Computers and Electronics in Agriculture 125 (2016) 1–11

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Automated cropping intensity extraction from isolines of wavelet spectra

Bingwen Qiu [a,*], Zhuangzhuang Wang [a], Zhenghong Tang [b], Chongcheng Chen [a], Zhanling Fan [a], Weijiao Li [a]

[a] National Engineering Research Centre of Geospatial Information Technology, Key Laboratory of Spatial Data Mining & Information Sharing of Ministry of Education, Fuzhou University, Fuzhou 350002, Fujian, China

[b] Community and Regional Planning Program, University of Nebraska-Lincoln, Lincoln 68558, NE, USA

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form 8 April 2016
Accepted 20 April 2016
Available online 4 May 2016

Keywords:
Cropping intensity
Intra-class variability
MODIS EVI
Time-series
Wavelet isolines

ABSTRACT

Timely and accurate monitoring of cropping intensity (CI) is essential to help us understand changes in food production. This paper aims to develop an automatic Cropping Intensity extraction method based on the Isolines of Wavelet Spectra (CIIWS) with consideration of intra-class variability. The CIIWS method involves the following procedures: (1) characterizing vegetation dynamics from time–frequency dimensions through a continuous wavelet transform performed on vegetation index temporal profiles; (2) deriving three main features, the skeleton width, maximum number of strong brightness centers and the intersection of their scale intervals, through computing a series of wavelet isolines from the wavelet spectra; and (3) developing an automatic cropping intensity classifier based on these three features. The proposed CIIWS method improves the understanding in the spectral–temporal properties of vegetation dynamic processes. To test its efficiency, the CIIWS method is applied to China's Henan province using 250 m 8 days composite Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) time series datasets. An overall accuracy of 88.9% is achieved when compared with in-situ observation data. The mapping result is also evaluated with 30 m Chinese Environmental Disaster Reduction Satellite (HJ-1)-derived data and an overall accuracy of 86.7% is obtained. At county level, the MODIS-derived sown areas and agricultural statistical data are well correlated ($r^2 = 0.85$). The merit and uniqueness of the CIIWS method is the ability to cope with the complex intra-class variability through continuous wavelet transform and efficient feature extraction based on wavelet isolines. As an objective and meaningful algorithm, it guarantees easy applications and greatly contributes to satellite observations of vegetation dynamics and food security efforts.

1. Introduction

Increasing cropping intensity is an efficient and promising way to promote global crop production without converting more lands for agriculture (Atkinson et al., 2012). However, agricultural intensification (e.g., increasing cropping intensity) has associated environmental consequences such as degraded soil fertility, water pollution, reduced biodiversity, and changes in atmospheric constituents (Matson et al., 1997). The potential environmental and social impacts from higher cropping intensity need to be carefully evaluated (Atkinson et al., 2012; Ray and Foley, 2013). Timely availability of large-scale information on the cropping intensity is useful to manage agro-environmental ecosystems (Estel et al., 2016; Fana et al., 2014). Often cropping intensity information is only available as statistical data at the level of administrative units and does not have accurate spatial details (Gray et al., 2014; Qiu et al., 2014b). Therefore, reliable cropping intensity mapping is vital for improving agricultural decisions and guaranteeing environmental security (Fana et al., 2014; Gray et al., 2014).

Previous studies have been conducted for estimating cropping intensity based on remote sensing vegetation indices time series datasets (Biradar and Xiao, 2011; Estel et al., 2016; Galford et al., 2008; Lunetta et al., 2010; Zhang et al., 2008). Among them, the most frequently utilized method is calculating the peaks and troughs from the vegetation indices temporal profiles (Biradar and Xiao, 2011; Galford et al., 2008; Jain et al., 2013; Sakamoto et al., 2006, 2009). However, these methods are difficult to be engaged with uncertainties introduced by various situations such as data noise (Galford et al., 2008). Recent research efforts aim to improve included delineating rice cropping activities using wavelet

* Corresponding author at: Spatial Information Research Centre of Fujian Province, Science Building, Floor 13th, Gongye Road 523, Fuzhou University, Fuzhou 350002, Fujian, China.

E-mail address: qiubingwen@fzu.edu.cn (B. Qiu).

http://dx.doi.org/10.1016/j.compag.2016.04.015

transform and artificial neural networks (Chen et al., 2012a), a shape-matching cropping index mapping method (Liu et al., 2012), the k-means clustering method (Setiawan et al., 2014a) or iterative self-organizing data analysis technique algorithm (Nguyen et al., 2012) and setting constraint conditions affecting the peaks of vegetation indices temporal profiles (Chen et al., 2012b; Lv and Liu, 2010; Peng et al., 2011; Sakamoto et al., 2009).

There are at least two key challenges that needed to be further addressed. One challenge is introduced by intra-class variability of vegetation indices temporal profiles from croplands. The intra-class variability of the original MODIS vegetation index time series signals is almost inevitable due to complicated reasons such as altitudinal and latitudinal gradient, variations in climatic, local soil condition and land managements (Siebert and Ewert, 2012; Wardlow et al., 2007). Three typical groups of intra-class variability of original signals could generally be identified. The first group is the altered vegetation phenology shift (advancement or delay), reflected in a shifted vegetation indices temporal profile. It could be introduced by altitudinal and latitudinal gradient (Qiu et al., 2013b), inter-annual variability of climate conditions or any other possibilities (Böttcher et al., 2014; Cleland et al., 2007; Jeong et al., 2011). The second group is the varied plant growth, revealed by a strengthened (considerably better vegetation growth) or lessened vegetation indices temporal profile. It could be introduced by site-specific conditions such as fertility, water and management practices, and other potential reasons (Qiu et al., 2013a). The third group of intra-class variability is introduced by different vegetation types/agricultural crops (Davison et al., 2011). For example, the double-cropping croplands could be planted with two different combinations of agricultural crops (e.g., winter wheat plus maize, early rice plus late rice). Till now, the challenge of intra-class variability has not been efficiently accounted for yet (Foerster et al., 2012; Gumma et al., 2015; Liu et al., 2012; Yan and Roy, 2014).

