Detecting major growth stages of paddy rice using MODIS data

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Abstract: Phenological information of paddy rice is important for area extraction and growth monitoring. The purpose of this study is to detect the major phenological stages of paddy rice over China using remote sensing data. Time-series Terra moderate-resolution imaging spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) was smoothed with the low pass Fourier and wavelet filtering methods, then the stages of transplanting, beginning of tillering, heading, and maturation were obtained according to their characteristics. The paddy rice stages in 2005 derived from this study were significantly positive correlated and consistent with the statistical data ($P < 0.05$), and most of the absolute errors were less than 16 d. The methods presented in this study could be applied in other years, as well as the ability to generate the growth stages of other crops.

Key words: remote sensing, MODIS, EVI, paddy rice, growth stage, phenology

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1 INTRODUCTION

Remote sensing technology has the advantages of acquiring images macroscopically and periodically. It is a feasible and efficient way to monitor phenological information at a large scale.

Previous researches have been implemented to acquire phenological information by remote sensing data. For example, Tucker et al. (1979) used hand-held radiometer data to monitor the development of corn and soybean in their test fields. As the development of high temporal resolution satellites, such as NOAA-AVHRR, EOS-MODIS and SPOT-VEGETATION and so on, remote sensing technology was widely used in the researches of vegetation phenology, e.g., Gallo and Flesch (1989) estimated the silking stage of corn by the AVHRR vegetation index data. Myneni and Tucker (1997) identified vegetation phenology to testify the global changes in the high-latitude regions of the northern hemisphere using the AVHRR data. Zhou et al. (2001) found that the average NDVI increased in Eurasia and north America by the AVHRR-NDVI and the recorded ground temperature data during 1981—1999. In addition, some studies indicated that the spring became earlier and the autumn turned later in the northern hemisphere (Defila & Clot, 2001; Menzel, 2000; Parmesan & Yohe, 2003; Roetzer et al., 2000; Root et al., 2003; Studer, 2005). Meanwhile, many methods were developed to determine the beginning and the end of growth. For example, the vegetation index threshold method was used by many researchers (Fischer, 1994; Justice et al., 1985; Lloyd, 1990; Markon et al., 1995). The moving average vegetation index method (Duchemin et al., 1999; Reed & Brown, 1994; Repo et al., 1996; Schwartz, 1999), i.e., it removes the noises by calculating the moving average of the time series, and then gets the intersection points of the smoothed line and the delayed one, which denote the beginning and the end of the growing season. The inflexion method (Moulin et al., 1997; Sakamoto et al., 2005; Zhang et al., 2003), i.e., if the derivative of the time-series curve is a positive number after zero, then the date can be regarded as the start of the growing season; while if it is a negative number before zero, then the date can be regarded as the end of the growth. The maximum slope method (Yu et al., 2003), i.e., it judges the growth stages by the magnitude of variation in the time series vegetation index. The method of seasonal midpoint of NDVI (Schwartz et al., 2002), i.e., it determines the beginning and the end of the growing season by judging the average of the maximum and the minimum in the smoothed time-series vegetation index. The method of plant phenology and satellite data combination (Chen et al., 2000, 2001), i.e., seasonal information is obtained by the integration of ground observation data and remote sensing data.

The detecting principle of the remote sensing method is based on the changes of the time-series vegetation index, because they represent the development of vegetation growth.
This study attempted to detect the major growth stages of paddy rice in China using multi-temporal remote sensing data, and the results might provide useful references to the planting area detection and the growth monitoring of paddy rice at a large scale.

2 DATA AND METHODS

2.1 Study area

Paddy rice is one of the major staple food crops in China, which is planted in all provincial administrative units except Qinghai. According to the statistical data (NBSC, 2007), the sown area and the output of rice were stable in recent years. The average sown area was 30276 thousand hectares during 1990—2006, accounted for 27.8% of the average total grain area (108710 thousand hectares). The average output was 184353 tons, accounted for 39.3% of the average total grain output (468548 thousand tons). Therefore, rice plays an important role in meeting the national and the international grain requirement.

The cropping system of paddy rice is different in China because of the diversity of topography and climate, as well as the influence of economic factors. According to the agricultural statistics in recent years, double rice is dominant in Guangdong, Guangxi, Hainan, and Taiwan due to prolific rains and the high temperature; it is a mixed region of double and single rice in Fujian, Zhejiang, Jiangxi, Hunan, Hubei, and southern part of Anhui and Yunnan on account of less effective temperatures and the inferior quality of double rice; and single rice is dominant in the large regions beyond the above mentioned ones.

