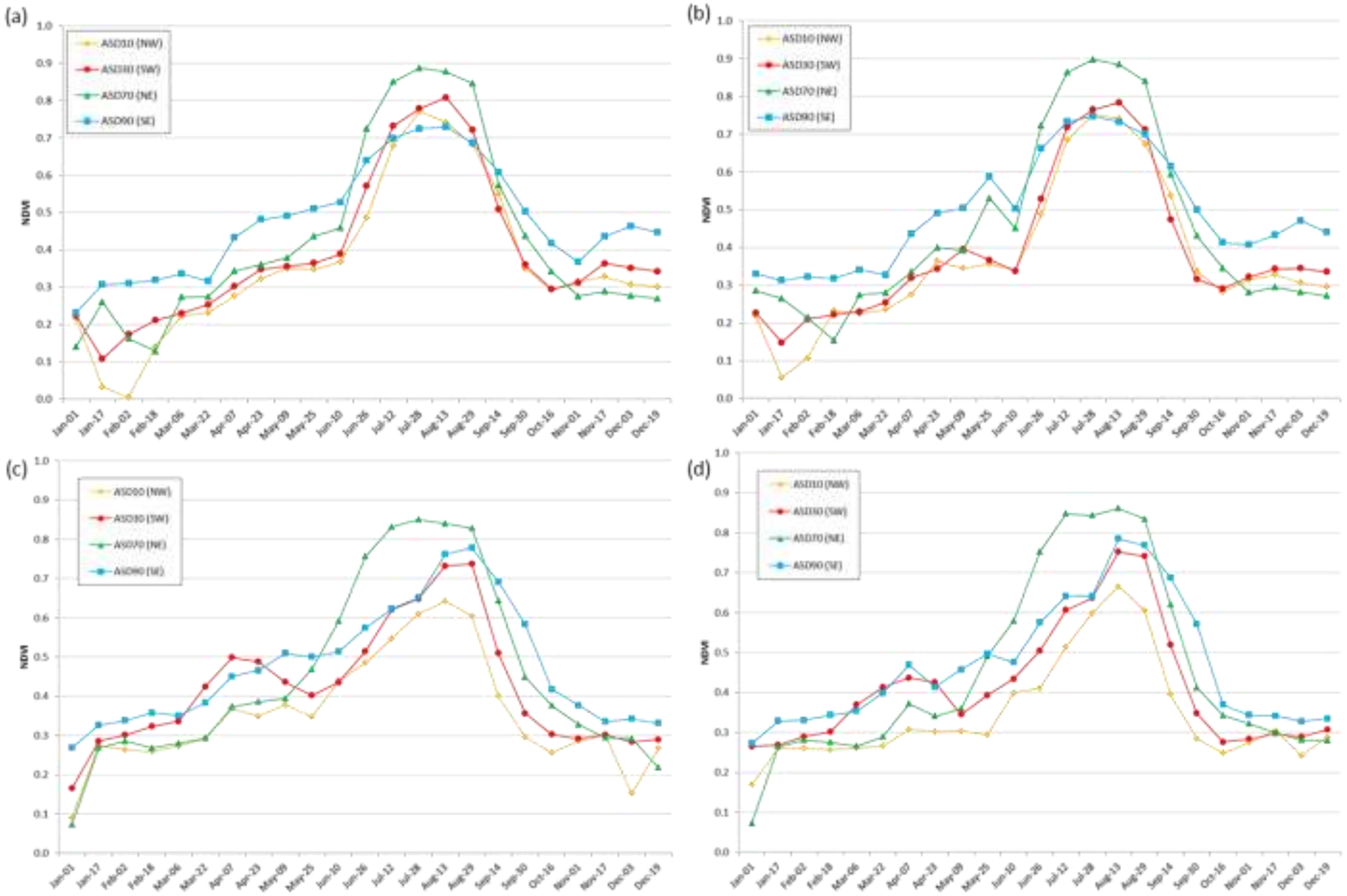

Figure 2.14 Soybeans NDVI profiles comparisons by ASDs (a) 2001, 16-day, (b) 2001, dual-8-day, (c) 2005, 16-day, (d) 2005, dual-8-day

Winter Wheat

Figure 2.15 illustrates the regional NDVI profiles for winter wheat and it also reflects the crop calendar distinctively showing the emergence of the crop in the fall. ASD90 shows a pronounced fall emergence peak in 2005, but still not as much as in ASD70 (Figure 2.15.c and d). In 2005, ASDs 10, 30, and 70 have strong NDVI response values in early spring and display rapid greenup during the March 22 composite period. As discussed earlier, it is difficult to see any substantial regional time of greenup differences in both years.

Figure 2.15 Winter Wheat NDVI profiles comparisons by ASDs (a) 2001, 16-day, (b) 2001, dual-8-day, (c) 2005, 16-day, (d) 2005, dual-8-day

2.6.8. Inter-class comparison of crop VI profiles

Figure 2.16 illustrates the inter-class separability of the study crops. First, alfalfa and winter wheat are clearly distinguishable from summer crops in the spring. Though alfalfa becomes undistinguishable from summer crops in early summer as the summer crops' NDVI values increase, winter wheat remains distinguishable throughout most of the growing season. While summer crops are harder to discriminate from each other, there are still a few composite periods where these crops show distinctive, visually separable, patterns during the greenup and senescence phases.

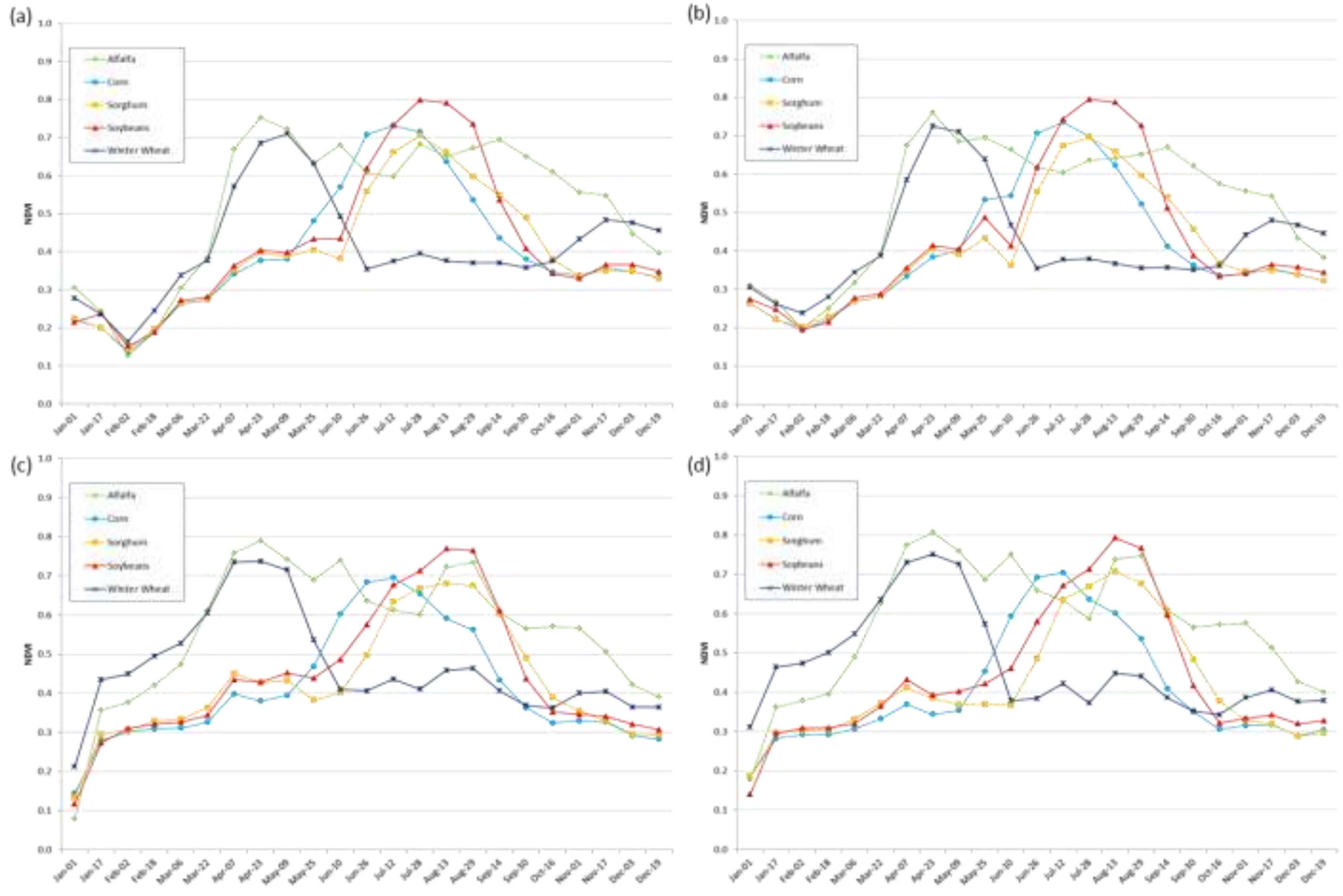

Figure 2.16 Inter-Class comparisons with NDVI profiles (a) 2001, 16-day, (b) 2001, dual-8-day, (c) 2005, 16-day, (d) 2005, dual-8-day

Based on the visual comparison of the average NDVI profiles in the figure, it is difficult to discern any noticeable differences between 16-day and dual-8-day time-series data. For example, the most separable times for corn and soybeans are during June and after mid-August, but there are no clear differences between the two datasets showing the same patterns.

