Agricultural Water Management 115 (2012) 83–91

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

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

Development of Variable Threshold Models for detection of irrigated paddy rice fields and irrigation timing in heterogeneous land cover

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ARTICLE INFO

Article history:
Received 25 February 2012
Accepted 23 August 2012

Keywords:
Satellite data
Spectral index
Surface water detection
Sub-pixel heterogeneity

ABSTRACT

Accurate monitoring of irrigated paddy field area and irrigation timing are of a great concern in agricultural water management due to the substantial consumption of fresh water when irrigating paddy fields. Spectral threshold methods (Xiao et al., 2005) have been widely applied to detect irrigated paddy fields and irrigation timing using Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) and Land Surface Water Index (LSWI). These methods applied constant additive threshold values (T) to LSWI and compared it to EVI to detect the irrigated paddy fields. In this study, we developed Variable Threshold Models that utilized different pixel-based threshold values depending on sub-pixel land cover heterogeneity and hence, improve detection performance on distributed small-scale paddy fields. Non-irrigated sub-pixels were quantified with irrigation maps produced by Synthetic Aperture Radar (SAR) microwave images. Significant positive correlation between EVI and the sub-pixel numbers of non-irrigated area were found ($r = 0.87$), which resulted in higher T for MODIS pixels with more non-irrigated sub-pixels. Accordingly, a Variable Threshold Model, i.e. a regression model between T and EVI, was developed. With the Variable Threshold Model, agreement rates between MODIS and SAR-based irrigated small-scale paddy field classification doubled compared with that from a fixed threshold value. In comparison with field observations, the Variable Threshold Models showed a mean error of +0.9 days, an improvement over the mean error of +2.8 days from a fixed threshold model. Combined utilization of SAR and MODIS images provides a useful tool for developing a Variable Threshold Model that can enhance accurate monitoring of irrigation dates across heterogeneous paddy field regions.

1. Introduction

Rice is one of world's major food resources, supporting more than 50% of the world population (Bouvet and Toan, 2011). The area covered by paddy rice fields has increased by +80 M ha yr^{-1} (UNDESA, 2004), which may lead to increased demands for fresh water to irrigate new paddy rice fields. Such increased demand may result in water resource problems in water-limited areas. Irrigation of paddy fields in Asia accounts for approximately 70% of fresh water outflows (Samad et al., 1992), and in some Asian countries over 95% of fresh water is used for irrigation (FAOSTAT, 2001; Xiao et al., 2006). Paddy field irrigation can also enhance evapotranspiration, which may result in an imbalance of local and regional water budgets. Hence, reliable monitoring of irrigation timing is an important concern in areas with insufficient water resources.

Satellite remote sensing has been utilized as a useful alternative means for monitoring irrigated area and irrigation timing over large areas, because acquiring irrigation data is highly limited in many countries and partially available only for administrative management units (Ozdogan et al., 2010). Since Moderate Resolution Imaging Spectroradiometer (MODIS) images have been available since 2000, there has been considerable progress in estimating the spatial distribution of irrigated fields (Xiao et al., 2005; Sakamoto et al., 2007; Sun et al., 2009; Gumma et al., 2011) and the timing of irrigation using the MODIS spectral indices (Jeong et al., 2011; Peng et al., 2011).

Xiao et al. (2005) proposed a simple threshold algorithm to detect paddy rice fields using MODIS EVI (Enhanced Vegetation Index), NDVI (Normalized Difference Vegetation Index), and LSWI (Land Surface Water Index). EVI and NDVI are vegetation indices sensitive to vegetation greenness and biomass, while LSWI is a

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http://dx.doi.org/10.1016/j.agwat.2012.08.012

spectral index sensitive to moisture content of the land surface. Any MODIS pixel meeting the condition, LSWI + $T \geq$ EVI (or NDVI), was identified as a paddy rice field. Here, T is a constant additive threshold value.

The threshold algorithm was based on their findings in southern China and Southeast Asia, from which paddy rice fields showed higher LSWI values than NDVI (or EVI) during the period of irrigating or transplanting. Compared to their earlier study (Xiao et al., 2002), they applied a constant additive threshold (T = 0.05) for LSWI to slightly relax the condition of the difference between LSWI and EVI (or NDVI) for irrigation detection because green non-irrigated sub-pixels can cause higher EVI (or NDVI) compared to pure irrigated paddy field pixels during irrigation periods. Although threshold (T) enhanced detection of irrigated paddy fields and timing was introduced, there were still several problems caused by background reflectance from other components such as ditches, roads, other crops, temporal mixing of irrigation caused by early and late transplanting, and single or multiple cropping.

Sun et al. (2009) and Peng et al. (2011) separated the planted area based on rice cropping systems and modified the threshold (T) accordingly: rice fields were separated into early and late rice fields. The improvements from this approach were most distinguishable in detecting irrigated area and irrigation timing of large-scale paddy fields, but significant uncertainty still remained in regions with highly distributed small-scale paddy fields. Jeong et al. (2011) applied the irrigation detection algorithm suggested by Xiao et al. (2005) and Peng et al. (2011) in the Republic of Korea with mixed results: irrigated areas were overestimated for regions with large-scale paddy rice fields, while those with small-scale paddy rice fields were underestimated. Similar uncertainties were also reported by other studies using the method of Xiao et al. (2005), especially for the small-scale paddy field regions (Uchida, 2007; Islam et al., 2010). A major cause of such uncertainties is the background reflectance from green non-irrigated sub-pixels within a MODIS EVI pixel (Sun et al., 2009; Jeong et al., 2011). The green non-irrigated portion tends to increase MODIS EVI (or NDVI) during the irrigation period, which subsequently requires a higher threshold (T) to detect the paddy field irrigation.

