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Spatiotemporal patterns of paddy rice croplands in China and India from 2000 to 2015

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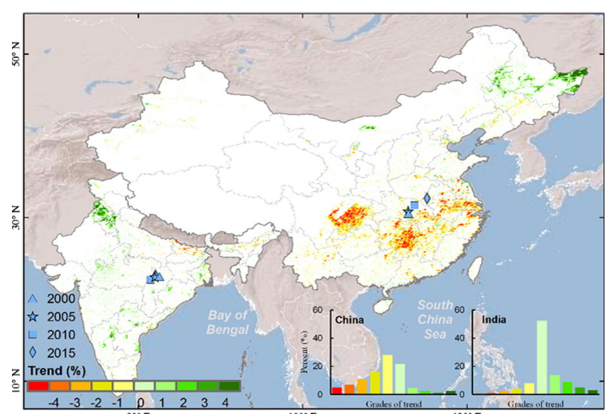
HIGHLIGHTS

- Annual paddy rice maps in China and India were generated for first time using MODIS data.
- Spatiotemporal patterns of paddy rice fields were analyzed in China and India during 2000–2015.
- Paddy rice area decreased by 18% in China but increased by 19% in India.
- Paddy rice area shifted northeastward in China while widespread expansion detected in India.

GRAPHICAL ABSTRACT



Paddy rice croplands underwent a significant decrease in South China and increase in Northeast China from 2000 to 2015, while paddy rice fields expansion is remarkable in northern India. The paddy rice fields centroid in China moved northward due to the substantial rice planting area shrink in Yangtze River Basin and rice area expansion in high latitude regions (e.g., Sanjiang Plain).

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ABSTRACT

Due to rapid population growth and urbanization, paddy rice agriculture is experiencing substantial changes in the spatiotemporal pattern of planting areas in the two most populous countries—China and India—where food security is always the primary concern. However, there is no spatially explicit and continuous rice-planting information in either country. This knowledge gap clearly hinders our ability to understand the effects of spatial paddy rice area dynamics on the environment, such as food and water security, climate change, and zoonotic infectious disease transmission. To resolve this problem, we first generated annual maps of paddy rice planting areas for both countries from 2000 to 2015, which are derived from time series Moderate Resolution Imaging Spectroradiometer (MODIS) data and the phenology- and pixel-based rice mapping platform (RICE-MODIS), and analyzed the spatiotemporal pattern of paddy rice dynamics in the two countries. We found that China

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China
India
MODIS
Food security
Phenology-based algorithm

experienced a general decrease in paddy rice planting area with a rate of 0.72 million (*m*) ha/yr from 2000 to 2015, while a significant increase at a rate of 0.27 *m* ha/yr for the same time period happened in India. The spatial pattern of paddy rice agriculture in China shifted northeastward significantly, due to simultaneous expansions in paddy rice planting areas in northeastern China and contractions in southern China. India showed an expansion of paddy rice areas across the entire country, particularly in the northwestern region of the Indo-Gangetic Plain located in north India and the central and south plateau of India. In general, there has been a northwesterly shift in the spatial pattern of paddy rice agriculture in India. These changes in the spatiotemporal patterns of paddy rice planting area have raised new concerns on how the shift may affect national food security and environmental issues relevant to water, climate, and biodiversity.

1. Introduction

Rice feeds more than half of the human population in the world (Kuenzer and Knauer, 2013). >90% of rice production is from Asia (Maclean and Hettel, 2002). China and India have the largest rice planting areas, the most grain production, and the highest amount of rice consumption in the world. Paddy rice agriculture in these two countries plays a pivotal role for both national and global food security. In addition to food security, rice paddy is related to a number of environmental and human health issues. For example, paddy rice field management regimes affect greenhouse gas (methane) emission and climatic warming (Chen et al., 2013; Li et al., 2003; Sass and Cicerone, 2002; van Groenigen et al., 2013), as well as water use and water resource security (Kuenzer and Knauer, 2013; Samad et al., 1992). Paddy rice agriculture was also found to be related to zoonotic infectious disease transmission, as rice paddies are an important habitat for wild birds and domestic poultry (Gilbert et al., 2014; Gilbert et al., 2008). Therefore, it is important to track the spatiotemporal changes in land use of paddy rice agricultural areas in these two countries.

