

Mapping crop seasonality parameters using NDVI time-series derived from HJ-1 A/B data

Zhuokun Pan^{a,b}, Jingfeng Huang^{a,c*}, Qingbo Zhou^d, Limin Wang^d, Yongxiang Cheng^{a,c}, Hankui Zhang^e, George Alan Blackburn^f, Jing Yan^g, Jianhong Liu^h

^a *Institute of Applied Remote Sensing & Information Technology, Zhejiang University, Hangzhou, 310058, China*

^b *Key Laboratory of Environmental Remediation and Ecological Health, Ministry of Education, College of Natural Resources and Environmental Science, Zhejiang University, Hangzhou, 310058, China*

^c *Key Laboratory of Agricultural Remote Sensing and Information System, Zhejiang Province, Hangzhou, 310058, China*

^d *Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences/Key Laboratory of Resources Remote Sensing and Digital Agriculture, Ministry of Agriculture, Beijing 100081, China*

^e *Institute of Space and Earth Information Science, the Chinese University of Hong Kong, Hong Kong, China*

^f *Lancaster Environment Centre, Lancaster University, Lancaster, UK*

^g *Hubei Meteorological Information and Technology Support Center, Wuhan 430074, China*

^h *College of Urban and Environmental Science, Northwest University, Xi'an 710127, China*

Abstract: With the availability of high frequent satellite data, crop phenology could be accurately mapped using time series spatial data. Vegetation index time-series data derived from AVHRR, MODIS, and SPOT-VEGETATION images usually have coarse spatial resolution. Mapping crop seasonality parameters using higher spatial resolution images (e.g., Landsat TM) is unprecedented. Recently launched HJ-1 A/B CCD sensors boarded on China Environment Satellite provided a feasible and ideal data source for the construction of high spatio-temporal resolution vegetation index time-series. This paper presented a comprehensive method to construct NDVI time-series dataset derived from HJ-1 A/B CCD and demonstrated its application in cropland areas. The procedures of time-series data construction included image preprocessing, signal filtering for time-series data, and interpolation for daily NDVI images then the NDVI time-series could present a complete and smooth phenological cycle. To demonstrate its application, TIMESAT program was employed to extract the seasonality parameters of crop lands located in Guanzhong Plain, China. The small-scale test showed that the crop seasonality parameters derived from HJ-1 A/B NDVI time-series were considerably accurate compared with local agro-metrological observation. Further study on technical issues regarding to time-series processing, and potential applications were discussed.

Keywords: HJ-1 A/B, NDVI time-series, S-G filter, interpolation, seasonality parameters

1. Introduction

The dynamic variation of regional vegetation phenology is an important indicator for climate change (Begue et al., 2014; Fensholt and Proud, 2012; Reed et al., 1994), e.g., changes in the phenological period and length of the growing

season may be caused by climate variability (Brown and de Beurs, 2008; Linderholm, 2006; Reed et al., 1994). According to crop physiology, the onsets of growth stages are most sensitive to temperature. Driven by temperature, crop growth period will either be prolonged or shortened (David and John, 1996; Estrella et al., 2009). Since higher temperature speeds up crop growth development, reducing time for dry matter accumulation; on the contrary, cooler temperature will prolong growth season length thus lower down the percentage of sterility before fully matured when frozen day comes (Shimono, 2011; Wilson et al., 1995).

Remote sensing offers a feasible tool for delineating spatio-temporal patterns of vegetation phenology on a per pixel basis (Liang et al., 2011; Mingwei et al., 2008; Sakamoto et al., 2006; Sakamoto et al., 2010; Wu et al., 2010; Xin et al., 2002). Recently the research on vegetation index-based time-series image stacks have received great interest in various fields of research (Begue et al., 2014; Ding et al., 2014; Eerens et al., 2014; Huang et al., 2014; Huang and Friedl, 2014; Lanorte et al., 2014; Lehmann et al., 2013; Verbeiren et al., 2008). The most common measure of the photosynthetic activity of vegetated land cover used to derive phenological parameters is the normalized difference vegetation index (NDVI) (Huete et al., 2002; Martínez and Gilabert, 2009; Reed et al., 1994; Tucker, 1979). Previously, NDVI time series data was obtained from NOAA-AVHRR (Advanced Very High-Resolution Radiometer) instruments (Jakubauskas et al., 2002; Martínez and Gilabert, 2009; Xin et al., 2002); afterward Aqua/Terra MODIS (Moderate Resolution Imaging Spectroradiometer) sensors had been launched, which can offer remote sensing products with higher spatial resolution as well as more perfect preprocessing system; and SPOT (Système Pour l'Observation de la Terre) VEGEATION product is also well-known for vegetation time-series analysis. A lot of literatures have reported to use MODIS for crop phenology study by analyzing vegetation index (VI) time series data (Galford et al., 2008; Peng et al., 2011; Sakamoto et al., 2006; Sakamoto et al., 2005; Wu et al., 2010). Nevertheless, at present these time series data are only available at coarse and medium spatial resolution (Martínez and Gilabert, 2009), i.e., 250 – 8000 meter. In addition, coarse resolution imagery is less capable of detecting small-scale disturbances such as those from agriculture activities scheduling (e.g., harvesting) (Begue et al., 2014; Estrella et al., 2009; Schroeder et al., 2011), as the mixed-pixel effect may seriously affect the spectral characteristics in coarse or moderate satellite images (Mingwei et al., 2008; Sakamoto et al., 2005). In China, this limitation is more obvious due to the individual-owned farmland (usually smaller than 1 hectare) and relatively rare vast-area of crop land. Therefore using relatively high-spatial resolution images is particularly important at county-scale study. Moreover, for wide-view angle sensors such as MODIS and AVHRR, the effect of bi-directional reflectance distribution function (BRDF) can be pronounced and confound in time-series data (Hansen and Loveland, 2012; Huete et al., 2002; Sakamoto et al., 2010).

Some researchers have used Landsat TM-like multi-temporal images to construct time-series data to investigate in land cover change mapping (Hansen and Loveland, 2012; Huang et al., 2010; Maxwell and Sylvester, 2012). The

applicability of the Landsat TM-like satellite archives depends on the availability of a temporally adequate supply of Landsat imagery (Huang et al., 2010). Because of the spatial and temporal variation in the ecological process occurred in crop plantation land, using remote sensing to measure or monitor crop phenology requires images with high temporal resolution (Wu et al., 2010), especially during biologically sensitive period. However, the infrequency of the Landsat TM-like images does not meet this requirement. Some researchers proposed to resolve the compromising between spatial and temporal resolution by using data fusion technologies to simulating the high spatio-temporal resolution images (Huang et al., 2013; Wulder et al., 2011; Zhang et al., 2013) .

Most of these satellite-based crop mapping associated with their phenological phases were produced using high-temporal-repeat observation image like AVHRR, MODIS and SPOT-VEG; moderate-to-high spatial image like TM, have relatively good accuracy due to the high spatial resolution, however these data were constrained by either low-temporal resolution or low-repeat cycles, limiting works at small regional scale. To this end, the Disaster Monitoring Constellation has such capability to ensure sufficient repeat cycle for medium-to-high spatial resolution images based on the satellite constellations; one distinct advantage is in meeting the needs for higher temporal resolution (Curiel et al., 2002; Curiel et al., 2004; Hansen and Loveland, 2012). Similar to these, the China's two-day-repeat HJ-1A/B CCD sensors, boarded on China Environment Satellites, provide plentiful satellite-observed materials (as described in Section 2.1). Released by China Center for Resources Satellite Data and Application (<http://www.cresda.com/n16/index.html>), these remote sensing data are freely assessable for public. The aim of this study was to employ HJ-1A/B data to develop a high spatio-temporal resolution time series for characterizing crop phenology. The objectives were to: (1) adopt critical processing methodologies including signal smoothing, and daily NDVI time-series interpolation; (2) extract seasonality information from the NDVI time series in order to measure phenology parameters; (2) evaluate the effectiveness of the derived phenology parameters by reference to field observations.

