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A new methodology to map double-cropping croplands based on continuous wavelet transform

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ABSTRACT

Cropping intensity is one of the major factors in crop production and agricultural intensification. A new double-cropping croplands mapping methodology using Moderate Resolution Imaging Spectroradiometer (MODIS) time series datasets through continuous wavelet transform was proposed in this study. This methodology involved four steps. First, daily continuous MODIS Enhanced Vegetation Index (EVI) time series datasets were developed for the study year. Next, the EVI time series datasets were transformed into a two dimensional (time–frequency) wavelet scalogram based on continuous wavelet transform. Third, a feature extraction process was conducted on the wavelet scalogram, where the characteristic spectra were calculated from the wavelet scalogram and the feature peak within two skeleton lines was obtained. Finally, a threshold was determined for feature peak values to discriminate double-cropping croplands within each pixel. The application of the proposed procedure to China's Henan Province in 2010 produced an objective and accurate spatial distribution map, which correlated well with in situ observation data (over 90% agreement). The proposed new methodology efficiently handled complex variability that might be caused by regional variation in climate, management practices, growth peaks by winter weed or winter wheat, and data noise. Therefore, the methodology shows promise for future studies at regional and global scales.

1. Introduction

Agricultural activities have played an essential role in providing food for China since 7500 BC. With the largest population in the world, China has less than 10% of the total global cropland area, ranked third after the US and India. As indicated by sown area from the statistical datasets, the cropping intensity (number of crops per year in a unit area) increased dramatically during the late 1980s and 1990s (National Bureau of Statistics of China, 2011). However, cropping intensity decreased slightly during the early 2000s, partially due to the large migration of the agricultural workforce to urban areas (National Bureau of Statistics of China, 2011). While triple rice crops were common in the 1970s, double paddy rice crops are currently more prevalent and there is an increasing trends toward single paddy rice in southern China (Peng et al., 2011). Stable agricultural intensity is crucial to guarantee future food security in China (Fan and Wu, 2004). In addition, understanding cropping intensity by using remote sensing technology provides insight into the direction and magnitude of impacts on the natural and agricultural environments (Galford et al., 2008). Accurate, updated, and spatially explicit information on cropping intensity is urgently needed but is not included in large-area land cover datasets.

Different crop types have distinct phenology that can be observed in Vegetation Index (VI) time series datasets (Lunetta et al., 2010). Over the past few decades, numerous methods were developed and successfully applied in the field of crop mapping (Xiao et al., 2005; Arvor et al., 2011; Howard et al., 2012; Singh et al., 2012; Vintrou et al., 2012). Only a few studies, however, aimed to provide information on cropping intensity (Galford et al., 2008; Zhang et al., 2008; Lunetta et al., 2010; Biradar and Xiao, 2011). In these studies, cropping intensity was generally evaluated through identifying the frequency of VI peaks and troughs from the intra-annual VI temporal profiles (Sakamoto et al., 2006; Galford et al., 2008; Biradar and Xiao, 2011). For example, two or three pairs of peaks and troughs were identified as double- and triple-cropping croplands respectively (Biradar and Xiao, 2011). Although these methods were easy to understand and implement, they might introduce error (Galford et al., 2008). There were at least two issues that needed to be further explored. The first issue

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was noise disturbances, especially cloud cover, which were commonly observed in the remote sensing datasets. The original VI time series datasets with cloud cover and abnormally low values, which could be identified as troughs, were examined using these methods. The second issue was that the growth cycle of one specific crop did not exactly correspond to one peak observed in the VI time series dataset. Two peaks could be observed within one growth cycle of a crop, which could have resulted from precipitation, management decisions, or other factors. For example, two peaks were observed in the annual VI time series in the winter wheat cultivated land, one in the winter and another in the spring. Although several studies have been conducted to diminish these problems, most of them focused on noise reduction or setting constraint conditions (Sakamoto et al., 2009; Lv and Liu, 2010; Peng et al., 2011; Chen et al., 2012; Liu et al., 2012). The existing Cropping Index (CI) mapping approaches largely rely on the de-noising filtering algorithms to obtain a smoothed VI profile before detecting peaks (Liu et al., 2012). Moreover, they are vulnerable to noise and need a priori knowledge and extra constraints that could not be directly derived from the VI time-series data to identify the true peaks, which hinder them from mapping CI accurately (Zhu et al., 2008). A more robust and generalized methodology was urgently needed to overcome these issues (Liu et al., 2012).

One major challenge associated with the NDVI-based categorization approach was the within-class variability of crop phenology across a large geographic study area (Lunetta et al., 2010). The time-series MODIS VI data for a given crop exhibited considerable intra-class variability due to regional variations in climate and management practices (Wardlow et al., 2007). For example, the phenology of a specific crop type (e.g., corn) in the northern part of a region may be different from that in the southern part. The crop VI profiles also vary from year to year due to specific weather conditions throughout the growing season (Siebert and Ewert, 2011). These within-class and inter-annual variations have not been accounted in existing approaches (Foerster et al., 2012; Liu et al., 2012).