Another challenge is the need for new perspective of developing automatic, accurate methods which are robust to inter-annual variability (Thenkabail and Wu, 2012). Automated and semi-automated classification methods of remote sensing imagery have been shown to both increase performance and efficiency, and thus, reduce workload (Ghamisi et al., 2014; Quin et al., 2014; Terletzky and Ramsey, 2014). However, most of the traditional methods rely heavily on ground-truth sites or human interpretation for developing standard vegetation indices profiles or establishing classification criteria. These approaches might be time-consuming, labor-intensive, and inconsistent across different regions and years (Terletzky and Ramsey, 2014; Thenkabail and Wu, 2012; Wu et al., 2014). Recently, the automatic approaches are favored in the field of croplands or forest disturbance mapping (Huang et al., 2010; Kennedy et al., 2007; Stueve et al., 2011; Thenkabail and Wu, 2012; Waldner et al., 2015; Wu et al., 2014; Yan and Roy, 2014). Significant efforts should be drawn in the field of automatic cropping intensity mapping (Chen et al., 2012a; Liu et al., 2012; Setiawan et al., 2014a).

In order to address these two significant challenges, this paper aims to develop an automatic Cropping Intensity extraction method based on the Isolines of Wavelet Spectra (CIIWS) obtained through continuous wavelet transform. The continuous wavelet transform has long been successfully applied for pattern recognition in agriculture and related research fields (Du et al., 2006; Gaucherel, 2002; Qiu et al., 2016, 2014a; Tseng et al., 2015; Zhang et al., 2014). These studies revealed that the wavelet spectra/features could efficiently capture the major signals of our study objects (Zhang et al., 2014). The peak detection method based on continuous wavelet transform can identify both strong and weak peaks while keeping false positive rate low (Du et al., 2006). Therefore, the continuous wavelet transform is selected to detect the real peak pattern representing the vegetation growth cycles for mapping cropping intensity. In the following sections, we give a detailed description of our methodology and present its application in Henan Province, China using the Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) time series datasets.

2. Study area

The study area is Henan Province (Fig. 1) in China. Henan Province is chosen since it ranked first in food production in China over the past decade. It is approximately 520 km long and 572 km wide. Henan Province is located between latitudes 31°23′–36°22′N, longitudes 110°21′–116°39′E. It is typically characterized with a warm temperate climate. The altitudes increase from 22 m in the east plain to 2319 m in the west mountain (Fig. 1). Almost one half (47.5%) of its areas are cultivated (Henan, 2010). There are overall double crops, principally winter wheat plus maize, cultivated in the east and southwest portion. Winter wheat is sown in October, tillers during November to December, and harvests in late May or early June (Fig. 2). Maize is sown immediately after the harvesting of winter wheat, and harvests from late September to early October. Single crop, primary single rice, is primary cultivated in the south portion. Single rice is transplanted in May and harvest in September. Some vegetables are cultivated near cities, especially in the middle portion (near the Provincial capital, Zhengzhou city). The cropping calendars of major crops are provided (Fig. 2) with reference to our field survey data and the agro-meteorological data obtained from the National Meteorological Information Centre of China. According to our field survey, the average parcel size of double crop in plain is usually larger than 500 m $\times$ 500 m. The average parcel size of croplands near mountains and hills could generally be less than 250 m $\times$ 250 m.

Due to the varieties of crops, altitudes and other site-specific conditions (i.e. land fertility), these three typical groups of intra-class variability of original signals introduced by different vegetation types/agricultural crops, altered vegetation phenology shift and the varied plant growth are very common in Henan province. Therefore, the Henan province provides good opportunity for us to develop an automatic method which is robust to inter-annual variability.

3. Data collection

3.1. MODIS EVI time series datasets

MODIS images offered a distinct opportunity for mapping agricultural changes for spatial and temporal density coverage from regional to global scales at no cost (Gumma et al., 2015). MODIS surface reflectance 8-day composite level 3 (L3) 250-m data from 2011 to 2013 were obtained. The level 3 products have been atmospherically and geometrically corrected. With red (R), near-infrared (NIR) and blue (B) bands, EVI was then calculated as $2.5 * (NIR - R)/(NIR + 6.0R - 7.5B + 1)$ (Huete et al., 2002).

3.2. Field survey datasets and agricultural census data

The field survey data were gathered in early August 2012, early February, Late April and late July 2013, middle January and August 2014, respectively. UniStrong MG858 hand-held GPS receivers with the accuracy of 1 m were utilized for ground survey in field sites. At each sampling sites, we recorded the cropping pattern (e.g., winter wheat plus maize) and their corresponding phonological stages, and measure the distribution areas. A total of 375 ground truth points were collected (see locations in (Fig. 1). Among them, 213 survey sites were double crops, cultivated with winter