2. Materials and methodologies

2.1 Study area and remote sensing images

Research area is located in Guanzhong Plain in Shaanxi Province, China. Four counties were selected as test: Fufeng, Yangling, Wugong, Xingping (see Fig.1). According to the agro-meteorological observation in this region, cropping-rotation systems and phenological calendar are summarized as: the winter wheat is sowed in October and harvested in June; the summer corn is sowed in June and harvested in October. Nowadays the double-cropping system in this region is at risk due to unfavorable climate condition, such as drought and low temperature.

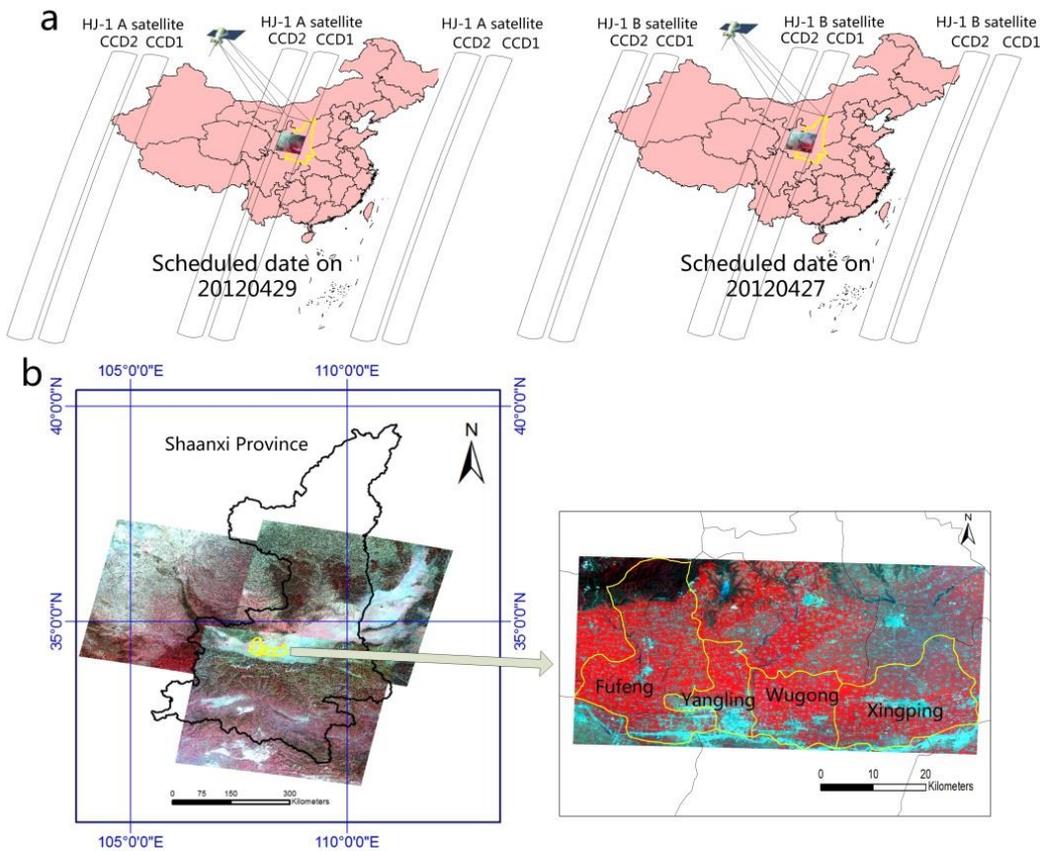


Fig.1. Description of the HJ-1 A/B satellites and their CCD images: (a) satellite orbit; (b) CCD image samples of test site.

The Chinese HJ-1 A/B satellites perform earth-observation sun-synchronously. The CCD sensors capture ground feature with 30-meters pixel resolution at nadir angle, with four bands covering visible and near-infrared wavelength range. Each satellite has two CCD sensors; and a constellation of two satellites constitute an observation network that covers China and its surrounding areas with two-day-repeat cycle.

The HJ-1 A/B satellites provide rapid imaging services for dynamic disasters monitoring. The satellites are now operating normally and playing an important role in China's ecological environment and disaster monitoring (Wang, 2012). The HJ-1 A/B satellites have two constellations which allow the repeat cycle in two days; therefore they can be used to construct a complete time-series dataset making it possible to obtain remote sensing data during the key periods of crop growth. Wang et al. (2012, 2011) and Chen et al. (2011) introduced the overall technical characteristics of the Chinese HJ-1A and HJ-1B satellites. They also investigated the spectral characteristics and suggested potential applications of HJ-1 A/B CCD images. Moreover, consistence evaluation between Landsat 5 TM and HJ-1 A/B CCD demonstrates the good quality of HJ-1 A/B CCD images (Liu et al., 2011b); and the capability of extracting crop planting area using HJ-1 A/B CCD images was also demonstrated (Chen et al., 2011; Liu et al., 2011a). The readers can visit web page of China Center for Resources Satellite Data and Application (<http://www.cresda.com/n16/index.html>) for more information concerning data introduction and acquisition.

2.2 CCD images preprocessing

We have downloaded the all-year-round HJ-1 A/B CCD images of 2011 - 2013. Images were basically cloud-free in the research area; there are 54, 73 and 57 scenes available in 2011, 2012, and 2013 respectively. Like most of optical remote sensing data, conventional preprocessing procedures are applicable for HJ-1 A/B CCD images. Detailed information of image status can be referred to the meta-data file attached with the image. Preprocessing procedures can be summarized as: (1) radiometric-calibration for each band, necessary coefficients for radiometric calibration are published on a web page (<http://www.cresda.com/n16/index.html>); (2) clipping CCD images to get a subset where the test site located; (3) atmospheric-correction by using the FLAASH module (embedded in the ENVI 4.8 software); (4) geometric-correction; (5) mosaicking image to ensure completely covering the test site when necessarily; (6) calculating NDVI; (7) layer stacking the NDVI images to construct a time-series stack.

2.3 Reconstructing NDVI time-series

Since the capacity of earth observation by optical sensors does not allow totally cloud-free or ideal imaging condition at any time. Remote sensing application is hindered by noise resulting from unfavorable atmospheric conditions and sun zenith angle change in year round (Hird and McDermid, 2009; Sakamoto et al., 2010). Thus noise reduction is necessary before further analysis.

The methods for reconstructing NDVI time-series mainly include: Harmonic Analysis of Time Series (Verhoef et al., 2005), Best Index Slope Extraction) (Viovy et al., 1992), curve fitting (e.g., polynomial, logistic and asymmetric Gaussian function-fitting) (Bradley et al., 2007; Jönsson and Eklundh, 2002), signal smoothing (e.g., wavelet and Fourier analysis) (Martínez and Gilabert, 2009; Mingwei et al., 2008; Sakamoto et al., 2010). Users are strongly recommended to consider both their objectives and the nature of the noise presented in an NDVI data set when selecting an approach to reduce noise, particularly when deriving phenological variables (Hird and McDermid, 2009; Julien and Sobrino, 2010). Moreover, the researchers must be careful about the maintenance of original characteristics of time-series profile during noise reduction (Hird and McDermid, 2009; Zhu et al., 2012).