Several efforts have been taken to document the spatial extent of paddy rice agriculture in China and India (Frolking et al., 2006; Gumma et al., 2015; Liu et al., 2014b; Xiao et al., 2005). In China, previous efforts to map paddy rice fields include: 1) combining a remote sensing-based land cover map for croplands type and agricultural census data (rice area and management) (Frolking et al., 2002); 2) land cover datasets in circa 5-year epochs including paddy rice category by using Landsat imagery and a visual interpretation approach (Liu et al., 2005; Liu et al., 2010); 3) simulation of paddy rice area based on the Spatial Production Allocation Model (SPAM), land distribution, administrative unit census of crop data, agricultural irrigation data, and crop suitability data (Liu et al., 2013; Liu et al., 2014b); and 4) paddy rice mapping through temporal profile analysis of time series MODIS data (Sun et al., 2009; Xiao et al., 2005). In India, the studies about paddy rice field mapping include the district-level rice cropping maps by combining a series of census data sets of rice cropping (Frolking et al., 2006), and MODIS-based paddy rice mapping (Gumma et al., 2011; Xiao et al., 2006). None of the aforementioned projects have generated annual maps of paddy rice agriculture in these two countries, and comparative analyses of spatiotemporal patterns of paddy rice fields between these two countries have not yet been conducted.

Considering the fact that no spatially explicit maps are available for understanding the spatiotemporal dynamics of paddy rice agriculture in these two largest rice-production countries, it is a priority to apply a robust method for national scale monitoring of paddy rice fields. Earlier studies used traditional classifiers such as supervised (e.g., Maximum Likelihood Classification) or unsupervised classifiers and single/multiple images for paddy rice mapping. However, these approaches are dependent on image statistics, training sample collection, and/or human visual interpretation, and may produce more uncertainties when transferring these methods to other regions or periods. Recent studies increasingly use the phenological characteristics of paddy rice in the flooding and transplanting phase to extract the location of paddy rice fields (Sakamoto et al., 2009; Shi et al., 2013; Sun et al., 2009; Xiao et al., 2006; Xiao et al., 2005), which is based on the discovery that the flooding/transplanting signals can be detected by using the relationship between the Land Surface Water Index (LSWI) and Normalized Difference Vegetation Index (NDVI), or Enhanced Vegetation Index (EVI) (Xiao et al., 2002b). This algorithm has recently been used for paddy rice mapping at regional or national scales, including in China (Sun et al., 2009; Xiao et al., 2005; Zhang et al., 2015), the Mekong Basin (Kontgis et al., 2015; Sakamoto et al., 2009), South Asia (Xiao et al., 2006), and the major rice growing countries of Asia (Nelson and Gumma, 2015). In these efforts, some improvements over the original algorithm have been made, including pre-determining the temporal window of transplanting phase by using land surface temperature (Zhang et al., 2015) or agricultural phenology observation (Sun et al., 2009), and modified threshold values in the formula ($LSWI + 0.05 \geq EVI$ or NDVI) when detecting flooding and transplanting signals for paddy rice fields (Sakamoto et al., 2009).

Although this phenology-based classification strategy has been widely used for paddy rice mapping, previous studies have not utilized the method to continuously monitor paddy rice fields at the national scale, because bad observation (clouds, cloud shadows, snow, aerosols, etc.) ratios and data availability to capture vegetation phenology are variable across large regions. The ability to continuously monitor paddy rice fields is particularly important for the tropical regions in China and India where a cyclic, monsoonal climate causes persistent cloud cover during rainy season (Kontgis et al., 2015). Although Synthetic Aperture Radar (SAR) imaging has advantages, such as not being affected by clouds or solar illumination, the SAR-based approach has not been used for large-scale paddy rice mapping due to the limited availability of SAR data (Bouvet et al., 2009; Dong et al., 2006; Miyaoka et al., 2013; Nelson et al., 2014; Wu et al., 2011; Yang et al., 2008).

In order to better understand the recent paddy rice agriculture dynamics in China and India, the objective of this study is two-fold: 1) to map annual paddy rice planting area for China and India from 2000 to 2015 using time series MODIS data and a phenology-based rice algorithm, and 2) to investigate the spatiotemporal changes in paddy rice fields in both countries from the perspectives of location, climate, and elevation. To our limited knowledge, this study provides the first picture of spatiotemporal changes in paddy rice fields for the two most populous countries. The resultant paddy rice maps are expected to serve land use management and planning, food security policy making, climate change monitoring, water resource usage, and other applications.

2. Data and methods

2.1. Study area

Paddy rice is generally distributed within the monsoon areas of China and India. In China, the continental monsoon climate can be classified as subtropical in the south and temperate in the north. Precipitation mostly falls in summer season, but with significant moisture gradients from southeast to northwest. Due to the temperature difference in northern and southern China, paddy rice monoculture occurs