Detecting winter wheat phenology with SPOT-VEGETATION data in the North China Plain

Linlin Lu a, Cuizhen Wang b, Huadong Guo a & Qingting Li a

a Center for Earth Observation and Digital Earth, Chinese Academy of Sciences, Beijing, China
b Department of Geography, University of Missouri, Columbia, USA


To cite this article: Linlin Lu, Cuizhen Wang, Huadong Guo & Qingting Li (2013): Detecting winter wheat phenology with SPOT-VEGETATION data in the North China Plain, Geocarto International, DOI:10.1080/10106049.2012.760004

To link to this article: http://dx.doi.org/10.1080/10106049.2012.760004

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
Detecting winter wheat phenology with SPOT-VEGETATION data in the North China Plain

Linlin Lu*, Cuizhen Wangb, Huadong Guoa and Qingting Liaa

aCenter for Earth Observation and Digital Earth, Chinese Academy of Sciences, Beijing, China; bDepartment of Geography, University of Missouri, Columbia, USA

(Received 10 July 2012; final version received 14 December 2012)

Monitoring phenological change in agricultural land improves our understanding of the adaptation of crops to a warmer climate. Winter wheat–maize and winter wheat–cotton double-cropping are practised in most agricultural areas in the North China Plain. A curve-fitting method is presented to derive winter wheat phenology from SPOT-VEGETATION S10 normalized difference vegetation index (NDVI) data products. The method uses a double-Gaussian model to extract two phenological metrics, the start of season (SOS) and the time of maximum NDVI (MAXT). The results are compared with phenological records at local agrometeorological stations. The SOS and MAXT have close agreement with in situ observations of the jointing date and milk-in-kernel date respectively. The phenological metrics detected show spatial variations that are consistent with known phenological characteristics. This study indicates that time-series analysis with satellite data could be an effective tool for monitoring the phenology of crops and its spatial distribution in a large agricultural region.

Keywords: winter wheat; phenology; SPOT-VEGETATION; time series

1. Introduction

Global land surface temperature has increased during the twentieth century by about 0.74 °C (IPCC 2007). According to the 2007 report of the Intergovernmental Panel on Climate Change, the ‘best estimate’ of future warming is 3.4 °C by 2100, with a likely range from 2.0 to 5.4 °C. In China, the annual mean air temperature is predicted to increase 2.3–3.3 °C by 2050 compared with 2000 levels (PRC 2007). Phenological developments such as leaf expansion and grain-filling are key physiological processes of crops and are strongly influenced by temperature (Sadras & Monzon 2006). Phenological development in agricultural land indicates a crop’s adaptation to its environment. Therefore, monitoring phenological changes in croplands could improve our understanding of their biological responses to a warmer climate.

The phenology of a specific crop type can be documented at local agrometeorological stations (e.g. Schwartz 1994; Menzel et al. 2006). When recorded at plot scales, however, these ground observations limit our interpretation of large-scale phenological patterns and the biological responses to global climate change (Schwartz et al. 2006). Remote sensing technologies provide promising data sources for monitoring phenology because of the...
large spatial coverage and frequent observations of satellite systems. Long-term time-series satellite images have been applied in phenology studies in recent decades. Among these data-sets, the most common ones are those acquired by the advanced very high resolution radiometer (AVHRR) onboard the National Oceanic and Atmospheric Administration (NOAA) satellite series since 1982 (Justice et al. 1985; Reed et al. 1994; Moulin et al. 1997; Myneni et al. 1997). The AVHRR-normalized difference vegetation index (NDVI) products are developed to examine phenological characteristics all over the globe. The NDVI represents normalized spectral variation and optimally represents greenness and productivity on vegetated land surfaces (Kidwell 1998). More recently, phenological studies have been enhanced with more data-sets that have coarse resolutions and global coverage, such as those from the VEGETATION sensor onboard SPOT-4 since 1998 and the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Terra and Aqua satellites since 1999 and 2002, respectively. These instruments record more accurate radiometric and geometric properties of Earth’s surface because of their improved atmospheric correction and cloud-screening techniques (Huete et al. 2002; Maisongrande et al. 2004).