Most of the local filtering methods require representation of a time-series that is continuous and evenly interval (Bradley et al., 2007; Eklundh and Jönsson, 2011; Zhu et al., 2012). Since the interval-fixed composite AVHRR-NDVI or MODIS-VI products are both providing standardized products for the users with their complete processing and producing system, the time-series analysis can be conveniently performed. However, the case of our study does not allow this. Although the HJ-1 A/B satellites have a two-day-repeat cycle, there were still invalid images during the crop growth period (e.g., cloud-contaminated), we have only 50~60 scenes acquired at unevenly distributed throughout the year. Since those vegetation seasonality analysis methods available in time-series software (e.g., TIMESAT) (Eklundh and Jönsson, 2011; Jönsson and Eklundh, 2004) do not function at unevenly distributed time-series. On the other hand, the Gaussian or

Fourier-based filters may be problematic when being applied to irregular VI time-series (Cong et al., 2012). Those standardized vegetation indices (VI) product such as MODIS, SPOT-VGT, they are organized in fixed day interval (e.g. 8 or 10 days composite); hence, when utilizing HJ-1 A/B NDVI time-series data, we need further processing to construct a complete time-series dataset. Given these constraints and requirements, the approaches described in Section 2.3.1 and 2.3.2 were adopted to achieve this goal. Above all, Figure 2 presents the schematic of entire processing flow.

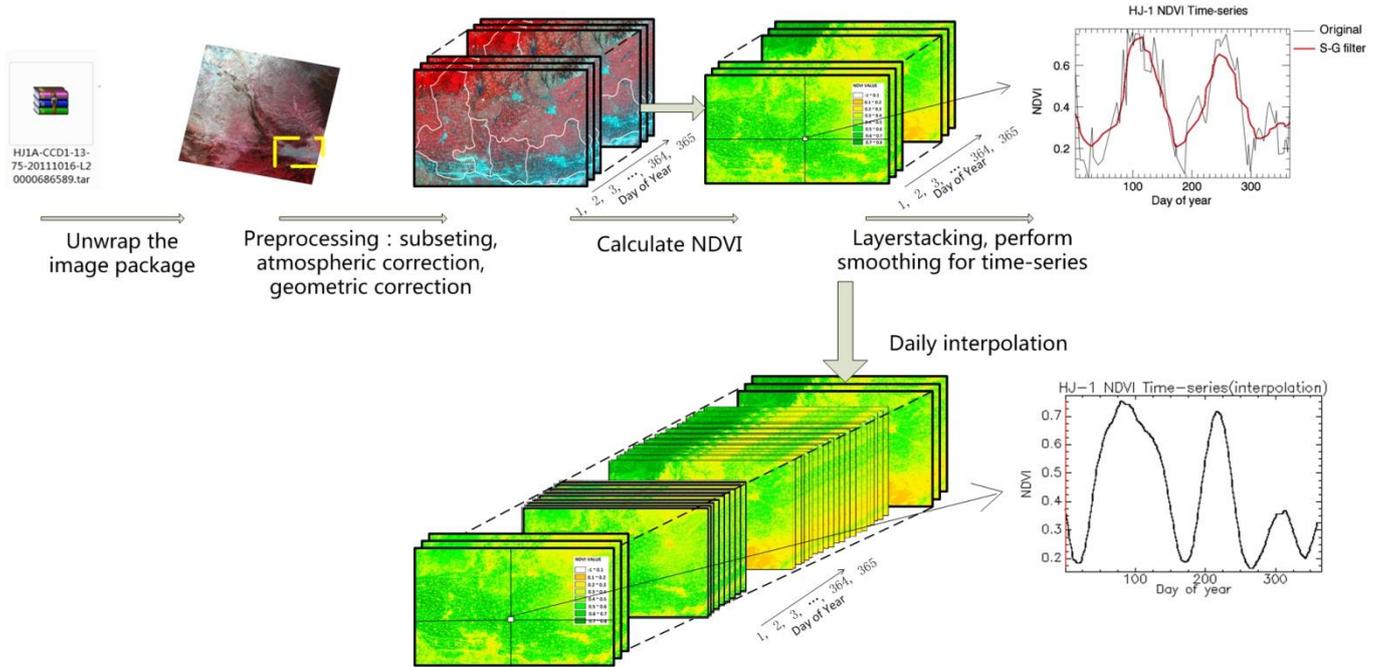


Fig.2. Schematic of the preprocessing and reconstruction for HJ-1 A/B NDVI time-series.

2.3.1 Using Savitzky-Golay filters to smooth NDVI time-series

Noise reduction related to time-series curve filtering must be done to reconstruct the essential shape of the curve. The Savitzky-Golay (S-G) smoothing filtering, also known as least squares or digital smoothing polynomial, can be used to smooth a noisy signal (Press et al., 1994; Savitzky and Golay, 1964). Because of the irregular spacing in HJ-1 A/B NDVI time-series, the S-G filtering has the ability to smooth such data point (Press et al., 1994). We used IDL 8.0 programming technique to implement the S-G filter to perform an image-based time series filtering. Algorithm description can be summarized as follow:

$$g_i = \frac{\sum_{n=-nL}^{nR} c_n f_{i+n}}{n} \quad (1)$$

In Eq.(1) f_i , represents original data value in time-series, g_i is smoothed value, which is the linear combination of c_n and f_i . Here n is the width of moving window to perform filtering, nL and nR corresponding to the left and right edge of the signal component. Originally, if c_n was a constant defined as $c_n = 1/(nL+nR+1)$, then the S-G filtering becomes a moving window

smoothing. The idea of Savitzky-Golay filtering is to find filtering coefficients c_n that preserve higher moments. Therefore, in Eq.(2), the c_n is not a constant but a polynomial fitting function, quadratic or quartic, depending on the user's preference. Then a least-squares fit is solved ranging from nL to nR to obtain the c_n . For a specific dataset of a time-series in a moving window, we defined the fitting function as quadratic polynomial for a specific f_i :

$$c_n(t) = c_1 + c_2t + c_3t^2 \quad (2)$$

Where t is corresponding to the day of year in NDVI time-series. Therefore, g_i can be obtained via Eq.(1).

The IDL S-G filtering is defined as a weighted-moving-average with weighting given as a polynomial of a certain degree. The filter can use any number of points for this weighted average. The returned-coefficients, when applied to a signal, perform a polynomial least-squares fit within the filter window. This polynomial is designed to preserve the high moments within the data and reduce the bias introduced by the filter. This filter works especially well when the typical peaks of the signal are narrow; the heights and widths of the curves are generally preserved.

2.3.2 Interpolating daily NDVI images

Given that many methods have been developed dedicating to reconstruct the trajectory of a time series, a feasible approach for simulating HJ-1 A/B NDVI time-series should be proposed to ensure the integrity before seasonality analysis. Generally, the approaches to obtain a daily-basis VI time-series can be summarized as function-based fitting (Bradley et al., 2007; Eklundh and Jönsson, 2011; Fischer, 1994; Jönsson and Eklundh, 2002; Zhang et al., 2003), such as asymmetric Gauss or double logistic functions; however, some curve fitting methods may result in "too strictly" then may reduce the effectiveness of detecting actual phenological phenomenon of vegetation (Cong et al., 2012; Hird and McDermid, 2009). Another strategy to complete the integrity of NDVI time-series is linear-interpolation technology, the missing observation was given a value according to trajectory of valid NDVI observation (Reed et al., 1994; Sakamoto et al., 2010; Zhu et al., 2012). Since the interpolation treats each pixel individually for a time-series in the image stack, thus the actual trajectory of any ground substance's VI can be delineated, unnecessary to consider the compatibility within a region.

Algorithm of linear interpolation between two images can be described as follow:

$$\frac{NDVI - NDVI_0}{DOY - DOY_0} = \frac{NDVI_1 - NDVI_0}{DOY_1 - DOY_0} \quad (3)$$

where $NDVI$ represents the missing day to be interpolated, $NDVI_1$, $NDVI_0$ represents the valid observations used for the interpolation. Therefore, the $NDVI$ between $NDVI_0$ and $NDVI_1$ can be treated as a linear relationship:

$$NDVI = NDVI_0 + (NDVI_1 - NDVI_0) * \frac{DOY - DOY_0}{DOY_1 - DOY_0} \quad (4)$$

Then, any $NDVI$ for a given day can be obtained between two valid observations. Apparently, a good performance of linear interpolation depends on the amount of valid NDVI images; and the even distribution of the acquisition dates should

also improve the interpolation performance. We used IDL 8.0 programming technique to achieve linear-interpolation to obtain an image-based daily NDVI time series.

