A logistic-based method for rice monitoring from multi-temporal MODIS-Landsat fusion data

Nguyen-Thanh Son1*, Chi-Farn Chen1, Ly-Yu Chang1, Cheng-Ru Chen1, Shin-Ichi Sobue2, Vo-Quang Minh3, Shou-Hao Chiang1, Lam-Dao Nguyen4 and Ya-Wen Lin5

1Center for Space and Remote Sensing Research, National Central University, Jhongli District, Taoyuan City 32001, Taiwan
2Remote Sensing Technology Center of Japan, 3-17-1, Toranomon, Minato-Ku, Tokyo, Japan
3College of Environment and Natural Resources, Can Tho University, Campus II, 3/2 street, Xuan Khanh Precinct, Ninh Kieu District, Can Tho City, Vietnam
4Vietnam Southern Satellite Technology Application Center, Vietnam Academy of Science and Technology,1 Mac Dinh Chi St., Ho Chi Minh City, Vietnam
5Department of Information Management, National Central University, Jhongli District, Taoyuan City 32001, Taiwan

*Corresponding author, e-mail address: ntsonait@hotmail.com

Abstract
Information on rice cropping activities and growing areas is critical for crop management. This study developed a logistic-based method to monitor rice sowing and harvesting activities and, accordingly, to map rice growing areas from the MODIS–Landsat fusion data in An Giang Province, Vietnam. The EVI2 data derived from the fusion data compared with that of Landsat data indicated a close correlation (R2 = 0.93). The comparisons between the estimated sowing and harvesting dates and the field survey data revealed the RMSE values of around 8 and 5 days for the winter–spring crop and 9 and 12 days for the summer–autumn crop, respectively. The rice mapping results compared with the ground reference data indicated an overall accuracy and Kappa coefficient of 93.2% and 0.86 for the winter–spring crop, and 91.7% and 0.83 for the summer–autumn crop, respectively. These results were reaffirmed by the government’s rice areas statistics, with the relative error in area values smaller than 3.3%.

Keywords: Rice monitoring, data fusion, double logistic, Vietnam.

Introduction
Food security is globally a critical issue in developing and third world countries. Nearly half the world’s population depends on rice for survival, and much of the Asian population consumes rice at every meal, accounting for approximately 30% of Asian caloric intake and more than 70% in many developing countries [Pandey et al., 2010]. Rice agriculture thus plays an important role in the developing world’s economy [Evenson and Rosegrant, 2003; Timmer, 2009]. In Vietnam, the rice crop has historically provided food for more than
90 million people and is considered an essential source of income for the majority of rural populations. Vietnam is one of the largest rice producers and suppliers on earth [Hossain, 1997; Maclean, 2002; FAO, 2010], annually producing about 39.9 million tons of grain rice [GSO, 2010] and exporting roughly 7.4 million tons [USDA, 2012]. More than 80% of the exported rice was produced from the Mekong River Delta (MRD), South Vietnam [Nguyen, 2004], which encompasses more than 53% of the country’s rice land.

Food security issues threaten the region due to a population rapidly growing at a rate of 1% per year and climate change impacts. Approximately 15.3% of the country’s population was estimated under the poverty line of per capita income of less than SUS 1 per day [Le Trong, 2012]; therefore, unstable food prices could influence the access of large rural populations to food. The MRD is one of three deltas in the world most vulnerable to the climate change [Mackay and Russell, 2011], which increases the frequency of droughts and floods [IPCC, 2007]. Changes in climate conditions could likely trigger the increase of insect populations and rice diseases, causing the potential loss of rice yields. Climate-change can locally alter climatic and hydrological conditions, which farmers depend on to determine the timing of sowing and harvesting. For instance, if rice seeds are sown too early under flooded soil water, rice plants can experience slow emergence, poor growth, lack of seedling vigor due to cool weather, increased seedling disease damage, and increased predation by storks and ducks. If the seeds are sown too late, however, the potential yield may decline due to panicle blight problems associated with high temperatures during pollination as well as grain filling and increased potential for other disease and insect problems.