2.6.9. JM Distance analysis

From the discussion in the previous sections, in general it is clear that major crop types generally were visually separable at different times of the growing season based on their phenological characteristics and differences. However, Wardlow *et al*. (2007) also pointed out that variations in environmental conditions and management practices can lead to considerable intra-class variability of a crop across a large geographic area, which may increase the overlap in the VI signals among the crops and reduce their separability. In this section, the JM distance is used to statistically evaluate distributional properties between each pair of crops to measure the degree of their separability.

Table 2.5 represents JM distance results for all pair-wise crop comparisons, which is calculated using NDVI values. The growing season defined for this analysis spans the March 22 to the November 1 time period as used in Wardlow *et al*. (2007) because it covers most of the crops' growth cycles and eliminates non-cropping periods. The results reveal that alfalfa and winter wheat exhibit distinctive JM distances from the other crops. Generally, JM distances calculated over the growing season showed that alfalfa and winter wheat had higher JM values than the other crops, which means they are more distinguishable from the other crops. The average JM distance of alfalfa when compared with each other crops is 1.82 and that of winter wheat is 1.77 for 16-day time-series data in 2001 (Table 2.5.a). For 8-day time-series data in 2005, the average JM distance of alfalfa is 1.94 and that of winter wheat is 1.80 (Table 2.5.b). These values decrease for 16-day time-series data in 2005 to 1.83 for alfalfa and 1.62 for winter wheat, respectively (Table 2.5.c). All the tables show that alfalfa and corn are the most separable (JM = 1.84, Table 2.5.a; 1.96, Table 2.5.b; and 1.89, Table 2.5.c).

JM distances calculated among summer row crops are much lower. Average JM distances among three summer crops are 1.09 (Table 2.5.a), 1.35 (Table 2.5.b), and 1.18 (Table 2.5.c). The least separable pair is soybeans and sorghum (JM = 1.22, Table 2.5.b; and 1.01 Table 2.5.c) except for 16-day time-series data for 2001. In that case, the JM distance for corn-sorguhm and corn-soybeans have the lowest separability (both JM = 1.05, Table 2.5.a).

Table 2.5 JM distance values for all pair-wise crop comparisons

(a) JM distance values for MODIS 250 m data collection version 5, 16-day time-series, collected in 2001

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	1.84	1.81	1.84	1.78
Corn	-	1.05	1.05	1.78
Sorghum	-	-	1.16	1.75
Soybeans	-	-	-	1.76

(b) JM distance values for MODIS 250 m data collection version 5, 8-day time-series, collected in 2005

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	1.96	1.94	1.94	1.90
Corn	-	1.42	1.41	1.83
Sorghum	-	-	1.22	1.72
Soybeans	-	-	-	1.73

(c) JM distance values for MODIS 250 m data collection version 5, 16-day time-series, collected in 2005

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	1.89	1.84	1.86	1.74
Corn	-	1.31	1.23	1.63
Sorghum	-	-	1.01	1.50
Soybeans	-	-	-	1.60

In Table 2.6, differences in JM distance values were calculated based on the results shown in Table 2.5. Table 2.6.a represents differences in JM distances between the NDVI values collected in 2001 and 2005. On the other hand, Table 2.6.b shows differences in JM distances between the two different compositing periods of data, or 16-day and 8-day. If the difference calculated from the different compositing period of data is larger than the difference calculated from the data collected in different years, it may be assumed that a shorter compositing period plays an important role in crop separability. Note that most of the JM distances calculated from 8-day time-series data (Table 2.5.b) are larger than those for 16-day time-series data (Table 2.5.a and c).

As the results discussed earlier showed, specific weather conditions resulted in variations in NDVI profiles of the crops for each year. According to Table 2.6.a, summer crops appear to be affected most by the different weather conditions between 2001 and 2005. For example, the difference in JM distance for corn-sorghum between the years is 0.26, which is the largest in the table. However, alfalfa remains constant with all other crops, showing the lowest value range from 0.02 to 0.05. In Table 2.6.b, it appears the difference gets larger generally except for a few cases. Several changes in the differences among summer crops are notable (e.g. corn-sorghum).

However, the average difference for the two cases is very similar. The average difference in JM distance between 2001 and 2005 is 0.13, while the average difference in JM distance between 8-day and 16-day time-series data is 0.14.

Some interesting observations can be made about the summer crops. The average difference in JM distance among summer crops between 2001 and 2005 is 0.19, while the average difference in JM distance among summer crops between 8-day and 16-day time-series data is 0.26. It appears that NDVI extracted from higher temporal resolution (8-day) data is potentially more useful for crop separability for summer crops.

Table 2.6 Temporal difference in JM distance values

(a) between 2001.13Q1.005 and 2005.13Q1.005 (absolute value)

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	0.05	0.03	0.02	0.03
Corn	-	0.26	0.17	0.16
Sorghum	-	-	0.15	0.25
Soybeans	-	-	-	0.16

(b) between 2001.13Q1.005 and 2005.09Q1.005 (absolute value)

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	0.12	0.13	0.10	0.12
Corn	-	0.37	0.35	0.05
Sorghum	-	-	0.07	0.02
Soybeans	-	-	-	0.03

2.7. Conclusions

The objective of this research was to investigate the NDVI values between different compositing periods of time-series MODIS 250 m data for potential separability of crop types. NDVI values profiles extracted from different compositing periods for 2001 and 2005 were analyzed to see if 8-day (and dual-8-day) composited NDVI time-series data compared to 16-day composited NDVI time-series data would show finer scale spectral-temporal variability for improved crop separability. The major conclusions include:

1. **There are meaningful differences, both visually and statistically, among the different composite period datasets.** As with previous studies (Masialeti *et al*., 2010; Wardlow *et al*., 2008; Wardlow *et al*., 2007), this research verified and confirmed that time-series MODIS 250 m data's spatial, spectral, and temporal resolution for major crop separability among major crop types in the central Great Plains region were satisfactory for crop discrimination. Each crop had unique spectral and temporal patterns in its NDVI profiles for different composite period datasets. The crop separability was observed in the analysis of regional intra-crop NDVI profiles, inter-class comparisons, and JM distances as well.
2. **Time-series data that have shorter compositing periods generally are more effective in separating crop types.** In most cases, dual-8-day time-series data produced visual patterns different from those of 16-day time-series data. The different patterns observed in dual-8-day time-series data, however, did not mean that higher temporal resolution of the time-series data are always more helpful for crop separability. In 2005, for example, heavy showers, hail damage, and, flooding were reported (Kansas Field Office, 2006; NASS 2005) in June, which could possibly have led to lower NDVI values for corn (Figure 2.7.d). JM distance analysis, meanwhile, detected separability among the

different composite period datasets. Temporal differences in JM distance values between different compositing period datasets (16-day and 8-day, Table 2.7.b) were larger than those between different annual datasets (2001 and 2005, Table 2.7.a). Sorghum and winter wheat had the largest difference (0.23) and the differences were larger than 0.1 even among the summer crops (corn-sorghum 0.11, corn-soybeans 0.18, sorghum-soybeans 0.22). Considering the range of the JM distance values measured for the major crops and the differences in the values among the crops (Table 2.6), the temporal differences observed in JM distance values between different composite period datasets may prove to be beneficial for crop separability in land cover mapping.

3. **Any observed differences still should be exercised with care.** As discussed earlier, researchers should seek to understand the causes of subtle differences observed with 8-day or dual-8-day time-series data. The subtle differences may result from unusual weather conditions, changes in crop management practices, or other unknown reasons. Nonetheless, they may still be useful if employed in cooperation with additional variables such as harmonic analysis components (Jakubauskas *et al*., 2002), vegetation phenology metrics (Reed et al., 1994; Zhang et al., 2003) as Wardlow *et al*. (2006) suggested, to assist researchers in better understanding the VI profiles in conjunction with these variables. If the subtle differences are sensitive enough to reflect any environmental variations, as all the figures suggested in the previous discussion section, shorter compositing periods of time-series data might be especially beneficial in investigating smaller geographical areas such as at the ASD level used in this study. A primary conclusion to be drawn from the JM distance analysis is that it represents a strong

statistical tool for crop separability, especially when applied to shorter compositing periods of time-series datasets.