2.4 Extracting seasonality parameters

2.4.1 Case introduction

The onset of a specific phenological stage of crop may vary inter-annually which projects variations in the start of the planting season (Reed et al., 1994; Sakamoto et al., 2010), which is highly dependent on climate conditions permitting, as well as crop variety and agriculture activities scheduling, all these circumstances may cause slight decreases in yields as a result of phenology variation. Our research area was located in moderate latitude. Although the yearly thermal condition is sufficient for double cropping, the limited time for cropping rotation interval resulting in cautious when arranging planting/harvesting activities in order to reduce the risk of cold damage. To ensure the security of food crop production, using remote sensing to monitor seasonality parameters in a regional crop is of great significance (Linderholm, 2006; Sakamoto et al., 2005; Xin et al., 2002).

We used the TIMESAT program (Eklundh and Jönsson, 2011; Jönsson and Eklundh, 2004; Jönsson and Eklundh, 2002) to process time-series of HJ-1 A/B NDVI. TIMESAT provides algorithm for seasonality parameters extraction such as beginning, ending and length of a growing season. There is no unique definition for these concepts, readers also can refer to Hird and McDermid (2009), and Reed et al. (1994); these concepts are also named as NDVI metrics, the meaning is similar any way.

We defined the date of the maximum NDVI in the time-series as the beginning of reproductive growth period (Sakamoto et al., 2005), booting for winter wheat, silking for summer corn, respectively. By utilizing the TIMESAT program, we generated crop phenological parameters for the winter wheat and summer corn growth cycles in our test-site: planting date, harvesting date, maximum NDVI date, and length of growth duration (summarized in Fig.3), all of which represent critical growth periods of crop. Since these phenological parameters indicate actual crop growth process in a pixel basis, thus these parameters not only correspond directly to actual, ground-based phenological events, but also provide indicators of climate variations.

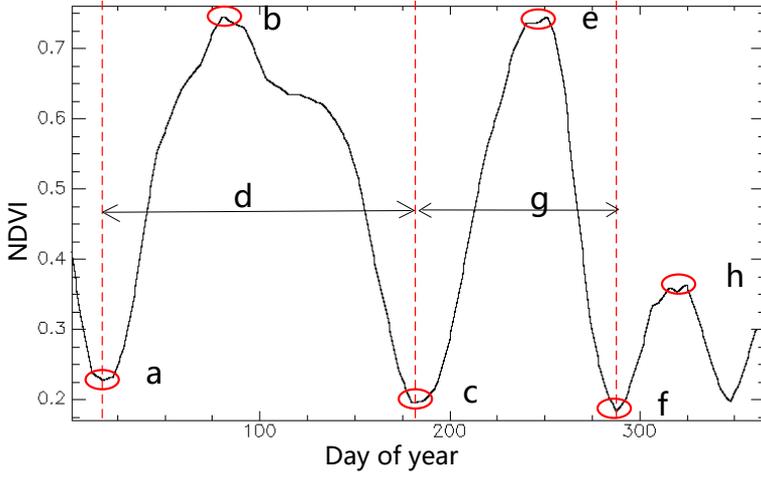


Fig.3. Seasonality parameters of double-cropping area in NDVI time-series (adapted from Eklundh and Jönsson, 2011). The points marked with red circle mean: (a) green-up date of winter wheat after hibernation; (b) maximum NDVI corresponding to wheat’s booting stage; (c) harvesting date of winter wheat, and planting date of summer corn; (d) length of growth duration of winter wheat (from green-up to harvesting); (e) maximum NDVI corresponding to corn’s silking stage; (f) harvesting date of summer corn, and planting date of winter wheat; (g) length of growth duration of summer corn; (h) winter wheat begins hibernation in winter.

2.4.2 NDVI threshold for season start/end

The most common method to extract seasonal data from NDVI time-series is based on value thresholds, assuming that a specific seasonality phenomenon has started when NDVI values exceed a given threshold (Jönsson and Eklundh, 2002; Reed et al., 1994). Based on this, the TIMESAT program loops each pixel throughout the image series, and then the extraction of seasonality parameters is individually depending on NDVI’s changing behavior.

In TIMESAT program, the NDVI threshold value of season start/end is a user-defined ratio to describe the distance between the minimum level and the maximum. To determine a threshold for NDVI, White et al. (2009) proposed the start of season (SOS) for NDVI is depending on the onset day of $NDVI_{max}$ and $NDVI_{min}$. Similar to this idea, this paper defined the NDVI threshold value based on the evidence of regional phenology dynamic. Given that the crop phenological phases and agriculture activities should be similar within a county level, the NDVI threshold value of season start/end was defined as:

$$NDVI_{threshold_value} = \frac{NDVI_{min}}{NDVI_{max}} \quad (5)$$

$NDVI_{min}$ is the minimum value that occurs throughout the year-round NDVI time-series; likewise, $NDVI_{max}$ is the maximum value that occurs throughout the year-round NDVI time-series. Figure 4 presented the normal distribution of NDVI ratio, and then NDVI threshold for season start/end was depending on the most probability. In time series data, those pixels that exceed this threshold value was identified and be processed.

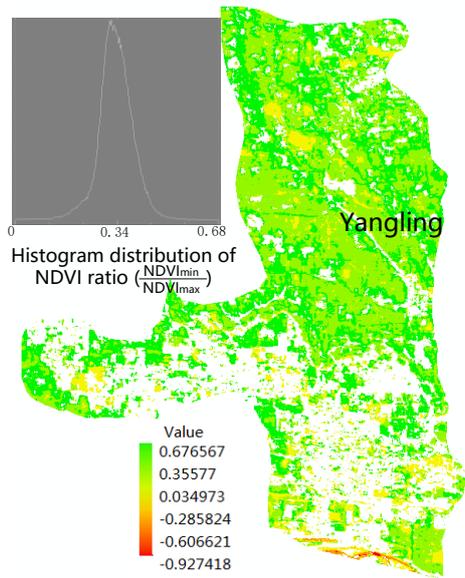


Fig.4. Definition of NDVI threshold value for season start/end

3. Results

3.1. Overview of performance in phenology detection

Since that the NDVI time series data provide a trajectory delineating the crop growth cycle, then TIMESAT would only identify those pixels which have the characteristic of vegetation phenology. Therefore, those vegetation-like ground features were automatically discriminated and their seasonality parameters were presented. We generated crop seasonality parameters in four counties: the date of season start/end, date of middle season, and duration of season length, which represent critical growth period of crop. These parameters indicate actual crop growth process in a pixel basis. This study presents seasonality parameters of winter wheat in 2011 and summer corn in 2012 (see Fig.5 and 6).

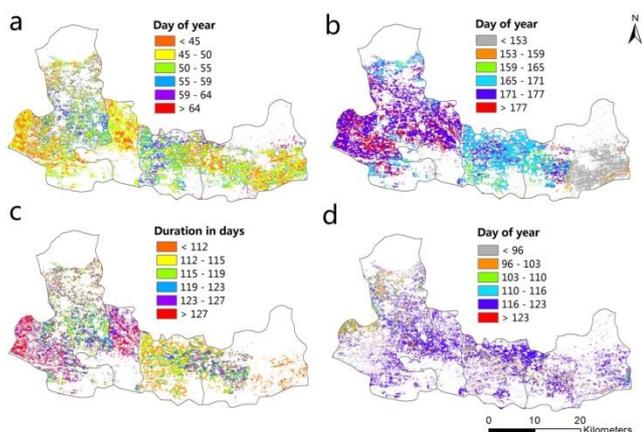


Fig.5. Seasonality parameters extraction for winter wheat in 2011: (a) green-up date, (b) harvesting date, (c) length of growth duration (from green-up to harvesting), (d) booting stage.