Various methods have been developed to derive vegetation phenology. A common method is to assign an NDVI threshold to mark the onset of vegetative growth (Lloyd 1990). This threshold, however, varies with vegetation types, soils and climate conditions (Reed et al. 1994). It is difficult to define a unique, single threshold to represent the onset of greenness in large geographic regions. In order to explore the variability of phenological characters for different land cover types, the strategy of trend analysis of NDVI time series on a pixel-by-pixel basis has been proposed. Phenological models and curve-fitting methods were used to identify the occurrence of significant phenological events (Zhang et al. 2003). The TIMESAT programme is developed to process time series of vegetation indices derived from satellite-based spectral measurements (Jönsson & Eklundh 2002, 2004). These methods have been successfully applied in deciduous forests and grasslands that are less disturbed by human activities (Heumann et al. 2007; Soudani et al. 2008). For example, Fisher and Mustard (2007) and Fisher et al. (2006) used two multiplicative sigmoid models modified from Zhang et al. (2003) to extract the phenological metrics of deciduous forests from MODIS and Landsat images. Delbart et al. (2006) extracted phenological data in boreal regions using a normalized difference water index derived from SPOT-VEGETATION imagery.

The phenological characteristics of croplands, however, can be complicated. Zhang et al. (2006) found that crops might have multiple growth and senescence cycles under different agricultural practices, making it more challenging to extract phenological metrics. Specific methods are developed to detect phenological stages of main crops in China (Zhang et al. 2004; Lu & Guo 2009). The phenological growth stages of winter wheat are first monitored with NOAA NDVI data in the North China Plain (Xin et al. 2001). However, the short growth cycle of rotated crops and high level of noise sometimes make it difficult to determine the growth and senescence cycles of winter wheat within a single year (Yan et al. 2010). The objective of this study is to develop a curve-fitting approach to enhance phenological extraction for winter wheat from a time series of SPOT-VEGETATION products. A simulation is developed to extract wheat phenology in the North China Plain, an important wheat production region in China. The satellite-derived vegetation phenology is then analysed and compared with observation records at local agrometeorological stations.
2. Materials and methods

2.1. Study region and data-set

2.1.1. Study region and crop phenology

The North China Plain is the largest agricultural region in China. It extends from 113° to 120° E longitude and 32° to 42° N latitude, covering three provinces (Shandong, Hebei and Henan) and two municipalities (Beijing and Tianjin) in northern China (Figure 1). The total area of the North China Plain is about 541,000 sq km. This land produces 64.53 million tonnes of wheat, which is 56% of the country’s total wheat production in 2011 (National Bureau of Statistics of China 2011). Within the context of climate change, it is very important to monitor winter wheat phenology in the plain for food security in China.

The landscape of the plain is dominated by wide, gentle alluvial and diluvial floodplains with an average elevation of 70 m above sea level. The climate is a typical temperate monsoon followed by a mild winter and there are, about 200 frost-free days per year. More than 60% of the plain is covered by cultivated agricultural lands. Except for the northern part of the plain, where spring maize and spring cotton (single-cropping system) are planted due to the cold climate, winter wheat–maize and winter wheat–cotton double-cropping is commonly practised in the plain. The growth cycle of winter wheat is about 230–260 days. It is sown in late September to early October, and begins to grow until entering a dormant stage as the temperature drops in winter. The plant renews its active growth cycle in the spring and is generally harvested in early summer. Winter wheat progresses through several major growth stages during its life.

Figure 1. The study region and local agrometeorological stations. The underlying image is a VEGETATION NDVI composition acquired on May 1 (R), July 1 (G), and November 21 (B), 2005. Winter wheat fields have a red/magenta tone in the image.
cycle, including germination, seedling, tillering, jointing, booting, tasseling (heading), flowering, milk, the dough stage and maturity (Tottman et al. 1979). Meteorological conditions affect the length of each growth stage and, ultimately, the grain yield.