This paper proposes an efficient methodology to map double-cropping croplands that accounts for regional variation in climate, management practices, growth peaks by winter weed or wheat, and data noise through continuous wavelet transform (CWT). CWT is emerging as a promising tool in the geographic, bio-chemistry and hydrology research fields (Gaucherel, 2002; Cheng et al., 2010; Ullah et al., 2012). CWT proved to be efficient in decomposing the original signal into a number of scale components, where each component was directly comparable to the original one (Gaucherel, 2002). In this study, we aim to extract wavelet features sensitive to changes in crop shifting but insensitive to variations in the temporal EVI profiles which are not corresponded to any specific crop growth cycles. It was hoped that the wavelet spectra, through continuous wavelet transform based on EVI time series, could provide adequate and non-redundant information on crop shifting. The proposed methodology was applied to Henan Province, the food base of China, and the validation of the algorithm was also provided.

2. Methodology

2.1. Remotely sensed input and data preprocessing

Moderate Resolution Imaging Spectroradiometer (MODIS) images have been utilized in recent years because they offer a distinctive capability in maintaining both spatial and temporal density for crop mapping from regional to global scales (Biggs et al., 2006; Pan et al., 2012; Singh et al., 2012). In particular, MODIS time-series datasets, with high temporal and intermediate spatial resolution, offered a unique ability for crop mapping from regional to global scales (Arvor et al., 2011; Biradar and Xiao, 2011). In this study, the 8-day, 250 m composite datasets (MOD09) were used. In order to calculate the EVI, the 8-day blue band at 500 m resolution was interpolated to 250 m resolution. The 8-day, 250 m EVI products were derived using the standard formula (Huete et al., 2002). EVI was chosen because it had a greater dynamic range than the more commonly used NDVI, and thus was more capable of discriminating dynamic crop phenology without reaching saturation (Huete et al., 2002).

In order to obtain a daily continuous EVI time series, the following data preparation processes were conducted. First, the non-vegetated areas were excluded from further processing. The mask of non-vegetated areas could be derived from existing land cover datasets or the MODIS EVI time series. For example, a pixel was assumed to be a non-vegetated area if its EVI values were less than a threshold (i.e., 0.14) in most observations (i.e., 42) in a year. Second, each observation (46 observations over the calendar year) with cloud contamination was discarded. If a value of "1" was obtained for an observation in its corresponding pixel reliability image, which indicated that the target was not visible and covered with clouds, the observation was considered unreliable and excluded for further analysis. Third, the daily continuous EVI time series datasets were produced through linear interpolation during the study period of one year. In order to eliminate the edge effects induced by wavelet transform, a total of 3 full-year daily continuous EVI time series datasets were developed through duplication.

2.2. Temporal EVI profiles of forest, single- and double-cropping croplands

The different temporal behaviors of forests, single- and double-cropping croplands are shown in insert Fig. 1 for 2010. The EVI value of a forest increased dramatically when spring came, reaching a peak, then leveled off for almost 4 months, and then descended quickly in late autumn or early winter (Insert Fig. 1a). For a single cropping site, the EVI value started to increase in April, which meant that crops were planted in spring. The EVI values then reached a peak in July, and then declined gradually until harvest in late September (Insert Fig. 1b). For a double-cropping site, the intra-annual EVI profile presented tri-modal dynamics: the first and third modes represented the crop cycle of winter wheat from October to next May, and the second mode represented the crop cycle from June to September (Insert Fig. 1c).

The forests, single- and double-cropping croplands exhibited clearly distinct temporal EVI profiles. It was possible to distinguish them by monitoring their seasonal behavior. Nevertheless, one peak did not necessarily correspond to one vegetation growth cycle (Insert Fig. 1). Many small local peaks and troughs were observed among their intra-annual EVI profiles, which might be might correspond to local climate conditions, management decisions, data noise problems, or other related factors. Therefore, a more robust method than peak detection was developed to deal with this problem, which is described in detail in the following sections.

2.3. Algorithm for double-cropping croplands mapping

A new methodology for quantifying double-cropping croplands based on continuous wavelet transform was developed (Insert Fig. 2). First, a continuous wavelet transform was performed on daily continuous MODIS EVI time series datasets of each pixel over the entire study area. A wavelet scalogram was obtained for each pixel, representing the similarity of the intra-annual EVI profile to the mother wavelet at each specific time and scale. Second, a feature selection process was performed to determine the intra-annual characteristic spectrum, from which two skeleton lines and characteristic points within those two skeleton lines at each scale were