This research to test the hypothesis that 8-day (and dual-8-day) composited NDVI time-series data compared to 16-day composited NDVI may show finer scale spectral-temporal variability facilitative of improved crop separability has demonstrated that shorter compositing periods of MODIS time-series data are more helpful for crop separability. In particular, JM distance analysis, a statistical approach, validated the capability of this method for determining potential crop separability.

3. Investigating Collection 4 versus Collection 5 MODIS 250m NDVI Time-Series Data for Crop Separability

3.1. Introduction

Since the first MODIS data were acquired in February, 2000, the MODIS standard products have experienced several updates based on evolving processing priorities (Justice *et al*., 2002). Reprocessing refers to employing the latest version of scientific algorithm to process the data and using the best available calibration and geolocation information, among others (Didan and Huete, 2006). Reprocessing of the entire MODIS inventory has been carried out several times and a number of important changes have included employing improved calibration algorithms, geo-location information, cloud masking, updating atmospheric profiles, and others. Each reprocessed data set is referred to as a “collection” or “version;” the most current version at the time of this research was version 5. The underlying expectation of this reprocessing performed by the MODIS Science Team was that the reprocessed data would have improved spatial and temporal characteristics. This change in updating the MODIS products to the latest version also directly affects the quality of the vegetation index (VI) products, as the process is related to improvements in VI compositing methods, methods of dealing with sub-pixel clouds, aerosol filtering, etc. (MODIS Vegetation Index Product Series, 2006).

When collection 5 was introduced with eight new refinements to the MODIS Land Surface Temperature and Emissivity (LST&E) product, Hulley and Hook (2009) analyzed the temporal and spatial variations of the MOD11B1[13] Land Surface Temperature and Emissivity (LST&E) product for collections 4, 4.1, and 5 to understand the impact of any version changes on their studies. Although the refinements for the latest version were designed to improve the

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[13] The product uses bands 20, 22, 23, 29, 31, and 32. See the Table 2.1 for more information about the bands.

spatial coverage, stability, and accuracy of the product, they concluded that users should consider using the older versions (collection 4 or 4.1) instead of the latest version (collection 5) for arid and semi-arid areas because the latest version degraded the accuracy of the derived emissivity over the arid areas (Hulley and Hook, 2009).

In designing the refinements for collection 5 of the MODIS vegetation index products, emphasis was placed on the algorithm for the CV-MVC (Constrained View-angle Maximum Value Composite) compositing method, sub-pixel clouds and mislabeled clouds, aerosol filtering, inland water bodies, and phased production for improved temporal frequency (MODIS Vegetation Index Product Series, 2006). All these are important items that potentially can affect the products' quality in terms of their spatial and temporal characteristics. In this study I analyzed temporal-spectral variations of the time-series MODIS 250 m vegetation index data between versions 4 and 5.

3.2. Problem Statement

The general goal of this research was to broaden the applicability of time-series MODIS 250 m VI data in characterizing crop-related LULC patterns for large areas such as the U.S. Central Great Plains. More specifically, the objective of this study was to investigate differences in the Normalized Difference Vegetation Index (NDVI) as they reflect phenological characteristics between collections 4 and 5 of time-series MODIS 250 m data. Close investigations of collection 4 and 5 time-series MODIS 250 m data were made to examine whether the most recent version (version 5) offered improvements in distinguishing 5 major crops (alfalfa, *Medicago sativa*; corn, *Zea mays*; sorghum, *Sorghum bicolor*; soybeans, *Glycine max*, and winter wheat, *Triticum aestivum*) grown in Kansas. Data from 2001 and 2005 were used in this study since ground reference data of good quality are available for these years at the Kansas Applied Remote Sensing Program (KARS).

The primary objective of the research was to investigate NDVI values between collections 4 and 5 time-series MODIS 250 m data for distinctive separability of crop types. If the results show significant differences between the two versions and the reasons for these differences can be identified, this will contribute to an understanding of how the VI processing and compositing techniques between the two collections may affect LULC classification limitations ascribable to calibration and instrument characteristics, clouds and cloud shadows, atmospheric effects, etc.

Research Issue: Investigate NDVI values over the growing season between collections 4 and 5 time-series MODIS 250m VI data to examine whether they differ in their ability to distinguish crop types

This issue involves an analysis using collections 4 and 5 of the MODIS 250 m vegetation index data. To see how collection 5 is different from collection 4 (Figure 1), several questions will be examined:

1. Are there meaningful statistical differences between the collections?

2. Does collection 5 of the time-series MODIS 250 m dataset have better ability to discriminate the study area's major crop types (alfalfa, corn, sorghum, soybeans, and winter wheat) compared to collection 4?

3. Can the causes of any differences be identified?

3.3. Study Area

The research area for this study is the state of Kansas where there is a strong east-west precipitation gradient in a mid-continental temperate climate. Most rainfall occurs during the growing season from April through September with average precipitation of 460-510 mm for western Kansas, 900 mm for central areas, and 890-1020 mm for eastern parts of the state. The temperature variation that increases from the northwest (mean annual temperature < 11 °C) to the southeast (mean annual temperature > 15 °C) affects temporal and spatial patterns of crop growth that in turn is reflected in NDVI values in the study area (Wang *et al*., 2001). The unique climate conditions obviously affect decisions regarding a range of crop management practices.

Winter wheat is the major cash crop cultivated predominantly on dryland farm fields over the Central Great Plains region. Alfalfa, corn, sorghum, and soybeans are also major crops grown on both non-irrigated and irrigated land.

3.4. Data Description and Processing

3.4.1. MODIS vegetation index 16-day composite 250 m data

MOD13Q1 is the 16-day 250 m vegetation index product that gathers information on a per-pixel basis through multiple observations over a sixteen day period. For this study, the images of the product were downloaded from the Land Process Distributed Active Archive Center (LPDAAC, https://lpdaac.usgs.gov/data_access/data_pool) for 2001. MODIS file names follow a defined naming convention, so that users get useful information regarding the specific product. For example, **MOD13Q1.A2001001.h09v05.005.2008270023446.hdf**, the name of one of the downloaded images indicates the product name (MOD13Q1), Julian date of acquisition

(A2001001), tile identifier (h09v05), collection version (005), Julian date of production (2008270023446), and data format (HDF-EOS).

By using the MODIS Reprojection Tool (version 4.0), all the downloaded images were processed, reprojected, and saved in GeoTiff format. Later the converted images were mosaicked to cover the Kansas state area (three tiles are required to cover the state: h09v05, h10v05, and h10v04). Then 12-month time series MODIS 250 m NDVI data spanning from January to December for 2001 were created. The same data for 2005 were also used for statistical analysis. MOD13Q1 consisted of 23 16-day composite periods of the VI data to cover one growing season. Table 3.1 summarizes the imagery used in this study.

Table 3.1 Summary of 16-day time-series MODIS 250 m NDVI data

Product name	MOD13Q1		
Spatial resolution / Composite period	250 m / 16-day		
Year	2001		2005
	Collection 4	Collection 5	Collection 5
# of dates / # of scenes[1]	23 / 69	23 / 69	23 / 69

[1] Three scenes (h09v05, h10v05, and h10v04) are needed to cover whole Kansas area.

3.4.2. Field site database

For this research, I used the same ground verification data that Wardlow *et al.* (2007) used in their research. The information from annotated aerial photos was provided by the United States Department of Agriculture (USDA) Farm Service Agency (FSA), which was used to create a database of field site locations. The important point in acquiring field sites was to secure an adequate number of field sites from widely distributed fields for each crop class. In this research, the field sites were selected from up to 48 counties from a total of 105 counties in the state. The minimum field size was limited to 32.4 ha which covers approximately five pixels at 250-m resolution so that each site would be represented by multiple pixels (Wardlow *et al.*, 2007).

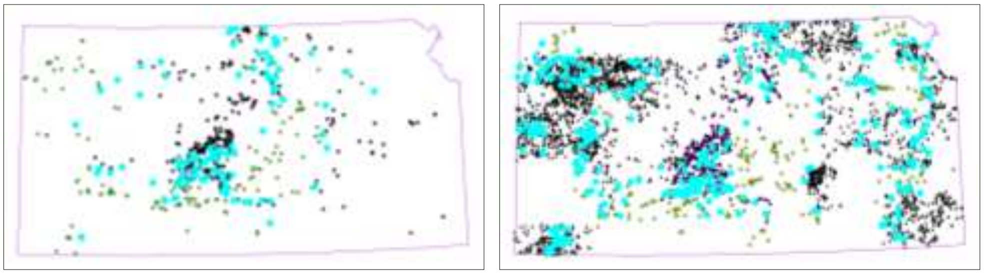
The distribution of the field sites for 2005 was different from 2001, so the field sites for 2005 were selected by using a proximity analysis functions in ArcGIS tools. Table 3.2 shows the number of field sites for each dataset and the selected nearest sites.