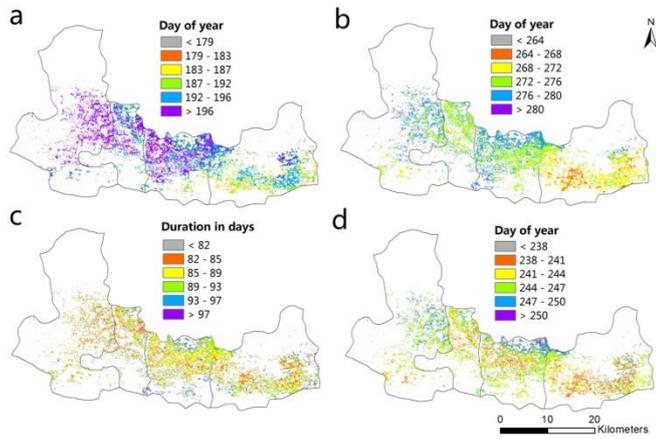


Fig.6. Seasonality parameters extraction for summer corn in 2012: (a) planting date, (b) harvesting date, (c) length of growth duration, (d) silking stage.

Double-cropping system did not happen at every individual farmland as diverse vegetation plantations exist, which depended on the farmer's preference and marketing demand. The seasonality parameters detection was satisfactory for winter wheat; however, detection in length of growth duration for summer corn was not easy, the reason might be that subtle appearance of NDVI when the corn was in seeding period whereas soil background was dominating. Although the cropping area presents unique phenological trajectory in the NDVI time-series, the summer corn has a synchronized growth stage with other vegetation, making it difficult to be distinguished: crop growth status or cultivation management might be different among different farmlands that eventually influence the NDVI value in pixel basis; and arrangement of farmers' activities are also critical influence in summer corn's seasonality.

3.2 Small-scale investigation

We have many years average site-based observation of crop phenology in Yangling, see Table 1; and then a detailed investigation for this area was performed. One drawback should be addressed that, sowing and harvesting, have no exact record; because the sowing and harvesting require the availability of labor and farming machineries which are highly dependent on agriculture scheduling. Therefore, such activities are eventually resulted in the start/end of crop season. Inter/intra annual variation of cropping system can be presented in time-series; crop growth can be as indicator for climate variation. Based on the methodologies and processing procedure, we generated NDVI time series from 2011 to 2013 (see Fig. 7). The NDVI time-series derived from HJ-1 A/B was able to delineate crop phenology with fine spatial resolution. Assessment of field-level phenology detection results for Yangling demonstrated that HJ-1 A/B time series data provide accurate detection of crop season start/end in a daily basis with 30 m spatial resolution. Basically, over 80% of pixels were correctly identified at the specific timing of phenology, without too much bias according to the histogram of the pixels (Table 2 presents the seasonality maps and pixel histogram measured in days). Nevertheless, the onset date of

start/end, length of season projects the variation of climate inter-annually.

Table 1

Description of crop phenological calendars in Yangling

Crop	Phenology phases	month/day	Day of year
Winter wheat	Sowing	10/10	283
	Emergence	10/18	291
	Tillering	11/6	310
	Hibernation	12/20 - 2/16	354 – 47 (next year)
	Jointing	3/20	79
	Booting	4/15	105
	Flowering	4/28	118
	Ripening	6/4	155
	Harvesting	Nodata	Nodata
	Summer corn	Sowing	6/10
Emergence		6/19	170
Seven leaf		7/5	186
Tasseling		8/5	217
Silking		8/9	221
Ripening		9/23	266
Harvesting		Nodata	Nodata