2.1.2. Satellite imagery

Time series of VEGETATION imagery was the primary data source in this study. The SPOT-4 VEGETATION sensor acquires data in four spectral bands: blue, red, near infrared and short-wave infrared, with a daily revisit capability at the 1 km spatial resolution. The 10 day synthesis (S10) NDVI product has been developed from daily images acquired in a ten-day period based on a maximum value composite technique (Holben 1986). Since the phenological records of in situ observations are relatively complete during the period 2003–2007, a total of 180 scenes of VEGETATION S10 NDVI products obtained during these five years are downloaded. The S10 NDVI products are stored as 8-bit images with digital numbers (DN) in a range of 0–255. The original DN values are transformed to real NDVI in a range of 0–1 using the calibration formula:

$$\text{NDVI} = \frac{(\text{RAW} - 0.004)}{0.1}$$

where RAW is the original pixel value.

A medium-resolution land cover map, the Globcover land cover product developed by the ESA Globcover Project (http://ionia1.esrin.esa.int/) served as a reference map of the study region. The product is derived from an automatic, regionally-tuned classification of a time series of ENVISAT MERIS FR mosaics covering a period from December 2004 to June 2006. Its 22 global land cover classes are defined using the UN Land Cover Classification System. Among these classes, post-flooding or irrigated croplands, rain-fed croplands and mosaic cropland were defined as agricultural fields for the purpose of this study. After resampling to the same resolution as the VEGETATION data (1 km), the 18 non-crop classes were merged into the ‘non-crop’ class and were masked out in this study.

2.1.3. Ground phenological records and sample sites

In general, winter wheat is planted in October and harvested in June of the following year. Yearly phenological data for major agricultural regions are archived at the National Meteorological Information Centre (NMIC) of China. Data in this study are recorded at the 17 agrometeorological stations established in the North China Plain (marked in Figure 1). For winter wheat, the Julian dates (Day of Year, or DOY) of the five phenological stages (greenup, jointing, tasseling, milk and maturity) recorded at each station are requested. The NMIC Phenology Observation Guide provides the criteria and instructions for recording each phenophase. After winter dormancy, the colour of wheat leaves turns green with the rising spring temperature (greenup stage). After head formation is complete, the stem begins elongating. The stage of jointing is identified when the first node of the stem is 2 cm higher than the soil surface. Tasseling is considered to have occurred when half of the head emerges through the slit of the flag leaf sheath. About 10 days after flowering, the wheat kernel begins to grow as a milky fluid and enters the milk stage. As the milk stage progresses, the kernel becomes hard and is ready for harvest as it enters maturity.
As marked in Figures 1 and 3 of the 17 sites are used as training sites and the other 14 serve as validation sites. The three training sites, Dingzhou, Jining and Zhengzhou, expand from the north to the south of the plain.

2.2. Time-series analysis and phenological metrics extraction

Close to each training station, 10 pure winter wheat pixels are randomly selected as sample points. NDVI at each sample point was then extracted from 180 VEGETATION S10 products acquired from January 2003 to December 2007 to create a five-year time series of NDVI values at this point. As shown in (Figure 2), the NDVI values of winter wheat follow the growing cycle and rotation with other crops in the plain, mostly

Figure 2. The five-year NDVI values from the SPOT-VEGETATION time series in three training sites: (a) Dingzhou (38.51°N, 113°E), (b) Jining (35.45°N, 116.58°E), and (c) Zhengzhou (34.72°N, 113.65°E).

Figure 3. Comparison between (a) SOS and jointing and (b) MAXT and milk date at 14 validation sites, 2003–2007.
maize. The NDVI curves in (Figure 2) display similar patterns and show peak values during April and May (DOY 90–150). There is an NDVI minimum in June (DOY 150–180) after winter wheat is harvested. From July to October (DOY 180–270), the second growth cycle of double-cropping can be observed.