Because rice fields damaged by diseases or insects may affect neighboring rice fields, monitoring the cropping progress can provide agronomic planners with timely strategies to mitigate possible impacts on the potential yield. Rice disease and insect controls might be more efficient if spatiotemporal information of rice cropping progress was well managed. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite can acquire data over a wide area with high spectral and temporal resolutions, easily providing regional-scale information. However, the size of rice fields in the study region specifically and around the world in general are relatively small (from one to several ha on average). The use of MODIS data for small-scale monitoring purposes is challenging due to mixed-pixel issues, but this problem can be partly overcome by fusing MODIS data with a higher spatial resolution data, such as Landsat and SPOT imageries.

This study used the spatial-temporal adaptive reflectance fusion model (STARFM) [Feng et al., 2006] to fuse the multi-temporal MODIS data with Landsat data to create a synthetic time-series dataset with a higher spatiotemporal resolution for monitoring rice sowing and harvesting activities and, consequently, mapping rice growing areas. This technique, which can partly overcome mixed-pixel problems that typically challenge low spatial resolution data such as MODIS and advanced very high resolution radiometer (AVHRR), has demonstrated its ability to integrate low spatial but high temporal resolution satellite data (e.g., MODIS and AVHRR) with higher spatial resolution data (e.g., Landsat and SPOT) for environmentally related applications, including crop and forest phenology, agriculture management, and flood monitoring [Hilker et al., 2009; Gaulton et al., 2011; Watts et al., 2011; Schmidt et al., 2012; Zhang et al., 2014; Schmidt et al., 2015].

In this study, the enhanced vegetation index 2 (EVI2) was used to investigate rice crop
phenology and mapping because it is strongly associated with green biomass [Fangping et al., 2007] and more sensitive than normalized difference vegetation index (NDVI) in biomass areas [Chen et al., 2005; Fangping et al., 2007; Bartoszek et al., 2015]. The index has different correlation levels at different phenological stages, allowing extraction of phenological events (i.e., greenup, maturity, senescence, and dormancy points) from the EVI2 profile for rice crop monitoring in the region over space and time. Because the time-series EVI2 data (derived from STARFM) were contaminated by cloud cover, potentially affecting the results of crop phenology detection and classification, we applied the double logistic method to fit the time-series EVI2 data and simultaneously determined phenological events from the crop profile. The rationale for using this logistic method was that rice plants characterized distinct temporal patterns of rice crops [Xiao et al., 2005; Chen et al., 2011; Son et al., 2013; Gumma et al., 2014; Tornos et al., 2015; Zhang et al., 2015] that can be represented using a series of piecewise logistic functions of time to approximate the variation in spectral reflectance of EVI2 for rice crops during growth stages. The phenological transition events (i.e., greenup onset, maturity onset, senescence onset, and greenness offset) corresponding to the times at which the rate of change in curvature of the EVI2 fitted using logistic models exhibiting local minima or maximums can be identified using derivative algorithms [Zhang et al., 2003]. A number of studies have been conducted to monitor vegetation and crop phenology at regional to global scales from satellite-based vegetation indices (e.g., NDVI and EVI) using the double logistic algorithm over the past decade [Zhang et al., 2003; Beck et al., 2006; Wardlow et al., 2006; Julien and Sobrino, 2009; Zhao et al., 2012].

In this study, the time-series EVI2 data were assumed to characterize the temporal responses of rice crop phenology through the growing season, following a typical “S” curve behavior of the logistic model and the key phenological growth stages of rice plants can be identified using derivative algorithms. The main objective of this study was to develop an approach to investigate rice sowing and harvesting progress and accordingly map rice growing areas in MRD using multi-temporal MODIS-Landsat fusion data. The data were processed for the 2007 winter-spring and summer-autumn cropping seasons using STARFM and double logistic algorithms.