Table 3.2 Size of the filed sites for each crop

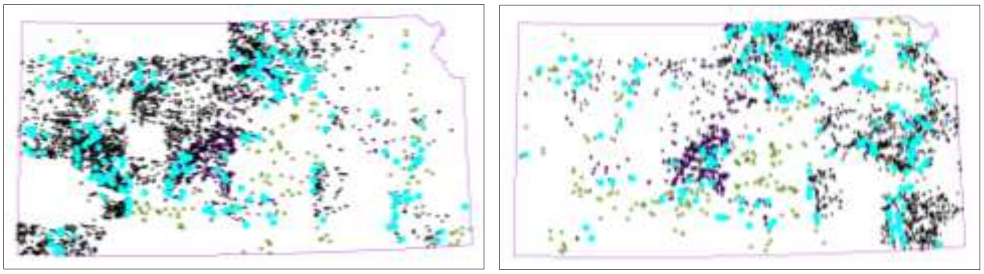
Crop type	2001	2005[1] (before refinement)
Alfalfa	243	109 (528)
Corn	609	349 (3,524)
Sorghum	354	239 (4,393)
Soybeans	454	217 (2,581)
Winter Wheat	446	356 (20,481)
Total	2,106	1,270 (31,507)

[1] The size of the field sites near to the field sites for 2001

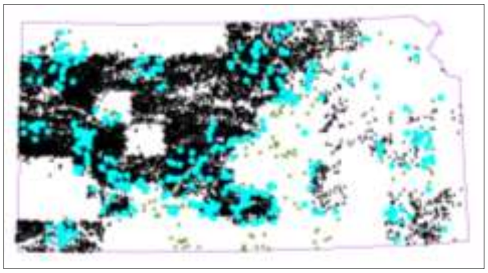
Figure 3.1 illustrates the geographic locations of each dataset and selected nearest points.



Alfalfa Corn



Sorghum Soybean



Winter Wheat

Figure 3.1 Field site locations by crop type for 2001 (circles) and 2005 (stars) datasets. Buffered circles show the selected nearest points of 2005 dataset.

3.5. Methods

3.5.1. NDVI profiles

The mean multi-temporal NDVI profiles for collections 4 and 5 were calculated at the state level, and these NDVI profiles were first visually compared to their crop calendars. The NDVI profiles also were visually compared for irrigated and non-irrigated crops to detect possible separability between these two crop management practices based on spectral-temporal differences during the year. The two different collections (collection 4 and 5) of MODIS 250 m datasets also were compared to analyze the potential causes of differences detected.

3.5.2. JM distance

A statistical method, JM distance analysis (Richards and Jia, 1999; Van Niel *et al*., 2005; Wardlow *et al*., 2007), was employed in this study to investigate separability within each crop class in the time-series NDVI data between the two collection versions. JM distance values range from 0 to 2. A JM distance of 2, the maximum possible value, between a pair of crop classes means that the two crops are completely distinguishable from each other. A minimum JM distance of 0, on the other hand, signifies that the two crops are not distinguishable at all.

3.6. Results and Discussion

3.6.1. Alfalfa

The NDVI profiles shown in Figure 3.2 compare not only different collection versions (4 and 5) for alfalfa in 2001 but also different crop management practices. Non-irrigated data are illustrated in Figure 3.2.a and irrigated data in Figure 3.2.b. The major phenological pattern of alfalfa is multiple ‘growth and cut’ curves, as the crop is normally harvested three or four times per year in Kansas (Shroyer *et al*., 1998). The cut-and-growth curves are clearly seen in Figure 3.2.a and b.

As previous researchers discussed (Wardlow *et al.*, 2008; Wardlow *et al.*, 2007), distinctive NDVI patterns were discovered for non-irrigated versus irrigated alfalfa in the time-series MODIS data. Slightly higher NDVI values were observed in the irrigated sites during the summer. Comparing collections, generally speaking, collection 4 had higher NDVI values than collection 5, especially for irrigated sites.

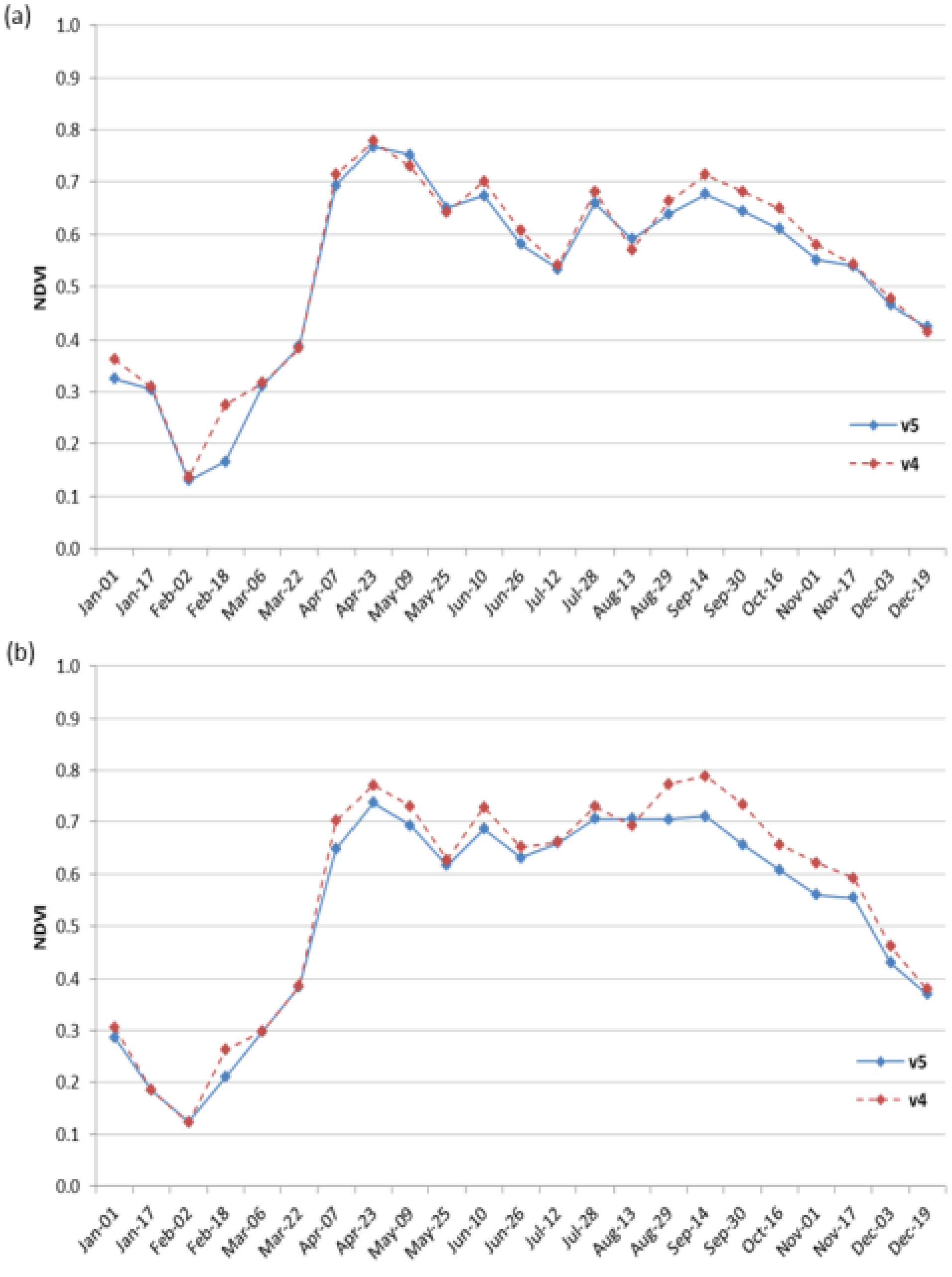


Figure 3.2 Alfalfa NDVI profiles comparisons (a) v4 vs. v5, Non-Irrigated, (b) v4 vs. v5, Irrigated

3.6.2. Corn

Although all three summer crops show similar phenological curves, unique spectral-temporal responses representing subtle differences in their growth cycles are reflected in their individual NDVI profiles (Wardlow *et al*., 2007) (Figure 3.3). Corn is one of the summer crops studied in this research and typically is the earliest planted summer crop in Kansas (April to mid-May) followed by soybeans (mid-May to mid-June) and sorghum (late-May to late-June) (Shroyer *et al*., 1996). Figure 3.3 (a) illustrates the NDVI profiles of corn for 2001/collection 4 vs. collection 5 (blue)/non-irrigated, (b) illustrates the data for 2001/ collection 4 vs. collection 5 (blue)/irrigated respectively.

