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Tracking the dynamics of paddy rice planting area in 1986–2010 through time series Landsat images and phenology-based algorithms

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ABSTRACT

Agricultural land use change substantially affects climate, water, ecosystems, biodiversity, and human welfare. In recent decades, due to increasing population and food demand and the backdrop of global warming, croplands have been expanding into higher latitude regions. One such hotspot is paddy rice expansion in northeast China. However, there are no maps available for documenting the spatial and temporal patterns of continuous paddy rice expansion. In this study, we developed an automated, Landsat-based paddy rice mapping (Landsat-RICE) system that uses time series Landsat images and a phenology-based algorithm based on the unique spectral characteristics of paddy rice during the flooding/transplanting phase. As a pilot study, we analyzed all the available Landsat images from 1986 to 2010 (498 scenes) in one tile (path/row 113/27) of northeast China, which tracked paddy rice expansion in epochs with five-year increments (1986–1990, 1991–1995, 1996–2000, 2001–2005, and 2006–2010). Several maps of land cover types (barren land and built-up land; evergreen, deciduous and sparse vegetation types; and water-related land cover types such as permanent water body, mixed pixels of water and vegetation, spring flooded wetlands and summer flooded land) were generated as masks. Air temperature was used to define phenology timing and crop calendar, which were then used to select Landsat images in the phenology-based algorithms for paddy rice and masks. The resultant maps of paddy rice in the five epochs were evaluated using validation samples from multiple sources, and the overall accuracies and Kappa coefficients ranged from 84 to 95% and 0.6–0.9, respectively. The paddy rice area in the study area substantially increased from 1986 to 2010, particularly after the 1990s. This study demonstrates the potential of the Landsat-RICE system and time series Landsat images for tracking agricultural land use changes at 30-m resolution in the temperate zone with single crop cultivation.

1. Introduction

As a fundamental component of global environmental change and sustainability research (Turner, Lambin, & Reenberg, 2007), land cover and land use change (LCLUC) greatly affects the carbon and water cycles (West et al., 2010), biodiversity (Gibson et al., 2011), and human welfare (Foley et al., 2005). Many areas in the world had expansion of crop and pastoral lands from natural ecosystems in the past decades (Lambin & Meyfroidt, 2011; Turner et al., 2007). Maintaining agricultural land area is a critical challenge for global food security (Thenkabail, 2009), particularly in China with a large and increasing population (Tao, Yokozawa, Liu, & Zhang, 2009). In some regions of China, large areas of cropland were either converted to built-up land due to urbanization or returned to forest and grassland due to ecological restoration projects (Liu et al., 2014). In high latitudinal areas, agricultural expansion is a new trend due to climatic warming (Dong, Liu, Tao, Xu, & Wang, 2009; Dong, Liu, Yan, Tao, & Kuang, 2011; Liu et al., 2014). Northeast China has been undergoing an especially rapid expansion of paddy rice in past decades that has yielded more grain production, resulted in the northeastward shift of the crop production center in China (Cheng, Wang, Guo, Zhao, & Huang, 2012), and had remarkable impacts on the carbon cycle and water management (Wang et al., 2010). The cropland reclamation that occurred in northeast China featured the conversion of wetland and upland cropland to paddy rice

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fields (Wang et al., 2011). High soil organic carbon, long crop seasons and high rice biomass in northern China enhanced methane emission in paddies (Zhang, Wang, Su, & Li, 2011). Therefore, the amount of methane emissions from paddy rice fields needs to be quantified in northeast China. In addition, paddy rice expansion has also raised a series of environmental problems, including water resource shortage (Tao, Hayashi, Zhang, Sakamoto, & Yokozawa, 2008), land degradation and biodiversity loss (Yang, Yan, & Zhu, 2011).

Several global land cover products include a layer of croplands in China, for example, the MCD12Q1 from the Moderate-resolution Imaging Spectroradiometer (MODIS) (Friedl et al., 2002, 2010), the GlobCover from the MEdium Resolution Imaging Spectrometer (MERIS) (Arino et al., 2008), and the Finer Resolution Observation and Monitoring-Global Land Cover (FROM-GLC) from Landsat (Gong et al., 2013). All of these efforts were based on the spectral features of land cover types in certain phases using supervised or unsupervised classification approaches. Due to different data resolutions, classification schemes, algorithms, research aims, and validation intensities, these products differ to various degrees (Dong et al., 2012; Fritz, See, & Rembold, 2010; Waser & Schwarz, 2006). The algorithms of these land cover datasets rely on image statistics, training sample collection and/or human visual interpretation. The image statistics are image-dependent, therefore, the repeatability of these algorithms is low. In these land cover datasets, cropland was typically considered as one land cover category that contains different crop species, and there were large discrepancies of cropland distribution among the various datasets (Wu, Shibasaki, Yang, Zhou, & Tang, 2008). More specific information on crop type, e.g., paddy rice, is still limited in these existing land cover products.

