An improved threshold method to detect the phenology of winter wheat

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***Abstract*—Crop phenology information is an important agricultural information which can offer key references for agricultural production, field management, and planning decisions. Generally, it is also considered as an important parameter for crop models. It is of great theoretical and practical significance to understand the features of phenological changes in estimating and forecasting crop production, monitoring and protecting the ecological environment. In the past three decades, the development of remote sensing technology has provided a new means for phenological monitoring and research. The vegetation index (VI) produced by remote sensing data can accurately reflect the vegetation coverage information, which provides conditions for the use of remote sensing to monitor plant phenology. For regional scale, dynamic threshold is the most commonly used method. However, the value of dynamic threshold is usually determined by empirical value, which is lack of quantitative determination method. An improved method based on dynamic threshold method to extract the spatial and temporal pattern evolution of winter wheat SGS and EGS in the North China Plain by using MODIS EVI 8-day time series data and ground-observed phenology calendar data was provided. The regression model of threshold and phenological parameters was constructed based on the relationship between threshold value and corresponding date. The accuracy of the simulated phenological parameters, including the start time of growing season (SGS) and the end time of growing season (EGS), was verified by the ground observation phenological data. The results show that both SGS and EGS had a significant correlation with threshold value for winter wheat. The result of the accuracy verification shows that the phenological parameters for remote sensing inversion using this method have appropriate reliability and can replace the ground observation data. Finally, according to the threshold values determined by this method, spatial maps of the phenological parameter in the study area were generated.**

Keywords—remote sensing, winter wheat, phenology detection, dynamic threshold, EVI, time series

I. Introduction

Phenology refers to the natural phenomenon that organisms in nature are affected by climate and other environmental factors and appear on an annual quasi-periodic basis [1-2]. The crop phenological stage is the date when crops reach the critical growth stages (such as returning to green stage, jointing stage, heading stage, and maturity stage of wheat). The dynamic change of crop phenology reflects how climate change affects the growth and development of crops, which is an important indicator of the impact of climate change on agricultural ecosystems [3-6]. Therefore, it has become one of the hot issues in the study of global climate change.

Crop phenological information can be obtained by field observation, accumulated temperature prediction and remote sensing monitoring. However, the field observation method is not only time-consuming and laborious, but also represents a limited area [7]. The forecasting method of accumulated temperature needs information such as sowing date, daily air temperature and accumulated temperature for a certain growth period [7]. Satellite observation has the ability of large area coverage and repeated sampling. In recent years, the study of vegetation phenology extraction from remote sensing data has been carried out in large numbers[8-12].

Generally, there are three methods to obtain vegetation phenological stages based on remote sensing, including threshold method, curve characteristic method, and mathematical analysis method[13]. Although the curve feature method and mathematical analysis method can effectively reflect the differences in the growth process of different crops, the process is complex and the accuracy of the results is greatly affected by the quality of data. In contrast, the threshold method is commonly used to detect phenological parameter because of its simplicity and flexibility[14]. The most important feature of threshold method is to use the date when vegetation index reaches a certain value to determine the phenological stage. When setting thresholds, however, the selection is usually empirical and subjective, lack of a set of reasonable quantitative methods[7].

Wheat is one of the main food crops in China. The annual sown area and total yield are second only to rice and maize. The North China Plain (NCP) is the main wheat production base in China, in which winter wheat is the main crop. Therefore , in this study, an improved threshold method was proposed to detect the star time of growing season (SGS) and end time of growing season (EGS) for winter wheat in NCP. The method used MODIS EVI time series data, ground-observed phenology data, and Asymmetric Gaussians filtering function (A-G) to determine the optimal thresholds.

II. Data

A. Remotes sensing data

Compared with MODIS-NDVI product, the MODIS-EVI product is more suitable for detecting crop phenology after eliminating the saturation problem [15-16]. MODIS EVI data for 2003-2013 with a spatial resolution of 250m and a temporal resolution of 8 days was obtained from NASA's Land Processes Distributed Active Archive Center (LP DAAC). Data corrections had already been processed to improve data quality, including atmospheric and geometric correction and resampling.

Cropland grid with 1km spatial resolution across NCP was accessed at the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC, CAS; http://www.resdc.cn)[17] (Fig. 1).