2.2 Data

The commonly used multi-temporal remote sensing data are NOAA-AVHRR, EOS-MODIS, SPOT-VEGETATION and so on. Considering the demands of spatial and temporal resolution, Terra MODIS data were chosen for rice growth stages detection in this study. The MODIS sensor has 36 spectral bands, 7 of which are designed for vegetation and land surface studies, the main parameters of the 7 bands are listed as Table 1. The MODIS Land Team provides a suite of standard MODIS products to the users from daily as well various composite products. All the data are available freely from the Land Processes Distributed Active Archive Center (LPDAAC) (http://lpdaac.usgs.gov).

<table>
<thead>
<tr>
<th>Band</th>
<th>Range/nm</th>
<th>Name</th>
<th>Spatial resolution/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>620—670</td>
<td>red</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>841—876</td>
<td>NIR1</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>459—479</td>
<td>Blue</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>545—565</td>
<td>Green</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>1230—1250</td>
<td>NIR2</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>1628—1652</td>
<td>SWIR1</td>
<td>500</td>
</tr>
<tr>
<td>7</td>
<td>2105—2155</td>
<td>SWIR2</td>
<td>500</td>
</tr>
</tbody>
</table>

Because heavy clouds may affect the quality of the images, the 8-day composite images were used in this study to reduce the impact of clouds and to guarantee their high temporal resolution. MOD09A1 is the 8-day composite land surface reflectance product with 500 m spatial resolution. It includes the first 7 bands of MODIS, which are sensitive to land surface reflectance. Each pixel in the 8-day composite images is the best one in quality within 8 days on the basis of high observation coverage, low view angle, the absence of clouds, cloud shadows and aerosols (http://modis-land.gsfc.nasa.gov/surfrad.htm). The MODIS Land Data Operational Product Evaluation (LDOPE) facility (http://landweb.nascom.nasa.gov/cgi-bin/QA_WWW/newPage.cgi) provides a coordination mechanism for MODLAND’s quality assessment (QA) activities (Roy et al., 2002). The band of QA at the pixel level is also provided together with the reflectance data in the products. Useful information is available on the basis of the description of the MODIS 8-day surface reflectance QA information (http://edcdaac.usgs.gov/modis/moyd09a1q1_qa_v4.asp) through binary calculation. Because it chooses the best pixels within 8 days in the MOD09A1 product, and the date selection could be regarded as a stochastic phenomenon from an overall perspective, so we used the middle date within the 8 days (official date, about the fourth day) to represent approximately the acquiring date of each composite image.

2.3 Methods

2.3.1 Selection of samples

To acquire rice phenological information over China, typical samples were selected in different regions with rice cultivation. In order to reduce the impact of the background as far as possible, we selected the bigger fields or some neighboring fields that can form into a big one in the image. In this study, 198 single rice samples and 87 double rice samples were selected. In addition, to validate the effect of the MODIS-derived results, we compared the results with the in situ observed data obtained from the agricultural meteorological observatories in the same year (131 effective single rice observatories and 87 effective double rice observatories were selected).

Because the positions of the agricultural meteorological observatories are different from the selected samples, in order to validate the effect of the MODIS-derived major rice growth stages, the distribution maps of rice growth stages in the whole country were obtained by spherical models of Ordinary Kriging interpolation in ArcGIS, and then the growth stages of the selected rice samples were obtained according to the maps as the ground truth data. Effective agricultural meteorological observatories were chosen as more as possible, because the accuracy of the interpolated results relies on the quantity and the spatial distribution of the samples. The errors of the interpolated results were controlled in the range less than 8 days in this study.

2.3.2 Pretreatment of the MODIS data

To amplify the difference between the features of interest and the background, index was used to enhance the vegetation

information. As the blue band is sensitive to the atmospheric conditions, it is used to adjust the reflectance in the red band as a function of the reflectance in EVI (Eq. (1)). EVI is an improved vegetation index, which accounts for the effects of residual atmospheric contamination and soil background, and it is much less sensitive to aerosols than the NDVI (Normalized Difference Vegetation Index), and not easy to reach the saturation in the regions covered with thick vegetation (Huete et al., 1997, 2002). For the LAI (leaf area index) of rice is high in the exuberant growth stage, so we chose EVI instead of NDVI for vegetation change detection.

\[
EVI = 2.5 \times \frac{\rho_{\text{NIR1}} - \rho_{\text{red}}}{\rho_{\text{NIR1}} + 6.0 \times \rho_{\text{red}} - 7.5 \times \rho_{\text{blue}} + 1} = 2.5 \times \frac{B_3 - B_1}{B_3 + 6.0 \times B_1 - 7.5 \times B_2 + 1} \quad (1)
\]