The phenology-based approach, based on a time series of spectral reflectance or vegetation indices at individual pixels, is an alternate way to identify and map land cover types. Several studies adopted phenological metrics (e.g., starting date, ending date) to map land cover types including soybean and corn (Zhong, Gong, & Biging, 2014). Spectral matching techniques (SMT) have also been used to map land cover and irrigated areas (Thenkabail et al., 2009; Thenkaball, GangadharaRao, Biggs, Krishna, & Turral, 2007). Other studies evaluated spectral properties of various phenological phases, carefully selected one or two unique phases and associated it with spectral signature to identify and map land cover types (Dong et al., 2013; Xiao et al., 2005, 2006). Specifically, a phenology-based approach was used to develop an automated paddy rice mapping algorithm (Xiao et al., 2002), as paddy rice fields have a phase of flooding and open-canopy (after rice transplanting) when a mixture of surface water and rice crops exists. This phenology feature has been used for mapping paddy rice in Southern China and Southeast Asia with MODIS data (Xiao, Boles, et al., 2005; Xiao et al., 2006).

The freely available Landsat archive data that have existed for the past forty years (1972 to present) offer unprecedented opportunities to document historical land cover change with a longer range than that of MODIS. The Landsat Thematic Mapper (TM) sensor, Enhanced Thematic Mapper Plus (ETM+) sensor, and Operational Land Imager (OLI) have the same spatial resolution and continuous temporal coverage. Several regional scale studies have used 30-m Landsat imagery to quantify changes in forest areas. For example, Hansen et al. (2013) mapped global forest extent and annual loss and gain from 2000 to 2012, and another study reported forest disturbance trends in the United States using Landsat time series data and the Vegetation Change Tracker (VCT) algorithm (Huang et al., 2010; Masek et al., 2013). Based on the visual interpretation and digitalization of individual Landsat images, multi-temporal land cover maps in China from the 1980s to 2010 with 5-year intervals have been generated in the China National Land Cover Datasets (NLCD China), including two categories of cropland: paddy cropland (mainly paddy rice) and upland cropland (Liu et al., 2005, 2014). However, the NLCD work was time-consuming and labor-intensive, and the accuracy was largely dependent on the experiences of interpreters and image selection (e.g., rice and wheat could have similar spectral features in some periods).

The application of time series Landsat images to quantifying long-term agricultural land use change at the regional scale is very challenging due to the variability and complexity of the spectral and texture signatures from different crop types. Our goal is to develop an automated time series Landsat- and phenology-based system and use it to map paddy rice fields for the last three decades. We plan to use all the Landsat images available in the U.S. Geological Survey Center for Earth Resources Observation and Science (USGS EROS) archive for one path/row. This process requires practical approaches for atmospheric correction and the identification and exclusion of bad-quality observations including clouds, cloud shadows, snow, and missing data in ETM+ due to scan line corrector off (SLC-off). The Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Masek et al., 2006) has been widely used for the time series Landsat image processing (Huang et al., 2009; Thomas et al., 2011). Previous studies indicated that cloud cover and their shadows have non-ignorable effects (Asner, 2001; Lindquist, Hansen, Roy, & Justice, 2008) and several algorithms have been developed to detect them (Goodwin, Collett, Denham, Flood, & Tindall, 2013; Simpson, Jin, & Stitt, 2000; Zhu & Woodcock, 2012). For example, Zhu and Woodcock (2012) developed an operational routine Fmask to detect clouds and cloud shadows. The snow detection algorithm has been developed and widely applied (Hall, Riggs, & Salomonson, 1995). SLC-off gaps can be acquired from the metadata. It will be valuable to build the time series datasets with all of the good-quality observations and evaluate its potential to map paddy rice, which would contribute to improving land cover mapping and change detection capability.

The objective of this study is three-fold: (1) to develop a Landsat- and phenology-based paddy rice mapping system (Landsat-RICE) to process time series Landsat data including vegetation index calculation, exclusion of bad-quality observations (cloud, cloud shadow, snow, and SLC-off gaps), subsetting and stacking of time series data, and phenology-based paddy rice mapping; (2) to improve and evaluate the feasibility and accuracy of pixel- and phenology-based algorithms in mapping paddy rice using all of the available Landsat images and air temperature-based phenology timing definitions; and (3) to provide satellite-based evidence for documenting paddy rice expansion in northeast China over the past three decades at such five-year intervals as the late 1980s (1986–1990), early 1990s (1991–1995), late 1990s (1996–2000), early 2000s (2001–2005), and late 2000s (2006–2010).

2. Materials and methods

In this study, we developed a Landsat data processing system for mapping paddy rice over decades, which is composed of two modules: (1) the image data preprocessing module (see Section 2.2 for details) and (2) pixel- and phenology-based paddy rice mapping module (Section 2.3). Fig. S1 shows the schematic diagram of the Landsat- and phenology-based paddy rice mapping system (Landsat-RICE). As a pilot and methodological study, we selected one Landsat scene (path/row 113/27) in northeast China as the study area. Using the resultant paddy rice maps over decades, we quantified the paddy rice expansion pattern and process from 1986 to 2010.

2.1. Study area

Our study area covers the border area of China and Russia between 133.153–136.125° E and 46.530–48.371° N, which is part of the Sanjiang Plain. The western part of the study area is largely flat and is dominated by paddy rice (Fig. 1). The climate of the study area is the middle temperate and humid zone with monsoons. The annual mean temperature is approximately 2.5 °C, with the lowest temperature occurring in January at around −20 °C, and the highest temperature in July at 22 °C. The annual accumulated temperature above 10 °C is over 2400 °C · day. The annual precipitation is approximately 500 mm. There are several large rivers in the study area, including the Heilongjiang River, Wusuli River, and Naoli

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