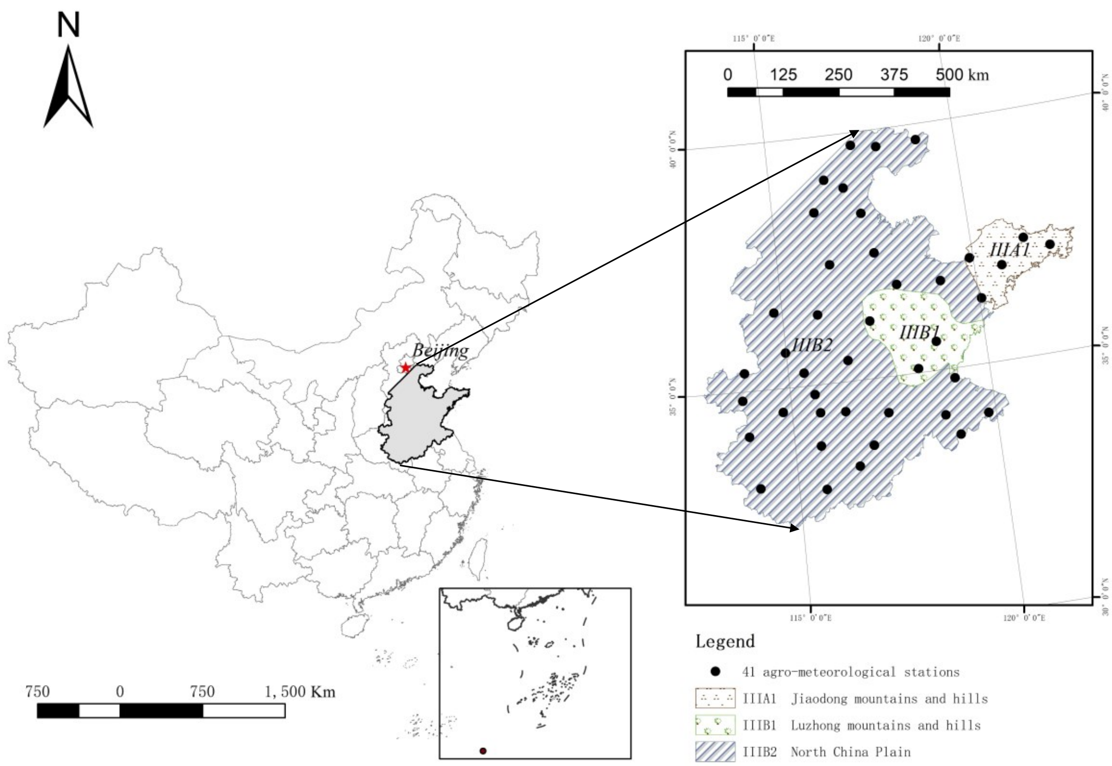


Fig. 1. Map of agro-meteorological stations distribution in study area

B. Ground-Observed Phenology Data

In situ observation data of SGS and EGS of winter wheat at 41 agro-meteorological stations was accessed at China Meteorological Administration (CMA). In this study, we defined the SGS of winter wheat as the time of returning-green, while defined the EGS as the time of harvesting stage. All date formats were converted to Julian day of year (DOY). Statistical analysis was used to calculate multi-year average of SGS and EGS for the study area based on 2003-2013 data from all 41 stations. As a result, the multi-year average DOY of SGS ($\overline{SGS}$)and EGS ($\overline{EGS}$) are 55.95 and 156.53, respectively.

III. Method

In this study, phenological stages of winter wheat in study area, SGS and EGS, were mapped through three distinct phases. Firstly, the EVI data was preprocessed to reconstruct the EVI time series curves, furthermore, to remove the cloud contamination [18]. Secondly, a modeling method was used to determine threshold values for SGS and EGS. Finally, the simulated threshold values were used to detect the SGS and EGS and the results were verified with ground-based observation data.