Time-series curves reveal growth trends, but are still affected by temporal variations caused by residual clouds and atmospheric conditions. In this study, time-series curves are smoothed with the Savitzky–Golay filter (Savitzky & Golay 1964). Using a second-degree least-square polynomial fit, the filter effectively preserves primary curvatures (Chen et al. 2004) while smoothing out noises from residual clouds and other effects (Wang et al. 2011).

In this study, two important phenological indicators of winter wheat are examined. One is referred to as the ‘start of season’ (SOS) that represents the start of the active growth cycle in the spring. It is defined as the date when the derivative of the NDVI composite series reaches its maximum. As the steepest point of the Gaussian function, it can be envisioned as the date when most leaves are likely to emerge (Fisher et al. 2006; Bradley et al. 2007; Fisher & Mustard 2007). The other is referred to as the ‘time of maximum NDVI’ (MAXT) that represents the transition between the end of vegetative stage and the beginning of the reproductive cycle for development of reproductive organs. It is defined as the the date of the maximum NDVI value in the time-series curve.

With sample points at the training sites, statistical properties of the five-year time series are analysed. For a typical double-cropped winter wheat pixel, the variation in NDVI between two growth cycles can be represented by a combination of two symmetric Gaussian functions. The equation can be given as:

\[
v(t) = a_1 e^{-\frac{(t - b_1)^2}{c_1^2}} + a_2 e^{-\frac{(t - b_2)^2}{c_2^2}}
\]

where \(v(t)\) is the NDVI observed at time \(t\) (DOY). Parameters \(a_1, b_1, c_1, a_2, b_2\) and \(c_2\) are fitting parameters, among which \(a_1\) and \(a_2\) are the amplitudes of the two Gaussian functions.

The parameters in Equation (2) are determined in an iterative process with predefined convergence criteria. Given an initial estimate for each coefficient, the model parameters are calculated using the Levenberg–Marquardt method following a non-linear least-square fit (Levenberg 1944; Marquardt 1963). With Equation (2), the NDVI trajectory is simulated and dates of phenological metrics (SOS and MAXT) are extracted.

At the 14 validation sites, correlation analysis is performed to compare the two data-sets, the phenological metrics derived from VEGETATION data and ground phenological records. To reduce the impact of the spatial heterogeneity around each station, 25 wheat pixels at each ground station were randomly selected within a distance of 5 km and their average SOS and MAXT values were calculated to represent the image-derived results at this station. The statistics used for the correlation analysis were the Pearson correlation coefficient, the root mean square error (RMSE) and the bias (average residual) between remotely sensed phenological metrics and predicted values from ground observations. The RMSE was used to evaluate the prediction uncertainty relative to in situ observations. The bias was used to evaluate the overestimation (positive bias) or underestimation (negative bias) of phenological dates.
3. Results

3.1. Comparison with ground phenological observations

The statistical properties of ground observations and remote sensing phenological metrics are compared at the 14 validation stations (Table 1). The average date of SOS (DOY 97) is only two days later than the date of jointing (DOY 95), which suggests that these are comparable phenological indicators. The average milk date (DOY 145) is very close to MAXT (DOY 151), indicating that MAXT, as defined in this study, may reflect the milk stage. The standard deviation of MAXT has a good agreement with the standard deviation of the ground observations. The standard deviation of SOS (25 days), however, is much larger than that of the in situ observations (<11 days).

Correlation coefficients of the phenological metrics extracted from the images and obtained from observation made on the ground are listed in (Table 2). Both SOS and MAXT show positive relationships for the five ground-recorded metrics (greenup, jointing, tasseling, milk, and maturity). The SOS and jointing are significantly correlated, having a correlation coefficient ($r$) of 0.724 and the lowest RMSE value (18.7 days). The MAXT extracted from the satellite data is closely correlated with the date of the milk stage where $r = 0.750$ and an RMSE value of 12.7. Both jointing and milk stages are overestimated and have positive bias values of 3.2 and 10.8 days with SOS and MAXT, respectively.