**Study region**

The study region (An Giang Province) is situated in the upper MRD (Fig. 1), covering approximately 3,536.7 km². The majority of agricultural land in this province is allocated for rice production [Sub-NIAPP, 2002] during two distinct seasons: rainy season (May-Oct) and dry season (Nov-Apr). Three rice cropping seasons are annually practiced, including the two main seasons, winter-spring (Nov-Dec to Feb-Mar) and summer-autumn (May-Jun to Aug-Sep), and a third season, autumn-winter (Jul-Aug to Nov-Dec). The length of a rice cycle in the study region generally lasts 90-110 days, with three cultivation periods: sowing, growing, and fallow. During the sowing period, a high-density field of grains is sown directly into flooded soil water. The growing period is characterized by increased plant height, number of tillers, and leaves on reaching a heading phase, after which the plants begin to wither and die. After harvesting, the fallow period begins, when rice fields are either burnt during the dry season or allowed to grow up in weeds.
**Data collection**

We used MODIS/Terra data (MOD09Q1) acquired from the U.S. National Aeronautics and Space Administration for 2007 rice cropping seasons (Nov 2006-Dec 2007). This data product has two spectral bands (red and near infrared) and a spatial resolution of 250 m. Each pixel of the data product contains the best possible L2G observation during an 8-day period, selected based on high observation coverage, low viewing angle, absence of clouds,
and aerosol loading. The data have been geometrically and radiometrically corrected for these two spectral bands [Vermote et al., 2008]. We also used two sets of Landsat TM images collected from the U.S. Geological Survey. The first dataset included an image acquired on 02 Jan 2007 (path/row: 125/053) and two images on 09 Jan 2007 (126/052 and 126/053) and was used for STARFM simulation with the multi-temporal MODIS data (41 images) to generate a new synthetic MODIS-Landsat dataset. The second dataset included an image acquired on 03 Feb 2007 (path/row: 125/053) and two images on 10 Feb 2007 (126/052 and 126/053) and was used to evaluate the simulation results. The Landsat TM data include seven spectral bands, with wavelengths from shortwave-infrared to visible regions and a spatial resolution of 30 m.

The sowing and harvesting dates were collected for seven sites throughout the study region through field surveys during the 2007 winter-spring and summer-autumn rice cropping seasons (Fig. 1). At each site, we recorded data from five rice fields least 500 m apart. We also used the 2005 provincial land-use/cover (LUC) maps (scale: 1/50,000) and the 2006 MRD LUC map (scale: 1/125,000), which we checked against Google Earth imagery and field survey data as well as updated for crosschecking and preparation of the ground reference data (Fig. 1) used for accuracy assessment of rice area classification. The rice area statistics for the 2007 winter-spring and summer-autumn cropping seasons at a district level were also collected from An Giang’s Department of Agriculture and Rural Development to further verify consistency with the mapping results.

**Methods**

An overview of the methodology shows four main steps of data processing for rice crop phenology detection and classification in the study region, including MODIS-Landsat data fusion, construction of time-series EVI2 fusion data, rice crop phenology detection and classification, and error verification of the estimated sowing and harvesting dates and the classification results (Fig. 2).

**Figure 2 - Flowchart of the methodology used in this study for rice crop phenology detection and classification in the study region.**
MODIS–Landsat data fusion

MODIS data were reprojected to the universal transverse Mercator and resampled to the same spatial resolution as the Landsat data (30 m). Both datasets were cropped over the study region. Because the study region was covered by Landsat images (one image of path/row: 125/053 acquired 02 Jan 2007 and two images of path/row: 126/052 and 126/053 on 09 Feb 2007), the histogram matching image normalization was performed using the path/row: 126/053 image, which covers most of the study region, as a reference base. This process was implemented to distribute the brightness values of the other two acquired images as close as possible to the reference image to minimize the spectral variations within each LUC class [Richards and Jia, 2006]. These images were then mosaicked and used in STARFM simulation with MODIS images. The same procedure was also followed for the Landsat images used to verify the results of data fusion.

