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Detection of rice phenology through time series analysis of ground-based spectral index data

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ABSTRACT

Monitoring crop phenology is of great importance for vegetation classification, yield estimation, and irrigation and fertilization management. To test the ability of ground-based remote sensing in detecting major phenological dates of rice, canopy spectra were collected by two portable spectrometers. The Red-edge Chlorophyll Index ($CI_{red\ edge}$) and Normalized Difference Vegetation Index (NDVI) time-series derived from ground-based spectrometers were employed to detect the main specific phenological dates. $CI_{red\ edge}$ was obtained from ASD FieldSpec Pro spectrometer, while NDVI was from ASD FieldSpec Pro spectrometer (referred to as $NDVI_{ASD}$) and GreenSeeker RT 100 (referred to as $NDVI_{GS}$). The phenology detection method consists of two procedures: (i) smoothing the temporal $CI_{red\ edge}$ and NDVI data with the double logistic regression function to represent intra-annual vegetation dynamics, (ii) determining the phenological dates through extracting the maximum, minimum and zero-crossing points (FD_{max}, FD_{min} and FD_{zero}) from the first derivative value of the smoothed NDVI and $CI_{red\ edge}$ temporal profiles. A comparison of remote sensing-based estimates with field observations over three growing seasons with different cultivars, planting densities and nitrogen (N) rates showed that $CI_{red\ edge}$ can accurately estimate the dates of jointing, middle booting and dough grain. NDVI from both spectrometers can be used to detect the dates of active tillering, middle heading and maturity. Specifically, $NDVI_{GS}$ yielded better performance than $NDVI_{ASD}$ for estimating the three phenological dates. Compared with growing season and planting density, rice cultivar and N rate exhibited more significant impact on the accuracy for phenology detection. This work has great potential to provide valuable support for assessing crop growth status and providing precise management strategy. The dates of active tillering, jointing and maturity detected from a combination of $CI_{red\ edge}$ and NDVI could be useful for irrigation and fertilization management, and harvest determination, respectively.

1. Introduction

Phenology information is essential for many applications, such as crop classification (Lloyd 1990; Peña-Barragán et al., 2011; Siachalou et al., 2015; Son et al., 2013), estimation of net primary production (Kimball et al., 2004) and decision-making about water and fertilizer supply (Dingkuhn and Le Gal, 1996). Paddy rice (*Oryza sativa* L.) is one of major food crops in the world, especially in China (Xiao et al., 2002). According to Moldenhauer and Slaton (2001), rice phenology is generally divided into: (i) vegetative phase, including germination, seedling, tillering and jointing stages; (ii) reproductive phase, including booting, heading and flowering stages; (iii) maturation phase, including milk, dough grain and maturity stages. Within these stages, several dates are critical for precision farming management, such as active tillering date (date for field drying), jointing date (date for panicle fertilizer) and maturity date (date for harvesting) (Ling et al., 2007). Irrigation scheduling is critical in the rice growth period, especially in the active tillering stage. Yang et al. (2006) reported that field drying at active tillering stage can control the non-effective tillers and adjust the relationships between soil and water, and those between root and shoot, which are beneficial to rice growth. Panicle fertilizer has great impact on rice grain yield and quality. Suitable application stage of panicle fertilizer could increase the chlorophyll and nitrogen (N) contents of high photosynthetic-rate leaves and thus increase the rice yield (Ding et al., 2003). Harvesting needs to be prompt because late harvesting

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results in reduced milling quality and rice yield (Moldenhauer and Slaton, 2001). All the aforementioned studies demonstrated that the determination of crop phenology is vital for precision management of irrigation and fertilization and determination of harvesting.

Traditionally, crop phenology studies relied on ground-based field visits that were limited by cost, labor and spatial coverage. Consequently, remote sensing (RS) techniques offer considerable benefits for detecting vegetation phenology in the past few decades (Table 1). For example, Tucker et al. (1979) used a hand-held radiometer to monitor corn and soybean growth and development successfully. Gallo and Flesch (1989) utilized the National Oceanographic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) data for monitoring the seasonal growth of maize at large scale and showed that the date of maximum normalized difference vegetation index (NDVI) agreed well with the silking stage. Meanwhile, several methods have been developed to determine vegetation phenological stages and the most commonly used methods are VI thresholding, inflection point and maximum slope. The VI thresholding method was used by many researchers (Delbart et al., 2006; Fischer 1994; Guo et al., 2016; Markon et al., 1995; Motohka et al., 2010; Nagai et al., 2010). Motohka et al. (2010) defined "GRVI = 0" as a site-independent single threshold for detecting the early phase of leaf green-up and the middle phase of autumn coloring in four different vegetation types. With the inflection point method, the start of the growing season can be identified when the first derivative (FD) value of the time-series curve changes from negative to positive, while the end of the growth can be determined when it changes from positive to negative (Moulin et al., 2010; Sakamoto et al., 2005; Soudani et al., 2008; Zhang et al., 2003). With the maximum slope method, the growth stages are determined by the magnitude of variation in the VI time series (Wang et al., 2014a; Yu et al., 2003).