A. Data preprocessing

Although part of cloud and aerosol contamination can be removed from EVI product generated by the maximum value composite (MVC) method, there are still residual cloud and haze or other noises that cannot be removed. Therefore, the Asymmetric Gaussians filtering function is used to eliminate noise and reconstruct a high-quality EVI-time series dataset. This method is a process from local fitting to global fitting, which is flexible, and the reconstructed EVI time series can better describe the complex and small changes in the data [7]. The equation of Asymmetric Gaussians filter could be expressed as follows:

$$f(t) = f(t; c_1, c_2, a_1, \dots, a_5) = c_1 + c_2 g(t; a_1, \dots, a_5) \quad (1)$$

$$g(t; a_1, \ldots, a_5) = \begin{cases} exp\left[-\left(\frac{t-a_1}{a_2}\right)^{a_3}\right] & (if\ t > a_1) \\ exp\left[-\left(\frac{a_1-t}{a_4}\right)^{a_5}\right] & (if\ t < a_1) \end{cases} \quad (2)$$

Where c_1 and c_2 determine the base level and the amplitude, a_1 is the position parameter for the peak or valley value of the time variable t, and a2, a3, a4, a5 are the width and flatness (kurtosis) of the left and right function half, respectively.

B. *Determining thresholds for phenology detection*

The proposed method was improved based on the threshold method, in which the phenological stage was assumed to occur when EVI reaches to a certain value [19]. Based on existing research, the two major stages, SGS and EGS, were defined when the EVI value equal to x_1% and x_2% of the difference between the maximum and minimum value in the rising and decline curves, respectively. The equations are as follows:

$$EVI(SGS) = (EVI_{max} - EVI_{min}) * x_1\%(SGS = 1,2, \ldots) \quad (3)$$

$$EVI(EGS) = (EVI_{max} - EVI_{min}) * x_2\%(EGS = 1,2, \ldots) \quad (4)$$

First, set the equal difference sequence to x_1 and x_2 at 5% interval, from 5% to 95%. Then the corresponding dates were estimated according to the formula 3 and 4, marked as SGSX1 and EGSX2 for convenient representation. Next, the regression model method was used to analyze the relationship between x_1 and *SGSX1 and* x_2 and *EGSX2*. Finally, the $\overline{SGS}$ and $\overline{EGS}$ derived from ground-based observations data were brought into models established in the previous step. Then new threshold values specific to winter wheat in the study area were output.

C. *Model validation*

To validate the remote sensing-based detection results, the average phenological information of a 5 × 5 window centered at each station was extracted to compare with ground-based observation phenology. In this study, the coefficient of determination (R^2) and root mean square error (RMSE) were used to verify the extraction accuracy. The equation of RMSE are as follows:

$$RMSE = \sqrt{\frac{\sum_i^N (x_i - y_i)^2}{N}} \quad (5)$$

Where x_i is the estimated value derived from the new threshold method, y_i is the in situ data, and N is the total number of paired samples.

IV. RESULTS AND ANALYSES

A. *Phenology detection thresholds*

Fig.1 show the relationships between x_1 and *SGSX1 and* x_2 and *EGSX2*. Results show that in the rising phase of EVI time series curve, with the increase of x_1, the *SGSX1* increases, and the increasing rate decreases gradually (Fig. 1a). This trend can be described by the left branch of the inverted parabola, which offered the best performance after making a comparison with other models including linear, exponential, and logarithmic models. However, the relationship between x_2 and *EGSX2* showed a significant linear decline in the descending stage (Fig. 1b). The simulation equations for SGS and ESG are as follows:

$$SGSX1 = -27.813{x_1}^2 + 61.815x_1 + 53.026 \quad (6)$$

$$EGSX2 = -64.469x_2 + 188.86 \quad (7)$$

In the regression models of SGS and EGS, the R^2 values are 0.993 (P<0.01) and 0.973 (P<0.01), respectively, which show that both models can simulate the relationship between thresholds (x_1 and x_2) and corresponding dates (*SGSX1* and *EGSX2*) well.