Although the MODIS 8-day composite surface reflectance products have been strictly pre-processed to reduce the impact of clouds, shadows and aerosols, obviously residual noises still exist in the regions with lasting heavy clouds, which have a big impact to the information extraction. There are some methods for noise removing, such as the simplest method of the moving median or average. Some other more complicated methods, such as the BISE algorithm (best index slope extraction) (Vivoy et al., 1992), the Savitzky-Golay filter (Chen et al., 2004; Jönsson & Ekland, 2004; Savitzky & Golay, 1964), the Fourier-based algorithm (Cihlar, 1996; Sellers et al., 1994), and the wavelet transform function (Gillian et al., 2008; Lu et al., 2007; Sakamoto et al., 2005). We attempted to get a very smooth curve after filtering to model the process of vegetation changes. In the above mentioned algorithms, the BISE method was designed for reducing noise in the NDVI time-series NOAA satellite data initially, and which can be used to process the MODIS data. The main purpose of the algorithm is to reconstruct the time-series vegetation index for reducing the impact of cloud contamination; however, the algorithm is not suitable for seasonal information acquirement. The Savitzky-Golay method essentially performs local polynomial regression in the time-series to determine the smoothed value for each point, the main advantage of this approach is that it tends to preserve features of the distribution such as peak values and width, which are usually flattened by the simple moving average model. However, lots of noises still exist in the filtered time-series profiles for seasonal information acquirement. The Fourier-based algorithm and the wavelet transform function can model the regular changes easily with smoothed curves by removing the high frequency (local variations) components and preserving the low frequency ones. Both of them can remove the noises as far as possible in the time-series, and model the regular seasonal changes so as to reflect the characteristics of seasonal variation, thus, the two algorithms are superior to other ones for rice phenological stages determination.

The method of DFT (discrete Fourier transform), sometimes called the finite Fourier transform (Cooley et al., 1969), is a Fourier transform widely employed in signal processing and related fields to analyze the frequencies contained in a sampled signal and to perform other operations such as convolutions. The DFT algorithm is slow, but it can be computed efficiently in practice using a FFT (fast Fourier transform) algorithm. For the Fourier transform function can be transformed into the composition of sines and cosines according to the Euler’s formula, so the limitation of the Fourier transform is that it just fit for the periodic and stationary signals. While a wavelet is a kind of mathematical function used to divide a given function or continuous signal into different frequency components and study each component with a resolution that matches its scale. The advantages of using wavelet transform are that it has the abilities to represent functions that have discontinuities and sharp peaks, as well as accurately deconstruct or reconstruct finite, non-periodic or non-stationary signals. Because the seasonal change of rice is regular year by year, so both the Fourier transform and the wavelet transform algorithms are fit for removing the noises and modeling the changes.

In this study, we used the low pass filtering by FFT and DB (Daubechies) wavelet to cut off the noises in the time-series EVI. The phenomenological information of paddy rice was acquired by detecting the changes in the smoothed time-series EVI. Tests showed that the number of the window points in the low pass FFT filtering should be 4 for single rice, because the intervals of the peaks are large. If the number of the window points is too big (the larger of the window the smoother the curves will be), then the time-series curves will be flattened; if the number of the window points is too small, then there will be some peaks and cannot be used to determine the seasonal changes. Because the intervals of the peaks are small and the reflectance of late rice in the transplanting period tends to be impacted by the background, so the two peaks are not very clear. If the number of the window is too large, it might has only one peak in the profiles of the smoothed EVI and unable to get the seasonal information. Tests proved that the points of window should be 3 for double rice. We compared ten DB wavelets \((N=1, N=2, \ldots, N=10)\), and the results indicated that the DB10 wavelet \((N=10)\) was better than the others. Similarly, considering the difference between single rice and double rice, the cutoff frequency was 85.0% to remove the high frequency components for single rice (the larger of the window the smoother the curves will be), while the cutoff frequency was 75.0% for double rice. Three typical samples for single rice and double rice were selected to display the effects of noise removing by FFT and wavelet transform filtering algorithms (Fig. 1).

2.3.3 Algorithms for detecting paddy rice phenological stages

The existent period of paddy rice is from transplanting time to harvest time. In order to transplant rice seedlings, and to guarantee the healthy growth, rice fields are filled with persistent water since the flooding period because of the special physiological property of the crop. Rice is easy to be separated from other crops according to the characteristic. Therefore, the transplanting period is significant for rice identification using remote sensing technology. The period from the beginning of
tillering to the maturation is significant to the crop growth monitoring using remote sensing technology, because it is crucial to the development and the ultimate yield of rice.