As expected, irrigated corn (Figure 3.3.b) had higher NDVI values than non-irrigated corn (Figure 3.3.a) during the peak greenness period (July 12) and the senescence phase (June 26 – September 14). In comparing collections, collection 4 had higher NDVI values only during the peak greenness period. At most other times during the growth cycle (early growth and senescence), the values for collection 5 NDVI were higher. In other words, the range of NDVI values (lowest to highest) is greater for collection 4 than for collection 5, a pattern repeated for all the summer crops.

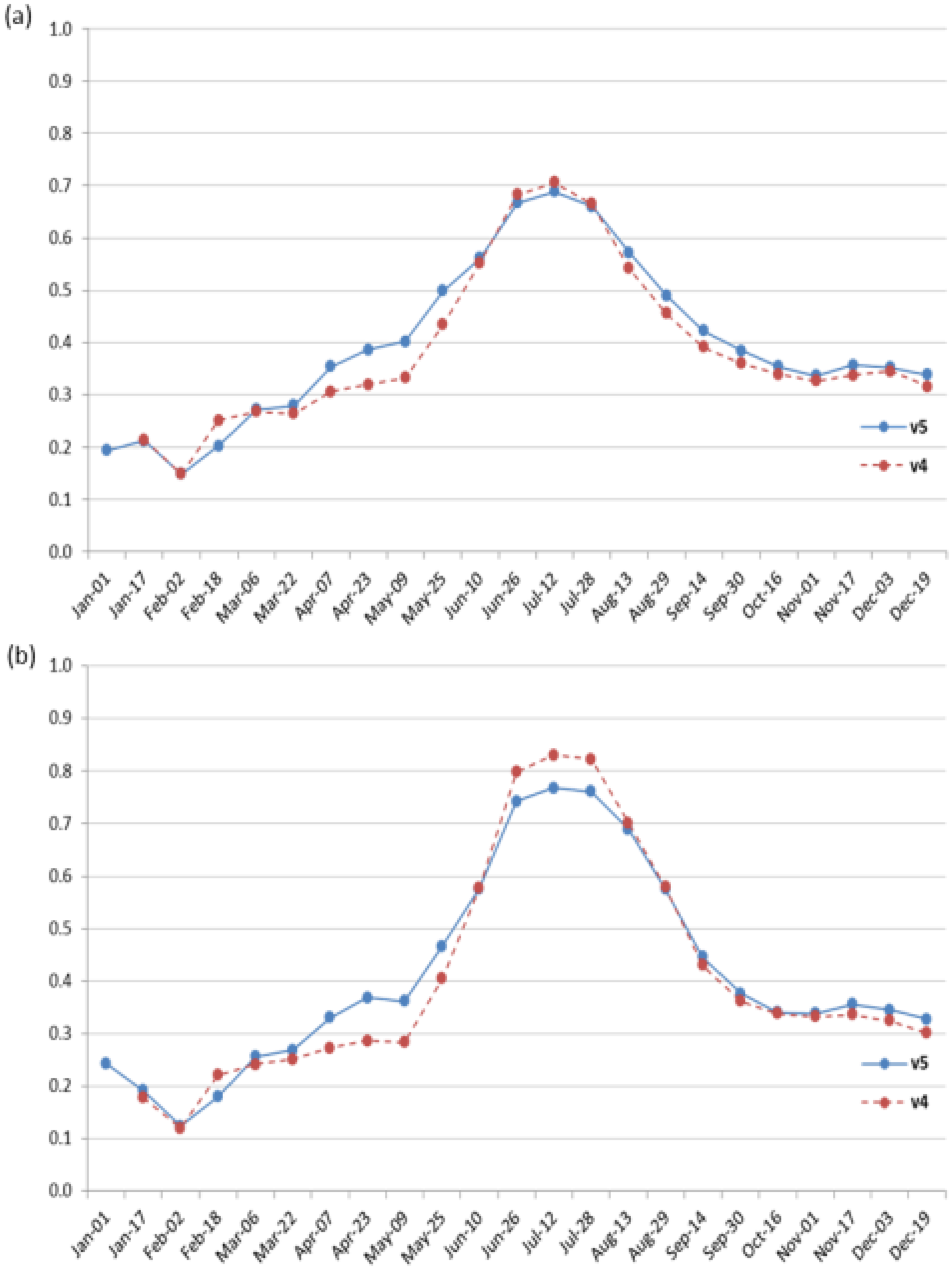


Figure 3.3 Corn NDVI profiles comparisons (a) v4 vs. v5, Non-Irrigated, (b) v4 vs. v5, Irrigated

3.6.3. Sorghum

Figure 3.4.a illustrates the sorghum data for 2001/collection 4 vs. collection 5 (blue)/non-irrigated, while Figure 3.4.b shows 2001/collection 4 vs. collection 5 (blue)/irrigated. For sorghum, the timing of the peak greenness occurs during the July 28 period and the crop has the lowest NDVI values among the summer crop (Figure 2.5). Similar differences between non-irrigated and irrigated sorghum are found during mid- to late-summer, but irrigated sorghum has slightly higher NDVI values (Figure 3.4.b) than non-irrigated sorghum (Figure 3.4.a) especially during the peak greenness phase. In comparing collections 4 and 5, collection 4 shows higher NDVI values from around peak greenness through senescence (from June 26 to October 16 periods). The difference is larger in the irrigated field sites.

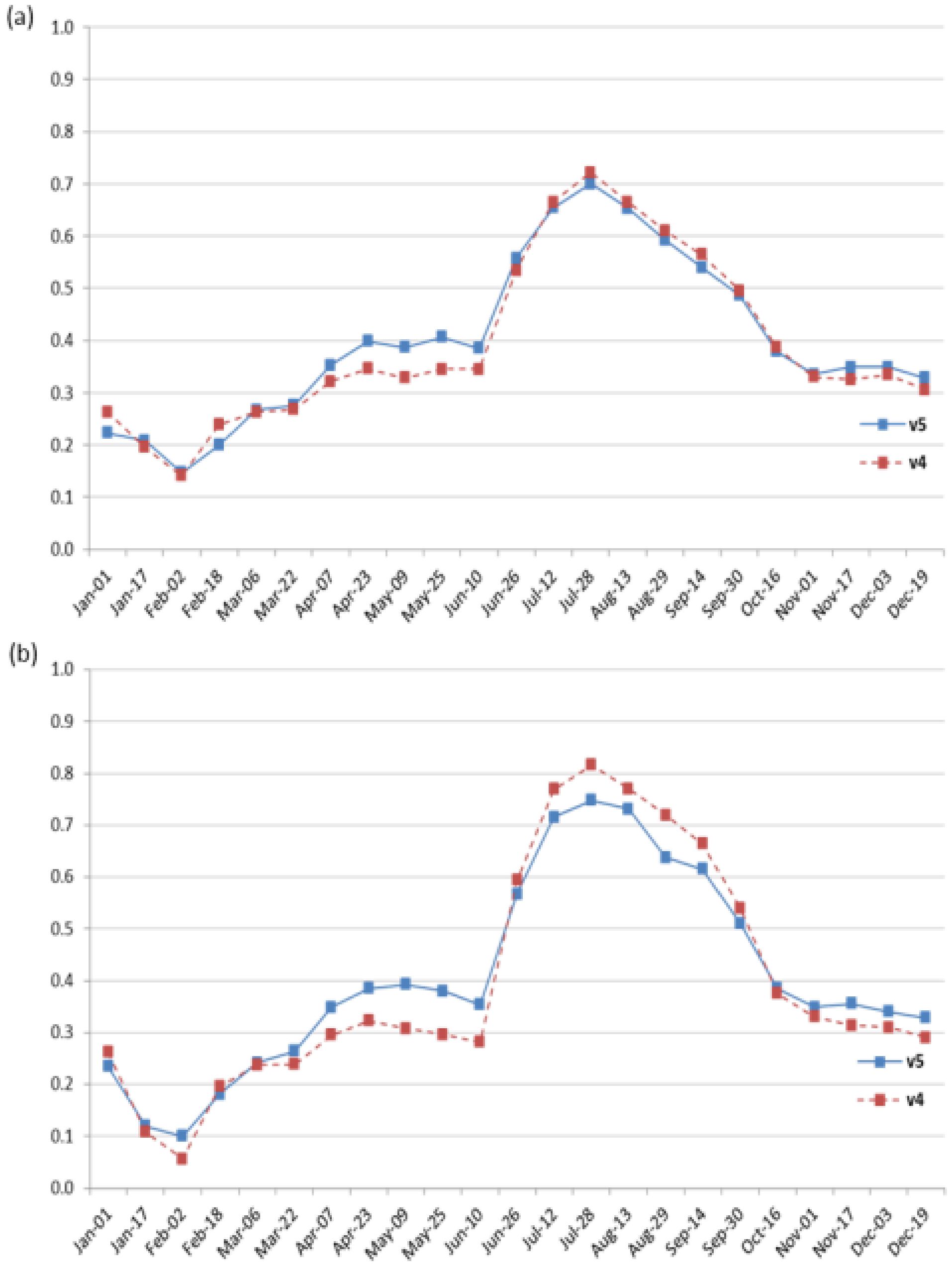


Figure 3.4 Sorghum NDVI profiles comparisons (a) v4 vs. v5, Non-Irrigated, (b) v4 vs. v5, Irrigated

3.6.4. Soybeans

Figure 3.5.a illustrates the soybeans data for 2001/collection 4 vs. collection 5 (blue)/non-irrigated, while Figure 3.5.b shows 2001/collection 4 vs. collection 5 (blue)/irrigated. Soybeans maintain the highest NDVI values (0.78) among all the major crops studied in this study and exhibit a rapid drop of NDVI values during the September 14 period (Figure 2.5). As with sorghum, similar differences between non-irrigated and irrigated soybeans are found during the senescence period in mid- to late-summer. Collection 4 shows higher NDVI values around peak greenness (from June 26 to September 14 periods). That difference is larger in the irrigated field sites.