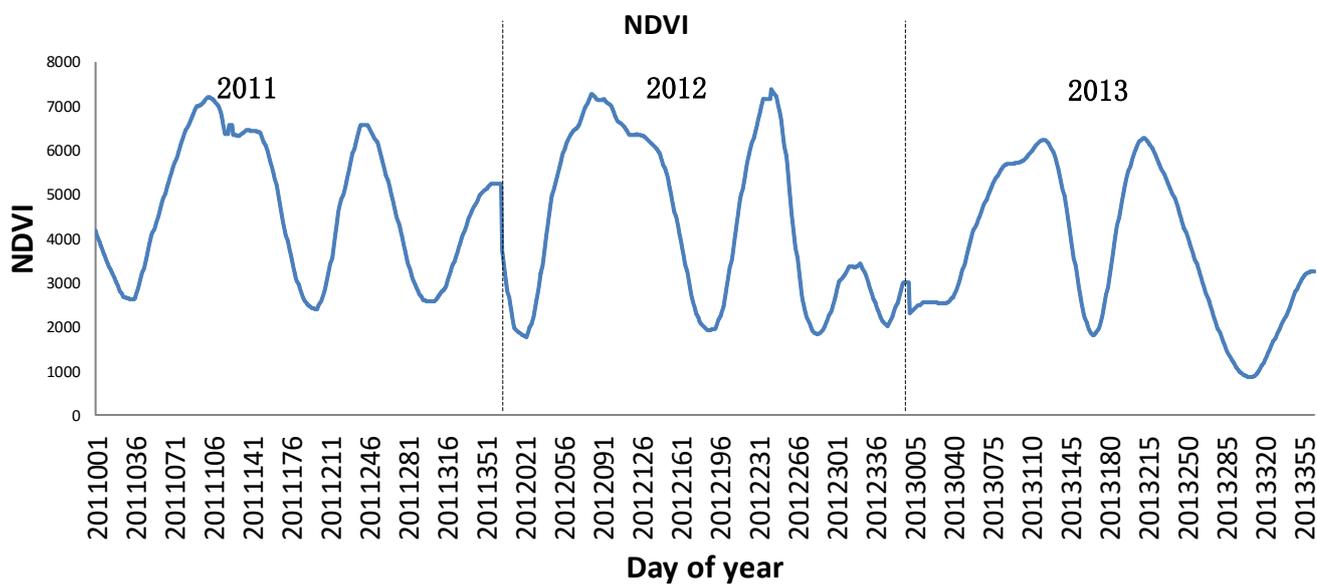
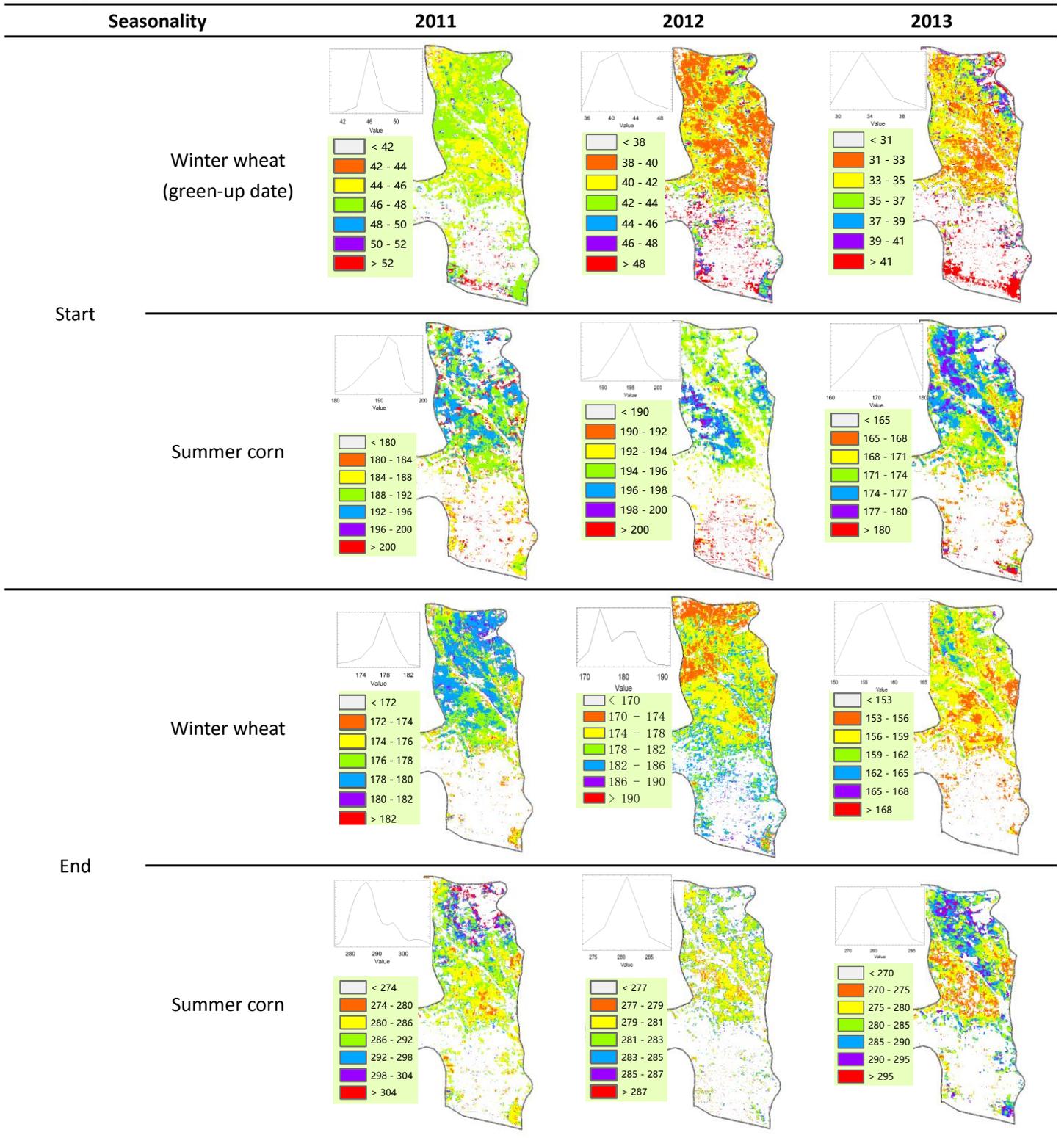
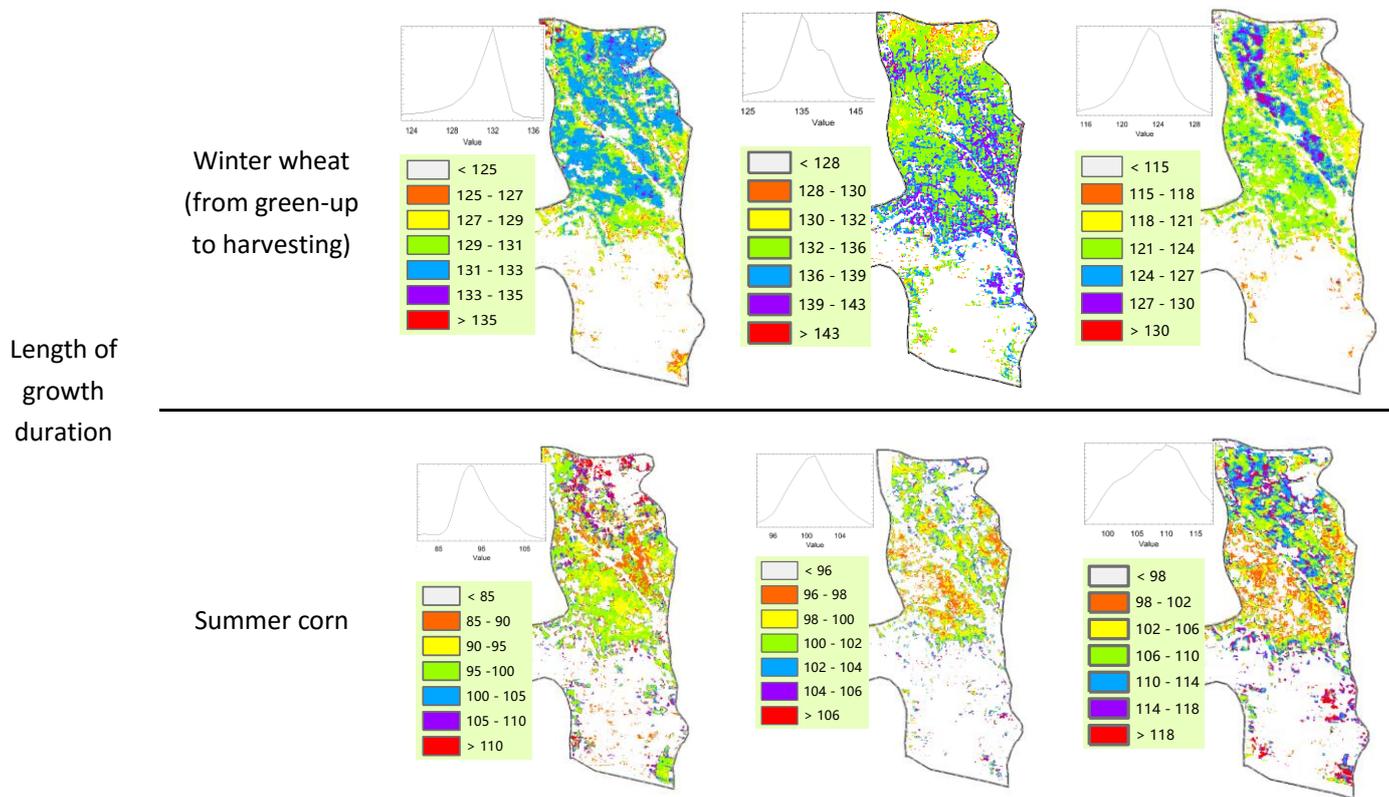


Fig.7. An example of NDVI time-series profile in Yangling, 2011-2013.

Table 2

Mapping crop seasonality in Yangling, 2011-2013





4. Discussions

Mapping cropland is an important task for providing geo-and-temporal referenced information that is useful for production management, planning and food security related issues. With the availability of high frequent satellite data, crop phenology variations could be accurately mapped using time series spatial data, which would help in understanding the effect of climate change on agricultural production and food security. Since a lot of researches in regional vegetation phenology by remotely-sensed monitoring were conducted using AVHRR, MODIS, and SPOT vegetation time-series, no research was found using the China's HJ-1 A/B satellite in crop phenology monitoring. This paper was aiming to introduce a new satellite image data-source for vegetation-indices time-series construction. The advantage of China's HJ-1 A/B is obvious for its high spatial and temporal resolution. We presented the data's characteristic, preprocessing technique to produce an image-based time-series with daily interpolation, and implemented the HJ-1 A/B NDVI time-series in detecting seasonality parameters. One question should be clarified is that, users should be acquainted the quality control is very important: the construction of time-series required sufficient archives of images throughout the year, which is cloud-free; and it is highly dependent on the weather permitting; this will also affect quality of time-series then leads to application effect.

Performance of noise-reduction and time-series construction techniques were judged by the capacity to reflect the true value regarding to the shape of the time-series, so that phenological metrics could be accurately extracted (Hird and McDermid, 2009). There is no unique method that could always perform the optimal effect. More comments and discussions can be referred to (Bradley et al., 2007; Cong et al., 2012; Eklundh and Jönsson, 2011; Hird and McDermid,

2009; Julien and Sobrino, 2010). Eklundh and Jönsson suggested that (Eklundh and Jönsson, 2011) S-G filtering is preferable when the time-series data is used to derive seasonality parameters. When performing the S-G filtering to smooth the time series, the width of moving window and the degree of polynomial fitting, is quite an art that depends on the users' satisfactory about the smoothing result.