STARFM (ledaps.nascom.nasa.gov/tools) was used for simulation between multi-temporal MODIS images (250 m spatial and 8-day temporal resolutions) and a Landsat image (30 m resolution) to create new datasets (30 m and 8-day resolutions) for two spectral bands (red and near-infrared). This algorithm predicts pixel values of changes in reflectance of MODIS images based on the spatial weights determined by the Euclidean distance and the spectral and temporal similarity with the target pixel between Landsat and MODIS image pairs [Feng et al., 2006]. STARFM can be expressed using the following equation:

\[
L(x_{\omega/2},y_{\omega/2},t_0) = \sum_{i=1}^{\omega} \sum_{j=1}^{\omega} \sum_{k=1}^{\omega} W_{ijk} \times (M(x_i,y_j,t_k) - M(x_i,y_j,t_k)) \quad [1]
\]

where \(L\) and \(M\) are Landsat and MODIS surface reflectance, respectively; \(\omega\) is the searching window size and \((x_{\omega/2},y_{\omega/2},t_0)\) is the central pixel of the moving window; \((x_i,y_j)\) is a given pixel location for a Landsat and MODIS image pair; \(t_k\) is the acquisition date for the image pair; \(t_0\) is the acquisition date for a simulated date; and \(W_{ijk}\) is the weight deciding the influence of each neighboring pixel to the simulated reflectance of central pixel \((x_{\omega/2},y_{\omega/2})\).

The algorithm has two operating modes with (1) one image pair of Landsat and MODIS and a MODIS image for a prediction date, and (2) with two Landsat and MODIS image pairs and a MODIS prediction between dates of image pairs. This study used mode (1) for the simulation, and the datasets used for the fusion process included 41 8-day MODIS images covering two rice cropping systems in 2007 (i.e., winter-spring and summer-autumn crops) from day of year (DOY) 305 in 2006 to 257 in 2007, and a Landsat image created from the three aforementioned Landsat images acquired in January. Thus, MODIS image dates between two consecutive MODIS images predicted the resolution of the Landsat data. In this study, the Landsat image (acquired in Feb) was used as a reference to verify the data fusion results of the DOY 033 image so that EVI2 were calculated for each dataset and compared using a simple linear regression technique.

Construction of time-series EVI2 fusion data

EVI2 [Jiang et al., 2008] was used in this study for rice crop phenology detection and classification, calculated using the following Equation:
where $\rho_{\text{red}}$ and $\rho_{\text{nir}}$ are surface reflectance of MODIS-Landsat fusion bands 1 and 2. Henceforth, EVI2 calculated from STARFM datasets is noted as sfmEVI2 to differentiate it from Landsat EVI2 data. To create the time-series sfmEVI2 data for the study period (DOY 305 in 2006 to DOY 257 in 2007), we first calculated sfmEVI for every 8-day MODIS-Landsat fusion image. In total, 41 images were generated and stacked into one 8-day composite scene (41 bands). Because the time-series sfmEVI2 data presented some individual band noise caused by cloud cover in the tropical region, the pixels covered by thick clouds were first identified and removed if blue band reflectance values (extracted from MODIS MOD09A1 product) were >0.2. The missing values were replaced with new values from the profile using temporal linear interpolation.

**Rice crop phenology detection and classification**

EVI2 evolutions throughout each cropping season were fitted using the double logistic equation, expressed as follows:

$$
y(t) = e + (f - e) \times \left( \frac{1}{1 + e^{-(t-b)}} + \frac{1}{1 + e^{c(t-d)}} - 1 \right) \quad [3]
$$

where $t$ is time and $y(t)$ is the sfmEVI2 value at time $t$ for a given cropping season; $e$ and $f$ are the maximum and minimum values in the time-series sfmEVI2 data; and $a$, $b$, $c$, and $d$ are fitting parameters, where $b$ and $d$ are related to the rates of increasing and decreasing inflection points $a$ and $c$. These parameters are retrieved through an iterative process on a pixel basis.