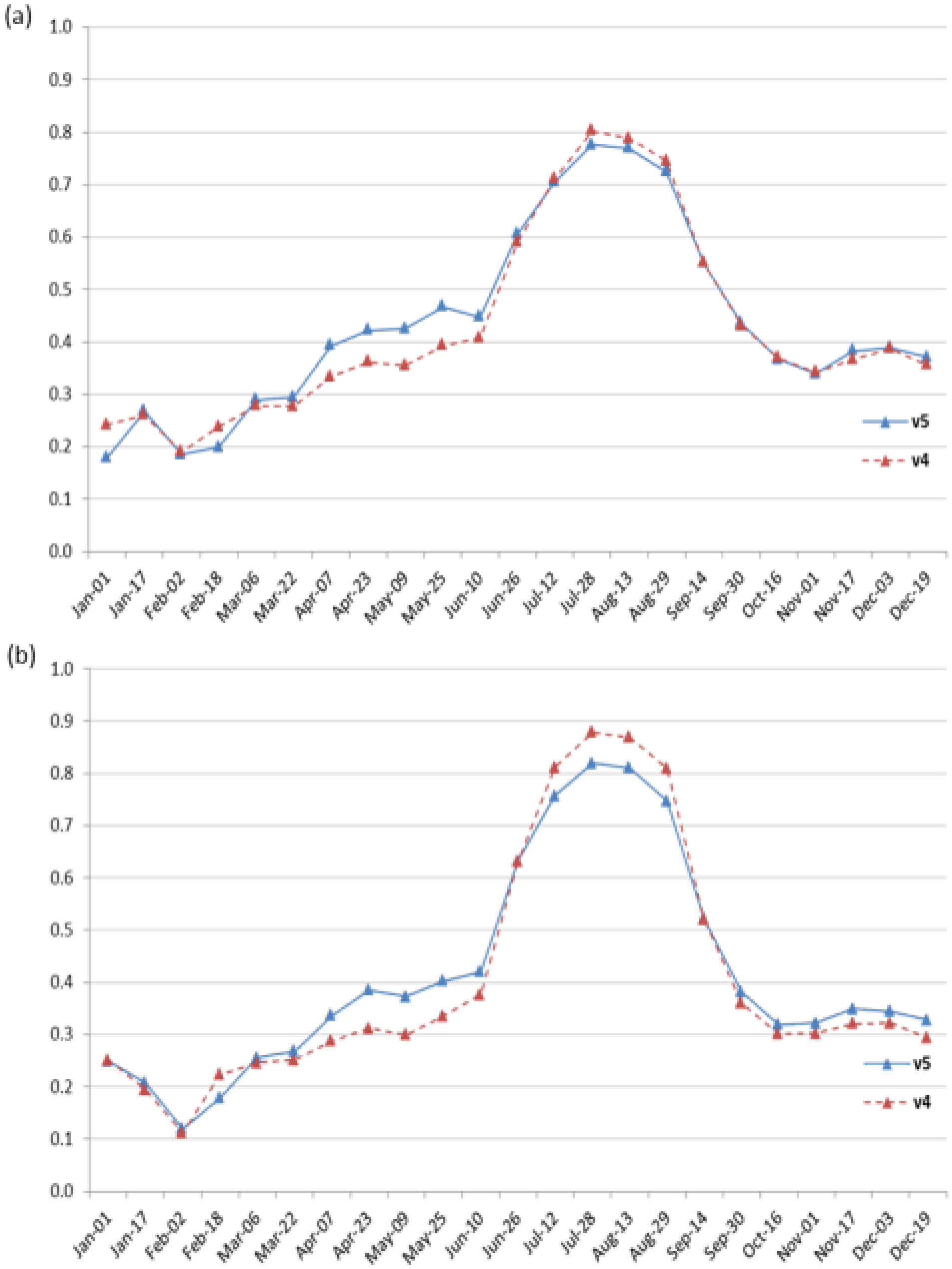


Figure 3.5 Soybeans NDVI profiles comparisons (a) v4 vs. v5, Non-Irrigated, (b) v4 vs. v5, Irrigated

3.6.5. Winter Wheat

Figure 3.6.a illustrates the winter wheat data for the 2001/collection 4 vs. collection 5 (blue)/non-irrigated, while Figure 3.6.b shows 2001/collection 4 vs. collection 5 (blue)/irrigated. The winter wheat NDVI profile is characterized by its planting and emergence before winter dormancy and resumption of growth in the early spring (Paulsen *et al*., 1997). It is difficult to observe any differences between the collection 4 and 5 data in the non-irrigated field data, but the differences are clear (higher in collection 4 NDVI values) in the irrigated field data.

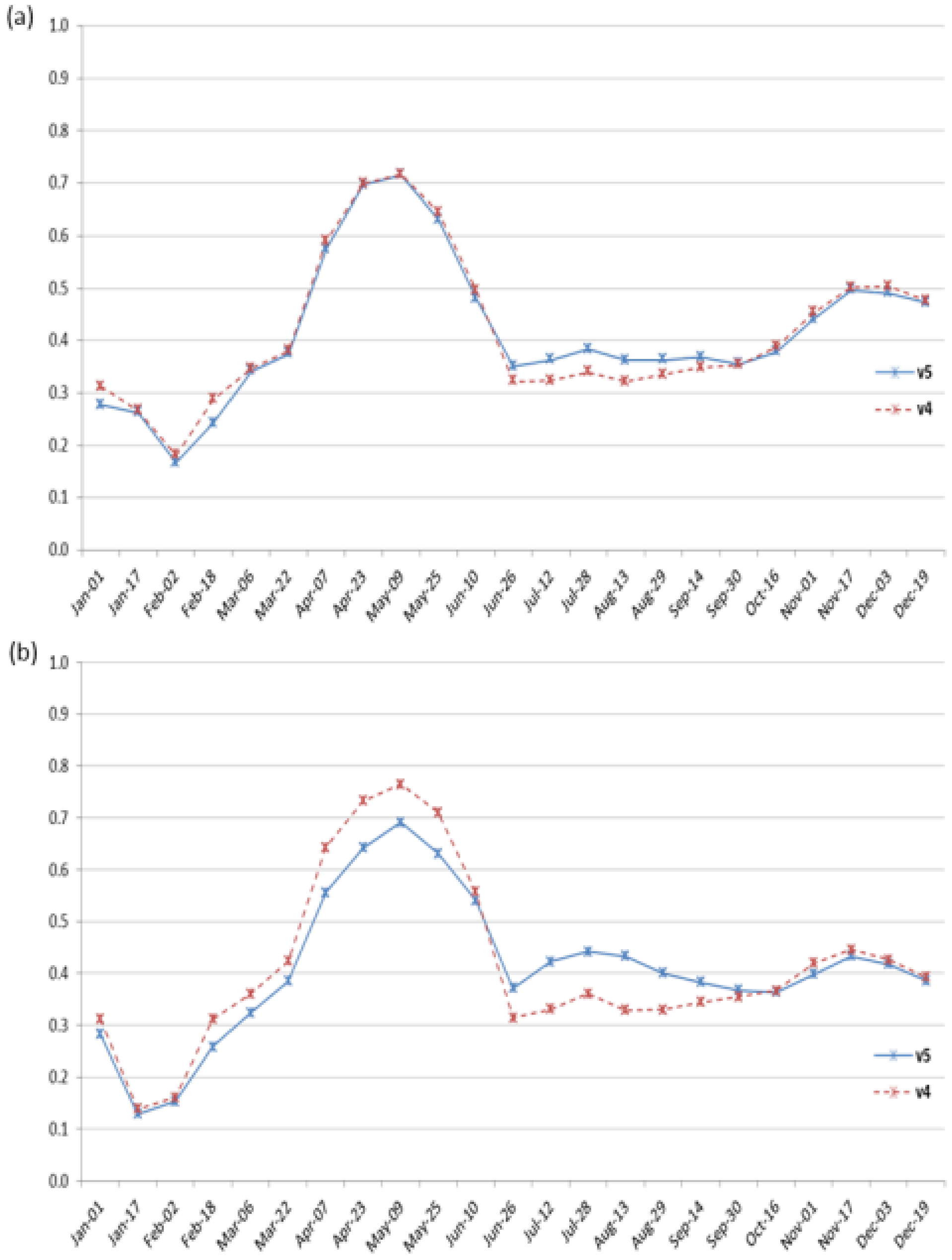


Figure 3.6 Winter wheat NDVI profiles (a) v4 vs. v5, Non-Irrigated, (b) v4 vs. v5, Irrigated