In utilizing the HJ-1 A/B NDVI time-series to derive useful information that is applicable, the major problem to be solved is reconstructing the integrity of time-series. We accomplished daily NDVI by using linear interpolation which is practical with considerable accuracy. In this study we did not consider any curve-fitting or shape-matching strategy to achieve time-series reconstruction (Bradley et al., 2007; Eklundh and Jönsson, 2011; Fischer, 1994; Jönsson and Eklundh, 2002; Zhang et al., 2003), because we had tried the other methods and considered that they may not be suitable for HJ-1 A/B data. Likewise, when considering software for time series processing, e.g., TIMESAT or SPIRIT (Eerens et al., 2014), they are both able to extract vegetation phenology. As a preliminary and exploratory study, we did not discuss the technical issue concerning which is suitable or better, which is beyond the scope of this paper. Further discussion should lead to contradictions in using different method.

Further studies should be focused on field data collection, smoothing method and phenology definitions using remote sensing time-series data. In the future, we should test the performance of others VIs (e.g., EVI2(Jiang et al., 2008)), to evaluate its suitability and capability in vegetation discrimination using HJ-1 A/B data. Furthermore, VI time-series contains a "spectral feature" on the time dimension, which reflects the process of crop growth and management level. Therefore, the processing techniques for hyperspectral image may be applied in time-series analysis (Galford et al., 2008; Verbeiren et al., 2008).

5. Conclusions and perspectives

Compared to VI time-series derived from MODIS, AVHRR and SPOT-VEGETATION, the advantage of China's HJ-1 A/B is obvious attributing to its high spatial and temporal resolution. In this paper we present a comprehensive analysis procedure to build the HJ-1 A/B NDVI time-series: the Savitzky-Golay filters smoothing method was employed to reduce noise components from original curve, to retrieve the raw shape of the time-series profile; afterward we interpolate daily NDVI in image basis by using linear interpolation based on the available images. To this end, we ensured an integrative time-series stack before extracting seasonality parameters on a daily basis. Finally we presented the application of HJ-1 A/B NDVI time series data in a fine-scale phenology characterization.

Since remote sensing time-series data has great potential applications. Researchers are encouraged to advance its applications in multidisciplinary. In the future, with more constellations launched, the satellite-network will definitely improve the capability of earth observation with shorter repeat cycle and higher spatial resolution. One major concern for

the user is the time and cost in data preprocessing, such as geometric and radiometric corrections. Therefore, China Center for Resources Satellite Data and Application should develop a standardized procedure for HJ-1 A/B, automatically processing software, and a relevant production system for the users, as did in the MODIS-VI product release.

Acknowledgements

Our research was supported by The National Key Technologies R&D Program of China during the 12th Five-Year Plan Period (Grant NO. 2012BAH29B02). Remote sensing data were provided by China Center for Resources Satellite Data and Application (<http://www.cresda.com/n16/index.html>). The authors would like to express much thanks to Prof. Jönsson, P. and Eklundh, L. for providing the TIMESAT 3.1 program; and thanks to our colleagues Bao she, Yuanyuan Chen, Zhen Zhou for their help in processing satellite images.

Reference

- Begue, A., Vintrou, E., Saad, A. and Hiernaux, P., 2014, Differences between cropland and rangeland MODIS phenology (start-of-season) in Mali. *International Journal of Applied Earth Observation and Geoinformation* (in Press).
- Bradley, B.A., Jacob, R.W., Hermance, J.F. and Mustard, J.F., 2007, A curve fitting procedure to derive inter-annual phenologies from time series of noisy satellite NDVI data. *Remote Sensing of Environment*, 106, 137-145.
- Brown, M.E. and de Beurs, K.M., 2008, Evaluation of multi-sensor semi-arid crop season parameters based on NDVI and rainfall. *Remote Sensing of Environment*, 112, 2261-2271.
- Chen, J., Huang, J. and Hu, J., 2011, Mapping rice planting areas in southern China using the China Environment Satellite data. *Mathematical and Computer Modelling*, 54, 1037-1043.
- Cong, N., Piao, S., Chen, A., Wang, X., Lin, X., Chen, S., Han, S., Zhou, G. and Zhang, X., 2012, Spring vegetation green-up date in China inferred from SPOT NDVI data: A multiple model analysis. *Agricultural and Forest Meteorology*, 165, 104-113.
- Curiel, A.S., Alex, W., Max, M., Lee, B. and Martin, S., 2002, Second generation disaster-monitoring microsatellite platform. *Acta Astronautica*, 51, 191-197.
- Curiel, A.S., Gomes, L., Morgan, K., Butlin, T., Harding, J., Cooksley, J., Boland, L. and Sweeting, M., 2004. Small satellite constellations for earth observation.
- David, A. and John, R.P., 1996, Temperature, plant development and crop yields. *Trends in Plant Science*, 1, 119-124.
- Ding, Y., Zhao, K., Zheng, X. and Jiang, T., 2014, Temporal dynamics of spatial heterogeneity over cropland quantified by time-series NDVI, near infrared and red reflectance of Landsat 8 OLI imagery. *International Journal of Applied Earth Observation and Geoinformation*, 30, 139-145.
- Eerens, H., Haesen, D., Rembold, F., Urbano, F., Tote, C. and Bydekerke, L., 2014, Image time series processing for agriculture monitoring. *Environmental Modelling & Software*, 53, 154-162.
- Eklundh, L. and Jönsson, P., 2011. *TIMESAT3.1 Software Manual*.
- Estrella, N., Sparks, T.H. and Menzel, A., 2009, Effects of temperature, phase type and timing, location, and human density on plant phenological responses in Europe. *Climate Research*, 39, 235-248.
- Fensholt, R. and Proud, S.R., 2012, Evaluation of Earth Observation based global long term vegetation trends — Comparing GIMMS and MODIS global NDVI time series. *Remote Sensing of Environment*, 119, 131-147.
- Fischer, A., 1994, A model for the seasonal variations of vegetation indices in coarse resolution data and its inversion to extract crop parameters. *Remote Sensing of Environment*, 48, 220-230.
- Galford, G.L., Mustard, J.F., Melillo, J., Gendrin, A., Cerri, C.C. and Cerri, C.E.P., 2008, Wavelet analysis of MODIS time series to