EVI reaches the minimum because of high soil moisture in the transplanting period, and the seedlings turn green and EVI has little increase in several days, so rice transplanting period can be detected by this characteristic. About one to two weeks after transplanting, rice turns into the tillering period. The tillering period is the beginning of the development of rice root and leaf systems, since then EVI increases rapidly. The vegetative development of rice reaches the maximum till the heading period, and then rice changes its growth phase from vegetative growth to reproductive growth. The nutrients are transferred into the seeds and EVI decrease gradually. In the maturation period, leaves lost most of the chlorophyll and begin to wither rapidly, and the vegetation index reaches the minimum in the harvest time. The characteristics of the major growth stages in smoothed time-series EVI are shown in Fig. 2. According to the above mentioned characteristics of each growth stage, the major rice growth stages can be detected through remote sensing technology.

Paddy rice has different characteristics in different growth stages, and the previous methods were summarized and each growth stage was detected by separate method. According to the multi-temporal remote sensing data of the single and double rice samples, the detecting method of each stage was depicted as follows:

The inflexion method was used to identify rice heading period and transplanting period in this study. The maximum of EVI (EVI_{max}) and the minimum of EVI (EVI_{min}) were determined from the smoothed time-series EVI processed by the low pass Fourier and wavelet filtering (tests showed that the minimum was set to 0.15 forcibly when the value is lower than 0.15), and ΔEVI (ΔEVI = EVI_{max} - EVI_{min}) was calculated. The date with the maximum is the heading period (there is only one maximum for single rice in a year, while there are two maximums for double rice). The transplanting period was identified after the heading period was determined. The date with the minimum can be regarded as the transplanting period when it appears before the heading period. If it appears after the heading period, then the date can be regarded as harvest period (the harvest time was not detected in the study).

The transplanting period is the date with the minimum if it is before the heading period, while if it is after the heading period, the date can be regarded as harvest (the harvest time was not detected in this study).

The relative vegetation index threshold method was used to determine the beginning of tillering. This method depends on the relative extent of EVI (percentage), so the impact of the background in different regions could be avoided. Tests indicated that if the total increment of EVI is over 10% of ΔEVI since the transplanting period, then the date could be regarded as the beginning of tillering.

As for rice maturation period, it could be identified by the maximum slope method. The maturation period could be identified by comparing the decrement of EVI between the present date and the previous date, the date with the biggest decrement could be regarded as the maturation period.

The process for the identification of the major growth stages of paddy rice using MODIS data is shown in Fig. 3 according to the above mentioned description.
3 RESULTS

The stages of rice transplanting, beginning of tillering, heading, and maturation could be acquired by the above mentioned algorithms. The meteorological data were used to validate the MODIS derived results. In this study, we analyzed the results of 2005 as a case study to show the correlations. The comparisons between the MODIS-derived rice phenological stages and the meteorological data in 2005 are shown in Fig. 4, Fig. 5 and Fig. 6.

The results in Fig. 4, Fig. 5 and Fig. 6 showed that most of the absolute errors of the four major growth stages derived from the low pass FFT and wavelet filtered time-series EVI data were less than 16 d. F-tests were applied to make a further analysis of the consistency between them. Analyses indicated that all of the results had significant consistency at the level of 0.05, so the MODIS-derived results were reliable. In addition, the root mean square errors (RMSE) were calculated to show the differences by the low pass FFT and DB10 wavelet filtered EVI on the hypothesis that the meteorological statistics are the ground truth (Table 2).

According to the above analyses, the results derived from the low pass FFT and DB10 wavelet filtered EVI data were consistent approximately, though Sakamoto et al. reported that the wavelet transform performed better than the Fourier transform to detect the seasonal information of paddy rice in Japan. The study showed that heavy clouds had a big impact on the time-series EVI in some regions. Because wavelet filtering can model non-periodic or non-stationary signals, so the method is more sensitive to the local changes of the signals caused by noises and easy to have bigger errors. The changes of the rice growth has strong periodicity in a year, so the low pass Fourier transform algorithm is also useful to model the periodic signals, and sometimes the results derived from the algorithm might be better. In conclusion, the results derived from the two above filtering methods were close.
4 DISCUSSION AND CONCLUSIONS