We estimated sowing and harvesting dates from phenological events of rice plant computed from the logistic-based fitted time-series sfmEVI2 data using second and third derivatives (Fig. 3). Because rice fields were often irrigated before sowing, sfmEVI2 responses from rice fields were relatively low during this period. The rice plants grow quickly after sowing, quickly increasing sfmEVI2 values; thus, the sowing date can be estimated using the greenup onset or inflection point (i.e., the point at which the concavity changes from negative to positive) using the third derivative. The point earlier than this inflection point was determined as the sowing date. Likewise, because sfmEVI2 values begin leveling off after harvesting, the harvesting date can thus be estimated from the inflection point (i.e., the point at which the concavity changes from positive to negative) using the second derivative. The point after this inflection point was determined as harvesting date.

Rice crop classification was subsequently performed using information for sowing, heading, and harvesting dates. We defined the heading date as the date at which the rice plant is completely emerged, leading to the maximum EVI2 value. This date can be identified from the smooth sfmEVI2 profile using the local maxima algorithm, and it must be between the maturity onset (i.e., the date when plant green leaf area reaches the maximum sfmEVI value) and the senescence onset (i.e., the date when photosynthetic activity and green leaf
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area begin to decrease). Similarly, the greenup and senescence dates can also be estimated by the transition dates corresponding to the times when the rate change in the curvature in the EVI2 data exhibit local minima or maximums. In this study, a threshold of 0.6 was set based on the analysis of sfmEVI2 rice profiles to remove unrealistic cropping patterns. Moreover, the duration from sowing to harvesting should not be longer than 120 days (15-day sfmEVI2 composite period), given the length of rice cycle in the study region is approximately 90-100 days. Because forests occupy mountainous areas, elevation higher than 50 m were masked out using Aster DEM (30 m resolution). Permanent water bodies and built-up areas were also ignored from the analysis for sfmEVI2 values <0.3 during at least 35 8-day composite periods (280 days) during a year.

![Figure 3 - A schematic illustration of the double logistic-based method used to determine phenological events of rice plant during a cropping cycle. The dash and solid lines are the original and double-based logistic smooth sfmEVI2 profiles.](image)

**Error verification**

The estimated sowing and harvesting dates were verified using the field survey data collected during the 2007 winter-spring and summer-autumn cropping seasons. The root mean squared error (RMSE) was used to measure the variation between the observed and estimated results. The accuracy of the mapping results were assessed so that 1,000 pixels for each class (i.e., rice and non-rice) randomly extracted from the ground reference data (Fig. 1) compared with those of the rice crop maps delineated from the MODIS-Landsat data fusion using the confusion matrix.
Results and discussion

Correlation between sfmEVI2 and Landsat EVI2 data

This study used the smooth time-series sfmEVI2 data (derived from double logistic method) to determine phenological events of rice plant for the winter-spring and summer-autumn cropping seasons and accordingly mapped spatial distributions of rice growing areas in the study region. Thus, we verified the accuracy of MODIS-Landsat data fusion results by examining the relationship between sfmEVI2 data (calculated from the MODIS-Landsat fusion data on 02 Feb 2007) and Landsat EVI2 data calculated from the three images covering the study region acquired on 03 Feb 2007 (path/row: 125/053) and on 10 Feb 2007 (126/052 and 126/053), ignoring cloudy areas where the reflectance value of Landsat blue band was >0.2 (Fig. 4).

Through visual interpretation, the sfmEVI2 intensity of rice fields in the fusion image (Fig. 4a) acquired in the winter-spring crop (Nov-Dec to Feb-Mar) was comparable with that of the Landsat EVI2 image (Fig. 4b). The EVI2 intensity of rice fields, in both cases, was clearly distinguishable from those of forested areas as well as the built-up areas located along rivers and canals. Thus, information of EVI2 intensity through the cropping season was important for exploring temporal changes of rice crop phenology at the MODIS 8-day temporal resolution and Landsat 30-m spatial resolution.