- detect expansion and intensification of row-crop agriculture in Brazil. *Remote Sensing of Environment*, 112, 576-587.
- Hansen, M.C. and Loveland, T.R., 2012, A review of large area monitoring of land cover change using Landsat data. *Remote Sensing of Environment*, 122, 66-74.
- Hird, J.N. and McDermid, G.J., 2009, Noise reduction of NDVI time series: An empirical comparison of selected techniques. *Remote Sensing of Environment*, 113, 248-258.
- Huang, B., Zhang, H., Song, H., Wang, J. and Song, C., 2013, Unified fusion of remote-sensing imagery: generating simultaneously high-resolution synthetic spatial-temporal-spectral earth observations. *Remote Sensing Letters*, 4, 561-569.
- Huang, C., Chen, Y. and Wu, J., 2014, Mapping spatio-temporal flood inundation dynamics at large river basin scale using time-series flow data and MODIS imagery. *International Journal of Applied Earth Observation and Geoinformation*, 26, 350-362.
- Huang, C., Goward, S.N., Masek, J.G., Thomas, N., Zhu, Z. and Vogelmann, J.E., 2010, An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment*, 114, 183-198.
- Huang, X. and Friedl, M.A., 2014, Distance metric-based forest cover change detection using MODIS time series. *International Journal of Applied Earth Observation and Geoinformation*, 29, 78-92.
- Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X. and Ferreira, L.G., 2002, Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83, 195-213.
- Jönsson, P. and Eklundh, L., 2002, Seasonality extraction by function fitting to time-series of satellite sensor data. *IEEE Transactions on Geoscience and Remote Sensing*, 40, 1824-1832.
- Jönsson, P. and Eklundh, L., 2004, TIMESAT—a program for analyzing time-series of satellite sensor data. *Computers & Geosciences*, 30, 833-845.
- Jakubauskas, M.E., Legates, D.R. and Kastens, J.H., 2002, Crop identification using harmonic analysis of time-series AVHRR NDVI data. *Computers and Electronics in Agriculture*, 37, 127-139.
- Jiang, Z., Huete, A., Didan, K. and Miura, T., 2008, Development of a two-band enhanced vegetation index without a blue band. *Remote Sensing of Environment*, 112, 3833-3845.
- Julien, Y. and Sobrino, J.A., 2010, Comparison of cloud-reconstruction methods for time series of composite NDVI data. *Remote Sensing of Environment*, 114, 618-625.
- Lanorte, A., Lasaponara, R., Lovallo, M. and Telesca, L., 2014, Fisher-Shannon information plane analysis of SPOT/VEGETATION Normalized Difference Vegetation Index (NDVI) time series to characterize vegetation recovery after fire disturbance. *International Journal of Applied Earth Observation and Geoinformation*, 26, 441-446.
- Lehmann, E.A., Wallace, J.F., Caccetta, P.A., Furby, S.L. and Zdunic, K., 2013, Forest cover trends from time series Landsat data for the Australian continent. *International Journal of Applied Earth Observation and Geoinformation*, 21, 453-462.
- Liang, L., Schwartz, M.D. and Fei, S., 2011, Validating satellite phenology through intensive ground observation and landscape scaling in a mixed seasonal forest. *Remote Sensing of Environment*, 115, 143-157.
- Linderholm, H.W., 2006, Growing season changes in the last century. *Agricultural and Forest Meteorology*, 137, 1-14.
- Liu, J., Tian, Q., Huang, Y., Du, L. and Wang, L., 2011a, Extraction of the corn planting area based on multi-temporal HJ-1 satellite data.
- Liu, S., Li, Q., Mao, X. and Zhang, J., 2011b, Evaluation on consistency between HJ-1 CCD and TM images in monitoring fractional green vegetation cover. 1005-1008.
- Martínez, B. and Gilabert, M.A., 2009, Vegetation dynamics from NDVI time series analysis using the wavelet transform. *Remote Sensing of Environment*, 113, 1823-1842.
- Maxwell, S.K. and Sylvester, K.M., 2012, Identification of “ever-cropped” land (1984–2010) using Landsat annual maximum NDVI image composites: Southwestern Kansas case study. *Remote Sensing of Environment*, 121, 186-195.
- Mingwei, Z., Qingbo, Z., Zhongxin, C., Jia, L., Yong, Z. and Chongfa, C., 2008, Crop discrimination in Northern China with double cropping systems using Fourier analysis of time-series MODIS data. *International Journal of Applied Earth Observation and Geoinformation*, 10, 476-485.
- Peng, D., Huete, A.R., Huang, J., Wang, F. and Sun, H., 2011, Detection and estimation of mixed paddy rice cropping patterns with MODIS data. *International Journal of Applied Earth Observation and Geoinformation*, 13, 13-23.

- Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., 1994. Numerical Recipes in C: The Art of Scientific Computing Second Edition. Cambridge University Press.
- Reed, B.C., Brown, J.F., VanderZee, D., Loveland, T.R., Merchant, J.W. and Ohlen, D.O., 1994, Measuring phenological variability from satellite imagery. *Journal of Vegetation Science*, 5, 703-714.
- Sakamoto, T., Van Nguyen, N., Ohno, H., Ishitsuka, N. and Yokozawa, M., 2006, Spatio-temporal distribution of rice phenology and cropping systems in the Mekong Delta with special reference to the seasonal water flow of the Mekong and Bassac rivers. *Remote Sensing of Environment*, 100, 1-16.
- Sakamoto, T., Wardlow, B.D., Gitelson, A.A., Verma, S.B., Suyker, A.E. and Arkebauer, T.J., 2010, A Two-Step Filtering approach for detecting maize and soybean phenology with time-series MODIS data. *Remote Sensing of Environment*, 114, 2146-2159.
- Sakamoto, T., Yokozawa, M., Toritani, H., Shibayama, M., Ishitsuka, N. and Ohno, H., 2005, A crop phenology detection method using time-series MODIS data. *Remote Sensing of Environment*, 96, 366-374.
- Savitzky, A. and Golay, M.J.E., 1964, Smoothing and Differentiation of Data by Simplified Least Squares Procedures. *Analytical Chemistry*, 36, 1627-1639.
- Schroeder, T.A., Wulder, M.A., Healey, S.P. and Moisen, G.G., 2011, Mapping wildfire and clearcut harvest disturbances in boreal forests with Landsat time series data. *Remote Sensing of Environment*, 115, 1421-1433.
- Shimono, H., 2011, Earlier rice phenology as a result of climate change can increase the risk of cold damage during reproductive growth in northern Japan. *Agriculture, Ecosystems & Environment*, 144, 201-207.
- Tucker, C.J., 1979, Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8, 127-150.
- Verbeiren, S., Eerens, H., Piccard, I., Bauwens, I. and Van Orshoven, J., 2008, Sub-pixel classification of SPOT-VEGETATION time series for the assessment of regional crop areas in Belgium. *International Journal of Applied Earth Observation and Geoinformation*, 10, 486-497.
- Verhoef, W., van der Kamp, A. and Koelemeijer, R., 2005. Climate Indicators from Time Series of NDVI images, National Aerospace Laboratory NLR, Amsterdam, The Netherlands.
- Viovy, N., Arino, O. and Velward, A., 1992, The Best Index Slope Extraction (BISE): A method for reducing noise in NDVI time-series. *International Journal of Remote Sensing*, 13, 1585-1590.
- Wang, Q., 2012, Technical system design and construction of China's HJ-1 satellites. *International Journal of Digital Earth*, 5, 202-216.
- Wang, Q., Wu, C., Li, Q. and Li, J., 2011, Chinese HJ-1A/B satellites and data characteristics. *Science China (Earth Sciences edition)*, 53, 51-57.
- White, M.A., de Beurs, K.M., Didan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'Keefe, J., Zhang, G., Nemani, R.R., van Leeuwen, W.J.D., Brown, J.F., de Wit, A., Schaepman, M., Lin, X., Dettinger, M., Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T. and Lauenroth, W.K., 2009, Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology*, 15, 2335-2359.
- Wilson, D.R., Muchow, R.C. and Murgatroyd, C.J., 1995, Model analysis of temperature and solar radiation limitations to maize potential productivity in a cool climate. *Field Crops Research*, 43, 1-18.
- Wu, W., Yang, P., Tang, H., Zhou, Q., Chen, Z. and Shibasaki, R., 2010, Characterizing spatial patterns of phenology in cropland of China based on remotely sensed data. *Agricultural Sciences in China*, 9, 101-112.
- Wulder, M.A., White, J.C., Masek, J.G., Dwyer, J. and Roy, D.P., 2011, Continuity of Landsat observations: Short term considerations. *Remote Sensing of Environment*, 115, 747-751.
- Xin, J., Yu, Z., van Leeuwen, L. and Driessen, P.M., 2002, Mapping crop key phenological stages in the North China Plain using NOAA time series images. *International Journal of Applied Earth Observation and Geoinformation*, 4, 109-117.
- Zhang, H., Chen, J., Huang, B., Song, H. and Li, Y., 2013, Reconstructing seasonal variation of Landsat vegetation index related to leaf area index by fusing with MODIS data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 1, 1-11.
- Zhang, X., Friedla, M.A., Schaaf, C.B., Strahler, A.H., Hodges, J.C.F., Gao, F., Reed, B.C. and Huete, A., 2003, Monitoring vegetation phenology using MODIS. *Remote Sensing of Environment*, 84, 471-475.

Zhu, W., Pan, Y., He, H., Wang, L., Mou, M. and Liu, J., 2012, A changing weight filter method for reconstructing a high-quality NDVI time series to preserve the integrity of vegetation phenology. *IEEE Transactions on Geoscience and Remote Sensing*, 50, 1085-1095.