The linear relationships for SOS–jointing and MAXT–milk are observed in (Figure 3). The regression line deviates from the 1:1 line of the scatter plot. There is a slightly higher correlation between MAXT and milk ($R^2 = 0.536$) than between SOS and jointing date ($R^2 = 0.522$).

3.2. Phenological patterns of winter wheat in the North China Plain

The average SOS (Figure 4(a)) and MAXT (Figure 4(b)) in 2003–2007 extracted from the VEGETATION time series reveal the geographic variations that shift from southern to northern areas of the North China Plain. In the south, the SOS occurs during DOY

---

Table 1. Average statistics of phenological metrics from ground observations at agrometeorological stations and SPOT VEGETATION NDVI time series.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Greenup</th>
<th>Jointing</th>
<th>Tasseling</th>
<th>Milk</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>57</td>
<td>95</td>
<td>117</td>
<td>145</td>
<td>158</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>11</td>
<td>11</td>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metric</th>
<th>SOS</th>
<th>MAXT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>97</td>
<td>151</td>
</tr>
</tbody>
</table>

| Table 2. Comparative analyses between phenological metrics from ground observations at agrometeorological stations and SPOT VEGETATION NDVI time series (five-year average). |

<table>
<thead>
<tr>
<th>Metric</th>
<th>Greenup</th>
<th>Jointing</th>
<th>Tasseling</th>
<th>Milk</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOS</td>
<td>RMSE</td>
<td>Bias</td>
<td>$r^a$</td>
<td>SOS</td>
<td>MAXT</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>----------</td>
<td>-----------</td>
<td>------</td>
<td>----------</td>
</tr>
<tr>
<td>RMSE</td>
<td>46.6</td>
<td>99.2</td>
<td>18.7</td>
<td>63.7</td>
<td>51.2</td>
</tr>
<tr>
<td>Bias</td>
<td>41</td>
<td>99.2</td>
<td>3.2</td>
<td>64</td>
<td>-46.7</td>
</tr>
<tr>
<td>$r^a$</td>
<td>0.458</td>
<td>0.486</td>
<td>0.724</td>
<td>0.766</td>
<td>0.681</td>
</tr>
</tbody>
</table>

*aAll Pearson’s coefficients of correlation are statistically significant at 95% confidence interval.
60–90 (shown in red in Figure 4(a)). Later, SOS (DOY 120–150) dates are observed in northern and northeastern areas (blue and yellow in Figure 4(a)). After occurring between DOY 90 and 120 in the south (red and yellow in Figure 4(b)), the MAXT spreads towards the north (blue in Figure 4(b)).

Figure 4. Spatial distributions of winter wheat phenological metrics, (a) SOS and (b) MAXT, in the North China Plain.
The latitudinal shifts in the winter wheat calendar over the North China Plain were also examined (Figure 5). The relationships between the phenological metrics (SOS and MAXT) and latitude were compared for pixels at the 14 validation sites for the period 2003–2007 (Figure 5(a)). The relationships between latitude and the corresponding jointing and milk dates taken from the ground records of the 14 stations were also explored for the same period (Figure 5(b)). At the regional level, the graphs have a slope of five to seven days per degree of latitude for the SOS and MAXT dates extracted from the imagery, while for the milk dates obtained from ground records the slope is less steep (about 2–5 days per degree).

4. Discussion

The SOS and MAXT were extracted from SPOT-VEGETATION NDVI time series as phenological indicators of winter wheat. Comparing these with the in situ observations, the results indicate that the SOS is comparable to the dates of jointing and the MAXT is comparable to milk stage. The spatial patterns of SOS and MAXT are consistent with the known phenological characteristics in the North China Plain. This study provides an effective method for monitoring growth conditions of winter wheat in large agricultural fields with satellite data.