3.6.6. Inter-class comparison of crop VI profiles

Figure 3.7 illustrates the inter-class separability of crops in the study area. The NDVI profiles for each crop type that were calculated from a 12-month (Jan – Dec, 2001) time series of 16-day composite MODIS 250 m data across Kansas are shown in the figure. Figure 3.7.a displays collection 4 data and Figure 3.7.b shows collection 5. First, alfalfa and winter wheat are clearly distinguishable from summer crops in the spring for both collection versions. Though alfalfa becomes undistinguishable in early summer as the summer crops' NDVI values increase, winter wheat remains distinguishable throughout most of the growing season. While summer crops are harder to discriminate from each other, there are still a few composite periods where these crops show their distinctive patterns during the greenup and senescence phases.

Based on the visual comparison of the average NDVI profiles in the figure, it is difficult to discover any noticeable differences between collection 4 and 5 time-series data. It, however, appears that the NDVI value range for collection 5 phenology curves is smaller than that of collection 4. For example, during the time between greenup and peak greenness (June 10 – July 28) the NDVI values of soybeans range from 0.3921 to 0.8405 (range = 0.4484) for collection 4, while the NDVI values for collection 5 range from 0.4337 to 0.7982 (range = 0.3645).

Although the observation confirmed that time-series MODIS 250 m data has adequate spatial, spectral, and temporal resolution for major crop separability in this study with both collection 4 and collection 5, it appears that collection 4 is potentially more helpful in distinguishing crops in this study than collection 5 because of the greater range of NDVI values in collection across the growing season for all crops studied.

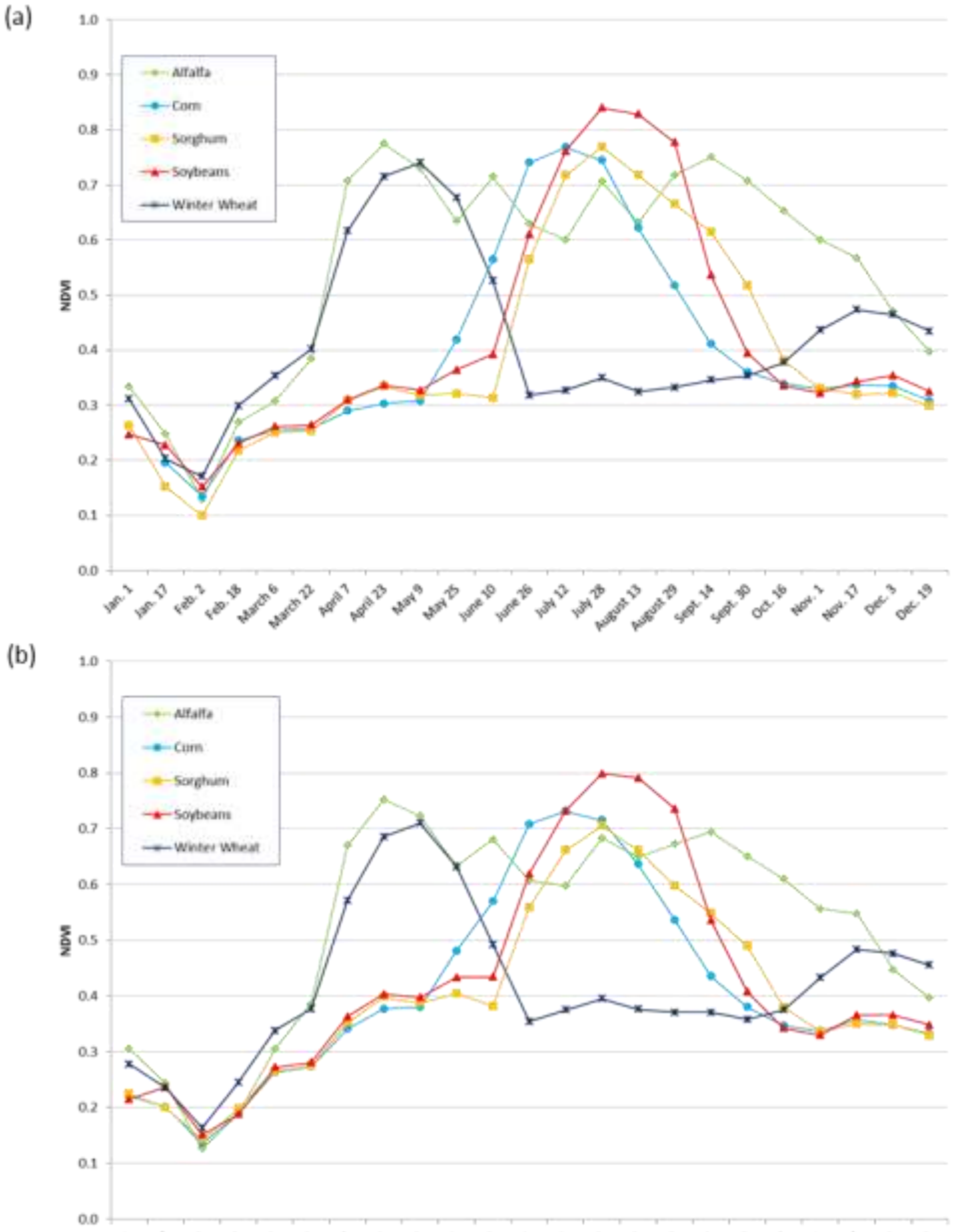


Figure 3.7 Inter-Class comparisons with NDVI profiles for 2001 (a) collection 4, (b) collection 5

3.6.7. JM Distance analysis

Table 3.3 represents JM distance results for all pair-wise crop comparisons to examine potential discrepancies between collections 4 and 5. The growing season defined for this analysis spans from the March 22 to the November 1 composite period as Wardlow *et al*. (2007) suggested because it covers most of the crops' growth cycles.

Table 3.3 JM distance values for all pair-wise crop comparisons

(a) JM distance values for 2001 collection version 4, 16-day time-series MODIS 250 m data

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	2.00	2.00	2.00	1.99
Corn	-	1.66	1.63	2.00
Sorghum	-	-	1.61	2.00
Soybeans	-	-	-	2.00

[1] Modified Table 3 in Wardlow *et al*., 2007

(b) JM distance values for 2001 collection version 5, 16-day time-series MODIS 250 m data

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	1.84	1.81	1.84	1.78
Corn	-	1.05	1.05	1.78
Sorghum	-	-	1.16	1.75
Soybeans	-	-	-	1.76

(c) JM distance values for 2005 collection version 5, 16-day time-series MODIS 250 m data

Crop Type	Corn	Sorghum	Soybeans	Winter wheat
Alfalfa	1.89	1.84	1.86	1.74
Corn	-	1.31	1.23	1.63
Sorghum	-	-	1.01	1.50
Soybeans	-	-	-	1.60

Table 3.3.a illustrates JM distances calculated for collection 4 for 2001. The average JM distance for all crops is 1.89. Due to similar crop calendars, JM distances among summer crops are lower than the distances between either alfalfa or wheat and the summer crops, and the average JM distance for summer crops only is 1.63. Table 3.3.b represents JM distances for collection 5 for 2001. Overall JM distances in the table are lower than those for collection 4 (Table 3.3.a) and, in particular, the decreased JM distances for summer crops are dramatic. The average JM distance for all crops is 1.58 and the average JM distance for summer crops only is 1.09 (Table 3.3.b). Table 3.3.c also represents JM distances for collection 5, but this time, for 2005. As would be expected, when compared to the preceding tables (Table 3.3.a and b), table 3.3.c shows a more similar pattern to Table 3.3.b with lower JM distance values than to Table 3.3.a. The average JM distance for all crops in the table is 1.56 and the average JM distance for summer crops only is 1.18 (Table 3.3.c).