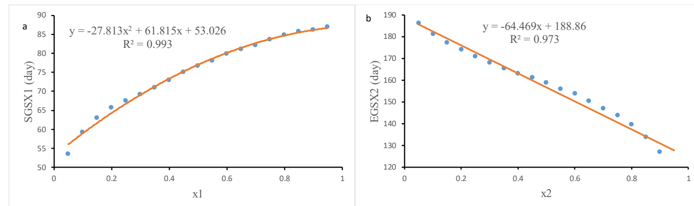


Fig. 2. Fitting results with SGS (a) and EGS (b)

According to ground-based observations, the $\overline{SGS}$ and $\overline{EGS}$ are 55.95 and 156.53, respectively. The above values were brought into the formula 6 and 7, respectively, and the corresponding thresholds to detect the SGS and EGS of winter wheat in the study area were determined, which is 4.8% and 50.2%. Compared with the existing literature, threshold to detect the EGS proposed in this study consistent with most studies [7,13,20]. However, our threshold to detect SGS is far lower than other results.

B. *Accuracy verification of Detection Results*

We used the in situ observation data from 41 local agro-meteorological stations for 2003-2013 to verify the estimated SGS/EGS date of winter wheat based on MODIS EVI time series data at multi-year average level and yearly level, presented in Figs. 3 and 4.

For SGS, there is a significant positive correlation between in situ observation data and simulated data, with the coefficient of determination (R^2) both greater than 0.5 (0.53 and 0.56, respectively) and lower RMSE (<12 days), at multi-year average level and yearly level (Fig. 3a and Fig. 4a). Considering the temporal resolution of the EVI data, the proposed method has satisfactory accuracy for extraction of SGS.

For the detection of EGS dates, similarly, there is a significant positive correlation between the observed values and the simulated values, with the R^2 both greater than 0.45 (0.48 and 0.65, respectively) . Although the R^2 of EGS is greater than SGS, the RMSE of EGS is also higher (14.07 days). Possible causes include a lower solar angle in the autumn, which exacerbates the effects of the atmosphere, and the double cropping system, leading to the time of winter wheat harvest and summer maize planting closely connected and difficult to distinguish in time.

As mentioned in the introduction, when threshold method used in previous studies, the threshold values are usually set empirically and the phenological extraction accuracy is often not very high. This method can provide quantitative threshold standard for specific crop varieties, thus improving the accuracy and applicability of dynamic threshold method.

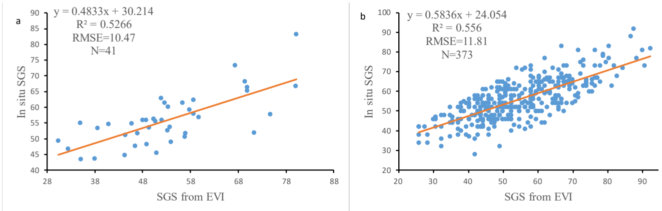


Fig. 3. Comparison of in situ data with model simulation results in SGS date (DOY): (a) at multi-year level; (b) at yearly level.

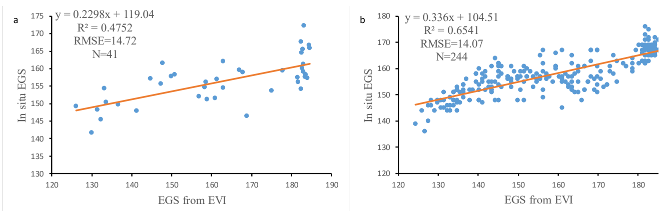
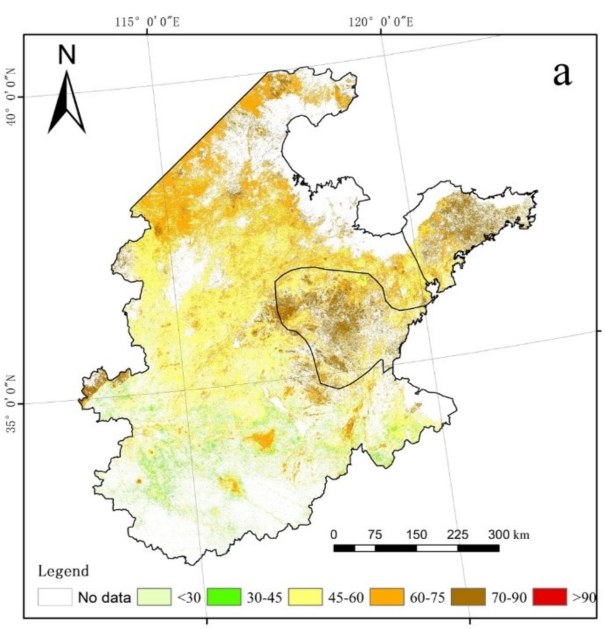


Fig. 4. Comparison of in situ data with model simulation results in EGS date (DOY) : (a) at multi-year level; (b) at yearly level.

