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Mapping paddy rice planting areas through time series analysis of MODIS land surface temperature and vegetation index data

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ABSTRACT

Knowledge of the area and spatial distribution of paddy rice is important for assessment of food security, management of water resources, and estimation of greenhouse gas (methane) emissions. Paddy rice agriculture has expanded rapidly in northeastern China in the last decade, but there are no updated maps of paddy rice fields in the region. Existing algorithms for identifying paddy rice fields are based on the unique physical features of paddy rice during the flooding and transplanting phases and use vegetation indices that are sensitive to the dynamics of the canopy and surface water content. However, the flooding phenomena in high latitude area could also be from spring snowmelt flooding. We used land surface temperature (LST) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to determine the temporal window of flooding and rice transplantation over a year to improve the existing phenology-based approach. Other land cover types (e.g., evergreen vegetation, permanent water bodies, and sparse vegetation) with potential influences on paddy rice identification were removed (masked out) due to their different temporal profiles. The accuracy assessment using high-resolution images showed that the resultant MODIS-derived paddy rice map of northeastern China in 2010 had a high accuracy (producer and user accuracies of 92% and 96%, respectively). The MODIS-based map also had a comparable accuracy to the 2010 Landsat-based National Land Cover Dataset (NLCD) of China in terms of both area and spatial pattern. This study demonstrated that our improved algorithm by using both thermal and optical MODIS data, provides a robust, simple and automated approach to identify and map paddy rice fields in temperate and cold temperate zones, the northern frontier of rice planting.

1. Introduction

Rice is a major staple food for almost 50% of the world's population (Kuenzer and Knauer, 2013), and paddy rice fields account for more than 12% of the global cropland area (FAOSTAT, 2010). Asia has the largest paddy rice fields (Maclean and Hettel, 2002), and produced more than 90% of the rice in the world in 2011 (Kuenzer and Knauer, 2013). Global emissions of rice-based methane total 21–30 teragrams per year (Sass and Cicerone, 2002) and account for more than 10% of the total methane flux in the atmosphere (Ehhalt et al., 2001). Irrigation for agriculture consumes approximately 70% of the global fresh water withdrawals (Samad et al., 1992), and approximately one-quarter to one-third of the developed freshwater resources in the world are used for paddy rice irrigation (Bouman, 2009). The high water demands of irrigated agriculture have raised concerns about improving water resource management, including water conservation and water quality protection (Kuenzer and Knauer, 2013). Water management for paddy rice fields also affects methane emissions (Sass et al., 1999). Recently, paddy rice fields are recognized as a key risk factor for transmission of highly pathogenic avian influenza A (H5N1) virus (Gilbert et al., 2014; Gilbert et al., 2008), as paddy rice fields are an important habitat for free-ranging ducks and wild waterfowl in winter where the avian influenza virus may be transmitted. Therefore, it is important to

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monitor and map paddy rice fields at regional and global scales in an effort to enhance our knowledge of food security, greenhouse gas emissions, water resource management, and transmission of infectious diseases.

Satellite remote sensing is recognized as a viable tool to map paddy rice fields, based on either optical or synthetic aperture radar (SAR) images. Although SAR data are not impacted by clouds or solar illumination, the SAR-based approach has not been used for large-scale paddy rice mapping due to limited data availability (Bouvet et al., 2009; Dong et al., 2006; Miyaoka et al., 2013; Wu et al., 2011; Yang et al., 2008). Many studies have used one to several optical images (e.g., Landsat) to map paddy rice at local scales with supervised or unsupervised classification methods (Li et al., 2012; Yoshikawa and Shiozawa, 2006). Optical sensors with high temporal resolutions (daily revisits) such as the Advanced Very High Resolution Radiometer (AVHRR), Système Pour l'Observation de la Terre (SPOT) (Kamthonkiat et al., 2005; Thi et al., 2012), and Moderate Resolution Imaging Spectrora diometer (MODIS), have also been used to map paddy rice fields at regional scales, based on the temporal characteristics of paddy rice fields (Chen et al., 2012; Gumma et al., 2011; Nuarsa et al., 2012; Peng et al., 2011; Son et al., 2013; Xiao et al., 2006, 2002b, 2005).

Rice is grown in flooded soils, and paddy fields are a mixture of open water and green rice plants during the early part of the growing season (transplanting phase). These characteristics can be readily identified using temporal profiles of vegetation indices such as the Land Surface Water Index (LSWI), Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). Spectral signature analysis has shown that the LSWI values can temporarily be greater than the NDVI or EVI values during the flooding and transplanting phases (Xiao et al., 2006, 2002b, 2005). Based on this unique feature of paddy rice fields during the early period of the growing season, we developed an algorithm to identify and track the image pixels that were flooded and transplanted with seedlings over time (Xiao et al., 2006, 2005). The algorithm was used to map paddy rice at regional scales in southern China, South Asia, and Southeast Asia, where the air temperature stayed above 0 °C for most of the year and there is little or no snow cover, using an 8-day MODIS dataset in 2002 (Xiao et al., 2006, 2005).