Reliable information on the counts of irrigated and non-irrigated sub-pixels is required to determine the effects of non-irrigated sub-pixels on MODIS spectral indices and hence, to determine the appropriate threshold (T) to minimize uncertainty from the mixed-pixel problem. Synthetic Aperture Radar (SAR) satellite imaging is a useful tool for differentiating irrigated paddy fields from other landforms and non-irrigated paddy rice fields because of its high sensitivity to surface water (Lee, 2006; Islam et al., 2010). In addition, the higher spatial resolution of SAR image compared to MODIS enables quantification of sub-pixel heterogeneity, assessment of its effect on the MODIS spectral indices, and analysis of errors caused by using coarse resolution MODIS images in determining the irrigation timing and the irrigated paddy rice fields (Park et al., 2005; Sakamoto et al., 2007).

In this study, the MODIS-based irrigation detection algorithm proposed by Xiao et al. (2005) was improved, with the particular purpose of reducing detection uncertainty caused by distributed small-scale paddy field regions. Our approach utilized SAR-based irrigated paddy field maps to develop the Variable Threshold Model for the threshold (T) in conjunction with MODIS EVI.

2. Materials and methods

2.1. Study area and land cover characteristics

The development of the Variable Threshold Model was conducted in the Yedang wide plains located in the mid-west of the Republic of Korea. Both large and small-scale paddy fields are mixed within the extent of each available Radarsat-1 SAR image (Fig. 1).

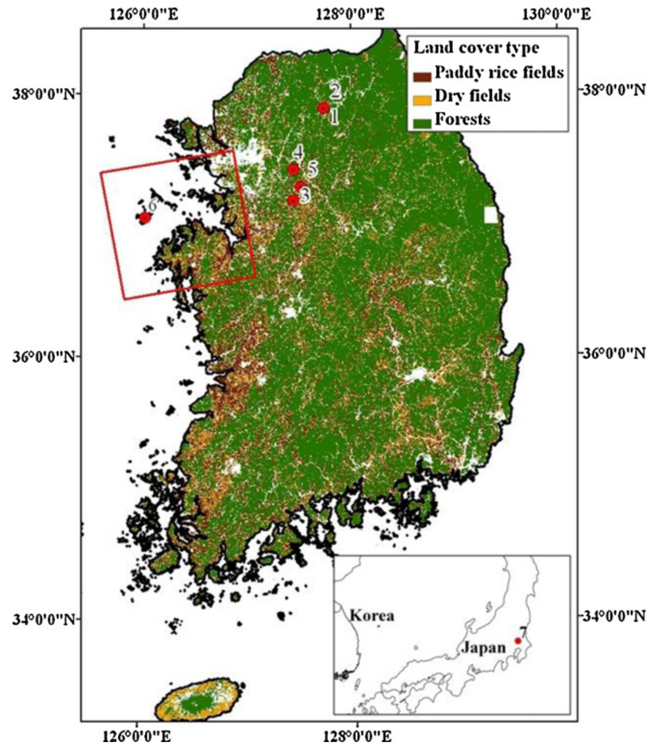

Fig. 1. Main land cover map of raster form (20 m) developed by the Ministry of Environment in the Republic of Korea. The square is the test area used to determine the error factor from land cover heterogeneity.

The annual average temperature and the annual total precipitation of this region ranged from 10 to 16 °C and 1000 to 1800 mm, respectively. Based on the National Land Cover Map (5 m resolution, produced by Ministry of Environment of Korea), 64.2% of the region is covered with forest, 10% by paddy rice fields, 8.3% by dry crop fields, and 17.5% by other land cover classes.

The validation of the Variable Threshold Model was based on six sites in Korea and one site in Japan, where field observation data on irrigation dates and field photos were available between 2001 and 2010 (Moon et al., 2003; Lee et al., 2005) (Table 1). As a final step, the Variable Threshold Model to the entirety of South Korea was applied to examine the spatial variation of irrigation dates.

Previous studies using the threshold method tried to detect both paddy field area and irrigation date, and hence, they developed their own MODIS-based paddy field maps that contain some uncertainties in the classification process. However, since the primary concerns were the improvement of the MODIS-based detection performance of distributed small-scale paddy rice fields and irrigation timing, the study was confined to only predetermined paddy rice areas that were extracted from the National Land Cover Map. The National Land Cover Map was aggregated into 20 m and 500 m resolution land cover maps to meet the spatial scales of SAR and MODIS, respectively. In the aggregation process, sub-pixel numbers for rice paddies, dry crop fields, and forests within a 500 m MODIS pixel were counted separately, which was later utilized to examine the relationships between MODIS spectral indices and sub-pixel land cover heterogeneity.

2.2. Data collection and manipulation

Two types of satellite images were collected in this study: two radarsat-1 SAR images from 2003 and MODIS 8-day reflectance products from 2001 to 2010. By producing 20 m resolution maps