C. *Maps of the phenological events*

Fig. 5 shows the multi-year average of start and end of the growing season (SGS and EGS) in 2003-2013 as detected by the proposed method.

Results shown that the distribution of time of returning-green tends to advance gradually from north to south (Fig. 5a). There is a gradual delay from inland to coastal areas for both SGS and EGS stages (Fig. 5a and 5b). In addition, the distribution of phenological period is also characterized by terrain differentiation, and the SGS period in hilly and mountainous areas is obviously later than that in plain areas (Fig. 5a).



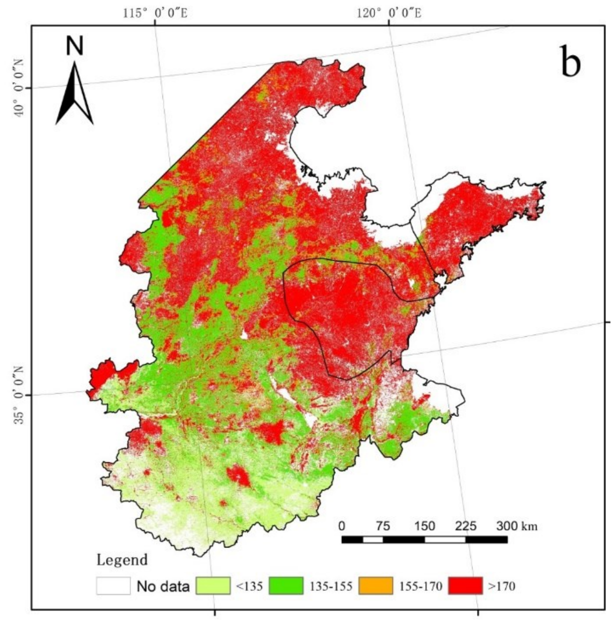


Fig. 5. Maps of the SGS (a) and EGS (b) at multi-year average level, 2003-2013

V. Discussion and Conclusion

In summary, we proposed an improved method based on dynamic threshold method to extract the spatial and temporal pattern evolution of winter wheat SGS and EGS in the North China Plain by using MODIS EVI 8-day time series data and ground-observed phenology calendar data. To do so, Asymmetric Gaussias filtering method was used to smooth the EVI curves to reduce noise. The regression model was established based on the relationship between threshold value and corresponding DOY, which is used to invert the thresholds suitable for phenological extraction of winter wheat in the study area. Finally, the updated thresholds was used to detect the SGS and EGS stages in the study area. The results show that the winter wheat phenology stages obtained by remote sensing inversion using the method demonstrated here, have appropriate reliability and can replace the ground observation data.

Traditional phenological detection methods are proposed for natural vegetation, but crops are affected by human management factors, so the applicability of crops is poor, or more complex methods are needed [7]. In this study, we use field observation data to retrieve the threshold, and then detect phenological period, which can eliminate the impact of human activities to a certain extent.

The main limitation of this method is that the field observation stations must be able to cover or represent the whole research area, and the threshold derived from this method needs to be updated periodically. Another limitation is the temporal and spatial limitations of MODIS data. The time resolution and rough synthesis products by using MVC method, can not guarantee the continuity of the time series curve. The ground-observed data is one-dimensional point data, while the MODIS-EVI data is two-dimensional raster data. The two data do not match, so there is a scale problem. In this paper, we try to use a certain area around the agro-meteorological station to represent the situation of the station, so as to match with the remote sensing data, but still could not avoid the problem of mixed pixels. In the future, we could try to improve the extraction accuracy by using higher spatial and temporal resolution image.

Furthermore, the applicability of the method to other crop varieties, such as maize, rice and soybeans, needs further study. The accuracy evaluation between the proposed method and the traditional method also need to be supplemented.

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