The stages of transplanting, beginning of tillering, heading, and maturation were obtained using the time-series EVI data smoothed by the low pass Fourier and wavelet filtering. The above analyses indicated that both of the algorithms were useful to extract the growth stages information. The sources of the errors were discussed as follows: Firstly, the 8-day composite
Table 2  Comparison of the root mean square errors of the phenological date by the low pass FFT and DB10 wavelet filtered EVI on the hypothesis that the meteorological statistics are the ground truth data

<table>
<thead>
<tr>
<th>Planting system</th>
<th>Growth stage</th>
<th>FFT/d</th>
<th>DB10 wavelet/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single rice</td>
<td>Transplanting</td>
<td>10.7</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>Tilling</td>
<td>11.1</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>Heading</td>
<td>11.2</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>Maturation</td>
<td>14.6</td>
<td>12.4</td>
</tr>
<tr>
<td>Early rice</td>
<td>Transplanting</td>
<td>11.6</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>Tilling</td>
<td>8.9</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>Heading</td>
<td>9.5</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>Maturation</td>
<td>9.6</td>
<td>12.9</td>
</tr>
<tr>
<td>Late rice</td>
<td>Transplanting</td>
<td>7.2</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>Tilling</td>
<td>7.8</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>Heading</td>
<td>9.3</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>Maturation</td>
<td>7.9</td>
<td>10.4</td>
</tr>
</tbody>
</table>

The methods in this study might be able to extract the growth stages of other crops according to their characteristics potentially.

Acknowledgement: The in situ field survey data of rice growth calendar are provided by National Meteorological Bureau of China; the MODIS data used in this study are distributed freely by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) (http://lpdaac.usgs.gov). The authors are very grateful to their generous supports.

REFERENCES


MODIS

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摘要: NOAA-AVHRR, MODIS, EVI, SPOT-VEGETATION, Terra MODIS-EVI (Enhanced Vegetation Index), EOS-MODIS, MODIS, SPOT-VEGETATION (Gallo Flesch, 1989), AVHRR, AVHRR, AVHRR, AVHRR, Zhou (2001)

1981—1999 AVHRR NDVI NDVI NDVI NDVI NDVI

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表1 MODIS传感器前7个波段的主要参数

<table>
<thead>
<tr>
<th>波段</th>
<th>波长/nm</th>
<th>分辨率/m</th>
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<tr>
<td>1</td>
<td>620-670</td>
<td>250</td>
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<tr>
<td>7</td>
<td>2105-2155</td>
<td>500</td>
</tr>
</tbody>
</table>

2.3.1 时刻

AVHRR\MODIS

MODIS

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MODIS

MODIS

MODIS

MODIS

MODIS

ArcGIS

Ordinary Kriging
2.3.2 EVI

EVI = 2.5 × \( \frac{\rho_{\text{NIR}} - \rho_{\text{red}}}{\rho_{\text{NIR}} + 6.0 \times \rho_{\text{red}} - 7.5 \times \rho_{\text{blue}} + 1} \)

(1)

2.3.3  

(a) 2005 (45°44′48″N, 132°40′06″E); (b) 2010 (32°17′41″N, 120°48′59″E); 
(c) 2015 (28°42′34″N, 116°11′36″E)
### Table 1

<table>
<thead>
<tr>
<th>处理</th>
<th>气象台站水稻发育期</th>
<th>MOD09A1数据</th>
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</thead>
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<tr>
<td>预处理</td>
<td>GIS空间插值</td>
<td>时间序列EVI</td>
</tr>
<tr>
<td></td>
<td>全国水稻生长发育期分布图</td>
<td>样本选择</td>
</tr>
<tr>
<td></td>
<td>时间序列EVI平滑滤波</td>
<td>关键生长发育期的识别</td>
</tr>
<tr>
<td>计算</td>
<td>样本实际的生长发育</td>
<td>利用MODIS数据得出结果的效果评价</td>
</tr>
</tbody>
</table>

### Figure 1

- **(a)** FFT
- **(b)** DB10小波

### Figure 2

- **(c)** MODIS 2005
- **(d)** MODIS 2005

(a): 1:1; (b): 1:1; (c): 1:1; (d): 1:1; (e): 1:1
图 5 MODIS 2005 (a) (b) (c) (d) ± 16d

图 6 MODIS 2005 (a) (b) (c) (d) ± 16d
表2 假设气象台站观测数据为真值，利用FFT和小波变换低通滤波处理的时间序列EVI对水稻生长发育期识别的均方根误差比较结果

<table>
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<tr>
<th></th>
<th>FFT/d</th>
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REFERENCES


附中文参考文献