Paddy rice has an expansion trend in mid- and high-latitude regions, such as northeastern China, where paddy rice croplands have rapidly expanded in the last decade. According to statistical data, the area of paddy rice fields in this region increased from 2.57×10^4 km^2 in 2000 to 4.33×10^4 km^2 in 2010, which represents an increase of approximately 68%. By 2010, paddy rice fields in the region accounted for more than 10% of the total rice agricultural area in China. As a result of this rapid growth, northeastern China has become a major food production region in China (Liu et al., 2013). The expansion of paddy rice could raise several environmental issues regarding water resources, soil erosion, bird habitats, and biodiversity because most paddy rice fields were converted from natural wetlands or land that was previously used to grow upland crops. Information and geospatial data about the area and spatial patterns of paddy rice agriculture in northeastern China is urgently needed because there is limited knowledge about their current distributions in this high-latitude region.

Direct application of the MODIS-based algorithms (Xiao et al., 2006, 2005) in temperate zones is likely to be complicated by snow and ice cover during the long winter season, by snowmelt in spring, and by the short plant growing season; and it is necessary to precisely identify the time period of the flooding and transplanting phases. Several previous studies have attempted to define the flooding and transplanting periods based on rice growth calendar data (such as the transplanting period) from agricultural meteorological stations (Peng, 2009; Peng et al., 2011; Shi et al., 2013; Sun et al., 2009). The rice growth calendar data were available from scattered agricultural meteorological stations, but there were large uncertainties when the station data were interpolated to regional or national scales. In addition, this station-based approach cannot be used for regions that have no agricultural meteorological stations. The determination of the transplanting phase is needed for the paddy rice mapping in the high latitude area where limited efforts have been made.

The objective of this study is twofold: (1) to develop an improved algorithm that combines land surface temperature (LST) and vegetation indices from MODIS sensors to map paddy rice fields in temperate and cold temperate zones, and (2) to quantify the area and spatial distribution of paddy rice agriculture in northeastern China in 2010 through the use of the improved algorithms and MODIS data in 2010. To achieve these goals, we first used MODIS-based land surface temperature data at a 1-km spatial resolution to determine the period that is suitable for flooding and rice plant transplanting over the course of a year for individual pixels. We then used vegetation indices to identify the pixels that contained a mixture of green rice plants and surface water within that period. The resultant paddy rice map at a 500-m spatial resolution was validated with samples from the very high resolution imagery in Google Earth and compared with the Landsat-based National Land Cover Dataset (NLCD) (Liu et al., 2014) and agricultural statistical data in 2010. This improved algorithm (robust, simple, and automated) will contribute to our future efforts to generate annual paddy rice maps and provide more accurate and updated data for studies of food security, water management, greenhouse gas emissions, and disease transmission.

2. Materials and methods

2.1. Study area

Northeastern China is composed of Heilongjiang, Jilin, and Liaoning Provinces (Fig. 1). It is located in a transition area between mountains and plains with an average elevation greater than 400 m (Fig. 1). The Lesser Khingan Mountain Range is located to the north and extends from the northwest to the southeast, and the Changbai Mountains are located on the southeast and extend from northeast to southwest. The plains are mainly located in the northeastern, western, and southern parts of the region and include the Sanjiang Plain, Songnen Plain, and Liaohe Plain. The river system is large and extensively distributed in the northeastern region, including the Heilongjiang River, Wusuli River, Songhua River, Nen River, and Liao River. The region has cold temperate and humid/sub-humid climate. The average annual precipitation is approximately 500–800 mm, which mostly falls in July and August. The annual accumulated air temperature above 0 °C ranges from 2000 to 4200 °C d, and the annual accumulated air temperature above 10 °C ranges from 1600 to 3600 °C d. The number of frost-free days varies between 140 d and 170 d. Due to temperature limit, there is only one crop system in this region.

This region is an important area of agricultural production in China; according to the National Land Cover Dataset (Liu et al., 2014), it had a total cropland area of 29.97×10^4 km^2 in 2010 (Table 1), which accounted for 16.8% of the total cropland area in the country. The main crop species include soybean, corn, wheat, and paddy rice. Paddy rice accounted for 15.5% of the cropland in this region in 2010, and the region provided 10.2% of the paddy rice yield in China (Table 1) (Liu et al., 2014). The paddy rice fields are mainly distributed in the plain areas along the rivers.

2.2. MODIS data and preprocessing

The MODIS Land Science Team provides an 8-day composite MODIS Surface Reflectance Product (MOD09A1) at 500-m