To date, most crop phenology studies relied on satellite RS data due to the widespread availability of high temporal resolution time series imagery from such instruments as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the NOAA/AVHRR. Although these satellite imagery can cover large areas, they are affected by many factors, such as atmospheric disturbances, solar radiation effects and cloud cover duration (Ricotta and Avena 2000; White et al., 2005). Therefore, the estimation error of phenology could be as high as seven days or even more (Sakamoto et al., 2005; Sun et al., 2009). Coarse resolution satellite imagery is not suitable for phenology detection in major rice growing regions such as south China because the rice fields in this region are relatively small, irregular and fragmented by well-developed roads and dense water networks (Wang et al., 2015). To the best of our knowledge, there was no report about phenology detection using airborne or unmanned aerial vehicle (UAV) imagery primarily due to the logistics complexity and resource limitation with frequent revisits over the growing season. Hence, ground-based RS has great advantages on phenology detection in south China due to its flexibility of spectral, spatial and temporal resolutions.

Recently, time series VIs from ground-based RS platforms have been applied to phenology studies. NDVI was commonly used in phenological studies and had good performance in phenology detection as shown in a summary of relevant references in Table 1. For instance, Wang et al. (2014a) used NDVI from a FieldSpec3 spectroradiometer and its slope curves to monitor rice development and demonstrated that they could be used as cultivar-independent phenological indicators. While handheld sensors with more bands become available in recent years for proximal monitoring of crops, more spectral indices could be obtained to detect crop vigor using red edge bands instead of the red band in NDVI. As one of the red edge indices, red-edge chlorophyll index ($CI_{red\ edge}$) was originally proposed for chlorophyll estimation and later be found to be a better indicator for leaf area index (LAI) and biomass than NDVI (Gitelson et al., 2003a).

For rice phenology detection, several stages (e.g. transplanting, tillering, heading and harvesting stages) were determined in previous studies (Motohka et al., 2010; Sakamoto et al., 2005; Wang et al., 2014a). However, other dates (e.g. the dates of active tillering and jointing) that are considered to be more important for irrigation scheduling and fertilizer management, have received little attention. To fill this gap in the previous phenological studies, this study attempts to detect all those main phenological dates of paddy rice with $CI_{red\ edge}$ and NDVI. Our research objectives are: (1) evaluating the performance of a chlorophyll index ($CI_{red\ edge}$) for rice phenology detection in comparison to the widely used NDVI; (2) determining rice critical phenological dates with the maximum, zero-crossing and minimum points from the first derivative (FD_{max}, FD_{min} and FD_{zero}) of VI time series. We expected that our work would provide useful guidance for water and fertilizer management and harvesting with portable spectrometer devices.

2. Materials and methods

2.1. Experiment design

Three field experiments were designed for this study, involving different rice cultivars, planting densities and N rates. All the experiments were conducted in the experimental station of National Engineering and Technology Center for Information Agriculture (NETCIA), which was located in Rugao city, Jiangsu province, China (120°45′ E, 32°16′ N). In 2013, one japonica rice cultivar Wuxiangjing14 (V1) and one indica rice cultivar Shanyou63 (V2) were seeded at DOY 138 and transplanted into the paddy field at DOY 172. Four N rates (0 (N0), 150 (N1), 300 (N2) and 375 (N3) kg N ha^{-1} as urea) were applied with 40% at preplanting, 10% at tillering, 30% at jointing and 20% at booting. Treatments with N rates of 0 and 375 kg N ha^{-1} were transplanted with a planting density of 220,000 plants ha^{-1} (D1), while treatments with N rates of 150 and 300 kg N ha^{-1} were transplanted with two planting densities of 220,000 plants ha^{-1} (D1) and 130,000 plants ha^{-1} (D2). The plot size was 30 m^2 with 6 m length and 5 m width. For all treatments, monocalcium phosphate and potassium chloride were applied prior to transplanting at 135 kg P_2O_5 ha^{-1} and 220 kg K_2O ha^{-1}. The experiment was in a randomized complete block design with three replications for each treatment. Other management followed local standard practices in rice production.

Experiment 2 and 3 were similar to the experiment 1. The cultivars were japonica rice cultivar Wuyunjing24 (V1) and indica rice cultivar Yliangyou1 (V2), which were seeded at DOY 135 and transplanted at DOY 167 in 2014. In 2015 growing season, rice was seeded at DOY 136 and transplanted at DOY 166. Four N rates (0 (N0), 100 (N1), 200 (N2) and 300 (N3) kg N ha^{-1} as urea) were applied as same as the experiment 1. Rice gains were harvested at DOY 286, 292 and 299 in 2013, 2014 and 2015, respectively.

2.2. Data collection

Two sensors were used to measure canopy reflectance spectra in this study: (1) ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Boulder, CO, USA) with a spectral range of 350–2500 nm and a 25° view angle, abbreviated as ASD; (2) GreenSeeker RT 100 (NTech Industries, Ukiah, CA, USA), abbreviated as GS. GS was selected as the reference active instrument due to its most wide use for in situ crop monitoring and the direct availability of NDVI. Measurements of each treatment were taken on the same day with irregular observation intervals varying from 3 to 10 days, with an average of 5 days. During sunny daytime, the measurements were