The double Gaussian model developed in this study improves the capability of extracting phenological transition dates of winter wheat. The model combines two Gaussian functions to reflect double-cropping practices, where the growth cycle of winter wheat is better simulated. The phenol-phases phenological metrics detected from remote sensing data depend to a great extent on the climatic–ecological zones of the study region. For single season ecosystems such as deciduous forest, the correspondence between vegetation growth stages and temporal fluctuation of NDVI is simple (Ahl et al. 2006; Fisher et al. 2006; Fisher & Mustard 2007). Due to the complexity of the phenological characteristics of winter wheat in double-cropping systems, the correspondence between in situ observations and corresponding markers of NDVI time series seems relatively complicated. The double Gaussian approach optimally identifies the two growing cycles and therefore, improves the accuracy of phenology extraction of winter wheat.

The large deviation between remotely sensed and ground-recorded metrics in (Figure 3) may come from different recording. The VEGETATION NDVI products
contain land surface information at 1 km by 1 km resolution at ten-day intervals. Ground
records at local stations, on the other hand, are the dates of occurrence of a limited
number of phenological events at plot scales. Although closely related, these two types
of data could be different from each other in spatial and temporal dimensions. Specif-
ically, the greenup dates at stations are recorded as the dates when some plants are
observed in field to start growth while the majority of plants still appeared dormant. In
early growing days, the plants are short and in recovery from winter dormancy. The
NDVI at this time is inevitably influenced by the soil background and surrounding veg-
etation in the case of data with a 1 km by 1 km resolution. Through comparative analy-
sis, the image-extracted SOS correlates well with the jointing stage instead of greenup
for winter wheat (Table 2). Instead, the SOST correlates better with the jointing stage
and has a bias value of 3.2 days. A possible reason for the higher correlation between
MAXT and milk than between SOS and jointing dates is the reduced background noise
when plants reach peak growth.

The latitudinal shift observed in this study agrees with the results of past studies.
Zhang et al. (2003) reported that the onset of greenness in both natural and cultivated
cropplands displayed a shift of around two days per latitude degree along a 40° to 45° N
latitude transect in North America. Wang et al. (2011) also found that corn and soybean
fields in the US Midwest have a shift of two days per degree in their peak dates, while
pasturelands have a peak date shift of three days per degree. As shown in (Figure 5),
the shift of SOS and MAXT may indicate that the remote sensing images captured the
spatial heterogeneity of winter wheat phenology in the plain, such as the delay in the
jointing stage along latitudinal transect that is related to climate variation in a large
region. However, the relatively larger magnitude of the shift in remote sensing data can
be attributed to the uncertainties of phenological metrics estimation which might be
caused by the mixed pixels that are common in km-resolution images, data noise
together with the ten-day intervals of the time-series data.

This study demonstrates an efficient way to monitor large agricultural regions domi-
nated by specific crops. In multi-crop agricultural lands, different phenological models
can be established and integrated to extract phenological features for a specific crop for
further investigation.

5. Conclusion

This study develops a double Gaussian model to fit the growth cycle of winter wheat in
double-cropping practices. With this approach, the SOS and time of maximum NDVI
(MAXT) are extracted from a time series of SPOT-VEGETATION data in the North
China Plain. By comparing the results with the five-year phenological ground records
of 14 validation sites, the SOS and MAXT derived from the satellite data were found
to be in close agreement with the jointing dates and milk-in-kernel dates, respectively,
that were derived from the in situ observations. The spatial variations of winter wheat
phenology are captured using the satellite data. This spatially explicit information could
be used to assist crop monitoring in a large region.

Acknowledgements

The authors are grateful to the China Meteorological Administration for providing the
phenological observation data. We also thank Dr Per Jönsson, Malmo University, and Dr Lars
Eklundh, Lund University, for their help with the TIMESAT software application. This research is

L. Lu et al.
supported by the Director Foundation of Center for Earth Observation and Digital Earth, Chinese Academy of Sciences and the National Natural Science Foundation of China under grant no. 41101393.

References