According to the analyzed JM distances, the difference in JM distance values between the different collection versions (between Table 3.3.a and Table 3.3.b or between Table 3.3.a and Table 3.3.c) are much larger than the difference between the inter-annual data (between Table 3.3.b and Table 3.3.c). Although the JM distance values measured among the summer crops dropped less dramatically in 2005, it is not clear if that is related to any specific weather conditions. It, however, is clear that the older version (collection 4, Table 3.3.a) showed much higher JM distance results in comparing separability of the crops statistically than the latest version (collection 5, Table 3.3.b and c).

3.7. Conclusions

The objective of this research was to investigate NDVI values between collections 4 and 5 time-series MODIS 250 m data to see if the latest collection version (version 5) is an improvement over version 4 for distinguishing the five major crop types in the study area. NDVI values profiles extracted from different collection versions for 2001 and 2005 (collection 5 only) were analyzed and JM distance calculations were also performed to compare separability of the crops statistically. The major conclusions include:

1. **Both collection 4 and collection 5 provide good visual separability of crops, and both likely would produce reasonably accurate land cover maps. However, collection 4 clearly has (a) a greater range of values over the growing season for all crops in the study, and (b) provides greater statistical separability among crops, as shown in the JM distance analysis.** As several previous studies concluded (Masialeti *et al*., 2010; Wardlow *et al*., 2008; Wardlow *et al*., 2007), I confirmed that time-series MODIS 250 m data's spatial, spectral, and temporal resolution for major crop separability were adequate with both collection versions. Each crop had its own unique spectral and temporal patterns in its NDVI profiles for different collection versions. I, however, could not find any evidence that the latest collection version (collection 5) was more helpful in separating a specific crop from other crops than the older collection version (collection

4). Rather, the results indicated that collection 4 was statistically better than the collection 5.

2. **The results were clear but the underlying causes are not.** As discussed above, collection 5 failed to provide consistent results that would indicate that it might improve crop separability with its new refinements over the older version, collection 4. Just as Hulley and Hook (2009) concluded that version 5 of the MODIS Land Surface Temperature and Emissivity (LST&E) product was inadequate for deriving accurate emissivity values for arid and semi-arid areas as compared to version 4, a major conclusion of this study is that the superior statistical separability of version 4 NDVI values versus version 5 suggests, at the very least, that version 4 data should be used for mapping the crops in this study region. Unfortunately, it is unclear why collection 5 did not work as well as would have been hoped for crop separability in this study. While it would certainly be possible to perform additional research to create and validate land cover maps from each of two collections, it is less clear how a research project could be designed to identify which parts of the algorithm that creates collection 5 NDVI data are responsible for the lowered separability evident in the data used in this study.

The underlying hypothesis for this research was that the latest version (collection 5) of MODIS 250 m time-series data might be more useful for distinguishing five major crops grown in Kansas. The observed and analyzed results failed in supporting the assumption. Observations of the ranges between low and high NDVI values over the growing season showed that version 4 consistently had greater ranges for all crops compared to version 5. Furthermore, a statistical approach, JM distance analysis, strongly suggested that the older version (collection 4) was more competent to carry out distinguishing crops than the latest version (collection 5). Further studies are needed to better understand how the algorithms applied to the latest version of MODIS 250 m time-series data affect LULC classification.

4. Summary

4.1. Dissertation Research Overview

4.1.1. Research Objectives and Goals Revisited

The primary objectives of this dissertation were to: (1) investigate the use of NDVI values to separate crop types using different compositing periods of time-series MODIS 250 m data and (2) analyze the use of NDVI values to separate crop types using collections 4 and 5 time-series MODIS 250 m data. The specific goals of the research were to:

- examine if there are meaningful statistical differences among the different composite period datasets
- test whether shorter compositing periods of time-series datasets are more effective in separating crop types than the 16-day time-series dataset
- examine if there are meaningful statistical differences between the earlier and later collection version (collection 4 versus collection 5)
- inspect whether the latest collection version of the time-series MODIS 250 m dataset has better ability to discriminate the study area's major crop types compared to the older collection version

4.1.2. Major Conclusions and Findings

For the first research issue (Chapter 2), NDVI profiles extracted from different compositing periods for 2001 and 2005 were analyzed to see whether 8-day (and dual-8-day) composited NDVI compared to 16-day composited NDVI would show finer scale spectral-temporal variability for improved crop separability. The major conclusions include:

- **There are meaningful statistical differences among the different composite period datasets.** This research confirmed that time-series MODIS 250 m data's spatial, spectral, and temporal resolution for major crop separability were satisfactory. Each crop showed clear and unique spectral and temporal patterns in its NDVI profiles for different composite period datasets. The crop separability was observed in the analysis of regional intra-crop NDVI profiles, inter-class comparisons, and JM distance as well.
- **Time-series data that have shorter compositing periods are more effective in separating crop types.** JM distance analysis detected meaningful differences among the different composite period datasets. Given the range of the JM distance values measured for the major crops and the differences in the values among the crops, the temporal differences observed in JM distance values between different composite period datasets can be beneficial for crop separability.
- **Any observed differences should be interpreted with care.** In spite of the subtle differences possibly resulting from unusual weather conditions, changed crop management practices, or other unknown reasons, they can still be useful if used in conjunction with additional variables such as harmonic analysis components (Jakubauskas *et al*., 2002) and vegetation phenology metrics (Reed et al., 1994; Zhang et al., 2003) since researchers may better understand the VI profiles with these additional variables useful for summarizing various characteristics. If the subtle differences are sensitive enough to reflect any environmental variations, as all the figures suggested in the previous discussion section, shorter compositing periods of time-series data might be especially beneficial in investigating smaller geographical areas. One of the primary conclusions drawn from JM distance analysis presented a good example of how the

analysis could become a very strong statistical tool for crop separability when it was applied to shorter compositing periods of time-series datasets.

For the second research issue, NDVI value profiles extracted from different collection versions for 2001 and 2005 (collection 5 only) were analyzed and JM distance analysis was also performed to compare separability of the crops statistically. The major conclusions include:

- **The results concluded that the latest version (collection 5) of time-series MODIS 250 m data was not more helpful in crop separability than collection 4.** Although each crop had its own unique spectral and temporal patterns in its NDVI profiles for different collection versions, I could not find any evidence that that the latest collection version was more helpful in separating a specific crop from other crops. Rather, the results indicated that collection 4 was statistically better than collection 5.
- **The results did not suggest an explanation for the inferior performance of collection 5.** Collection 5 failed to give any reliable evidence that it might be able to improve crop separability with its new refinements over the older version, collection 4. Just as Hulley and Hook (2009) concluded that the latest version of MODIS Land Surface Temperature and Emissivity (LST&E) product was inadequate for deriving accurate emissivity values for arid and semi-arid areas as compared to the older version, a major conclusion of this study is that the superior statistical separability of collection 4 NDVI values suggests, at the very least, that collection 4 data should be used for mapping the crops in this study region. It is unclear why collection 5 did not work as well as would have been hoped in crop separability in this study.

4.2. Future Research Suggestions

4.2.1. Building annual field site database

This research confirmed the earlier findings of Wardlow *et al*. (2007) hat time-series MODIS 250 m data's spatial, spectral, and temporal resolution were adequate for major crop separability and I demonstrated it with different compositing period of time-series data and with different collection versions. Each crop had its own unique spectral and temporal patterns in its NDVI profiles. However, two years's inter-annual comparisons could be expanded to yearly inter-annual investigations. A number of results from NDVI profiles illustrated in this dissertation showed deviation from their typical patterns. If we could build a field site database annually and use the annual datasets for crop separability, what advances might be made?

- We probably could recognize and understand what causes the anomalies in the VI profiles more clearly.
- In addition, the database then would be a valuable resource for related research topics such as phenology, crop progress estimation, etc.

4.2.2. Further research interests

The variety of processes and research activities for this dissertation has inspired some interesting future research ideas.

- **Day of Pixel Composite Analysis**

The 11th layer of MOD13Q1 contains information about the date of each pixel in the composite image, the day during the composite period when the best observation is recorded. For example, there are significant differences in maize green leaf area index (GLAI) especially during the vegetative stage between 8-day and 16-day time-series MODIS data (Guindin-Garcia *et al*., 2012). If this date has a relationship with quality of any MODIS products, it would widen our knowledge about the impacts of the Maximum Value Composite process. And, it also will provide a powerful tool for crop phenology and crop condition monitoring.

- **Products from the Aqua Platform**

Both MOD09Q1 and MOD13Q1 are surface reflectance products derived from the MODIS instrument on the Terra Platform. However, there are other products derived from MODIS on the Aqua Platform, including surface reflectance products. For example, MOD09A1 is an 8-day time-series Aqua product using seven surface reflectance bands with 500 m of spatial resolution. Combining the Terra and Aqua products for crop separability or phenology researches is an area yet to be studied.

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