Analyses of the relationship between these two sfmEVI2 and Landsat EVI2 images were carried out using a scatterplot, which indicated a strong positive correlation ($R^2 = 0.93$) between the two datasets (Fig. 5). A majority of the data points was evenly distributed along the diagonal line of the figure, and the slope value of 0.96 in the linear equation revealed little variation between the two datasets. Some individual outliers in the scatterplot toward sfmEVI2 values was observed, partly attributed to the timing difference between the
acquisition dates of Landsat EVI2 and sfmEVI2 images, as well as the edge effects of water bodies and built-up areas in the image during the MODIS-Landsat data fusion processing.

Figure 5 - A scatterplot shows the correlation between sfmEVI2 (04 Jul 2007) and Landsat EVI2 (05 Jul 2007).

**Figure 5**

### Compare estimated sowing and harvesting dates with field survey data

The results of the estimated sowing and harvesting dates obtained from the analysis of the time-series sfmEVI2 data using the second and third derivatives of the logistic-based fitting of the time-series sfmEVI2 data were compared with the field survey data and indicated satisfactory agreement between these datasets (Fig. 6). In general, the RMSE values were around 5-12 days, provided the interval between the synthetic MODIS-Landsat images was 8 days. The RMSE values of sowing and harvesting dates achieved for the winter-spring crop were, respectively, around 8 and 5 days (Fig. 6a, b), while the values for the summer-autumn crop were around 9 and 12 days (Fig. 6c, d). Larger errors were especially observed for the summer-autumn cropping season (compared to the winter-spring cropping season), partially attributed to unfavorable climatic conditions occurring by the end of this growing season. The onset of rainy months (May-Oct) often brings heavy cloud cover into the study region months and could affect spectral responses of MODIS bands, consequently contaminating the time-series sfmEVI2 data.

Some outliers exaggerated errors of crop phenology detection. For example, at the survey site of Long Dien B (Figs. 1, 6a), the sowing calendar noticeably varied among rice fields. The results from farmer interviews indicated that the sowing date of two rice fields was 16
Dec 2006, while that of the other three was 25 Dec 2006, although four of rice fields were harvested on 28 Mar 2007 and the other on 30 Mar 2007. The comparison between the estimated sowing dates and field survey data for the three rice fields, which had a sowing date 10 days later, was approximately 15 days, while the value for the other two fields was 6 days. The same problem was observed for the site of My Hoi Dong (Fig. 6a), where the sowing date of two rice fields was approximately 6 days late compared to the other three fields, leading to a relative error of 15 days. Similarly, at the Vinh Chanh site (Fig. 6d), based on information provided by farmers, rice cultivation began 7 Apr 2007 and was harvested 2 Jul 2007. This harvesting time was relatively early, and the length of the rice cycle was only 86 days (compared to a normal crop of 90-100 days), thus leading to a relative error of 28 days between the estimated harvesting date and field survey data. Although in this study we were unable to verify the results of sowing and harvesting dates provided by farmers through interviews, the quantitative information from satellite data could be used by crop managers to monitor sowing and harvesting activities to prevent potential effects of rice diseases and improve weed control.

![Figure 6](image)

**Figure 6** - Comparison results between: (a) estimated sowing dates and field survey data for winter-spring crop, (b) estimated harvesting dates and field survey data for winter-spring crop, (c) estimated sowing dates and field survey data for summer-autumn crop, and (d) estimated harvesting dates and field survey data for summer-autumn crop.

The results of the estimated sowing and harvesting dates were categorized into six classes corresponding to DOY in 2006 and 2007 to show the spatiotemporal distributions of the estimated sowing and harvesting progresses across the study region (Fig. 7). In general,
most of rice fields of the winter-spring crop in the study region were sown between DOY 321 and 329 (i.e., 25 Nov 2006-3 Dec 2006) (Fig. 7a), except for some areas located along rivers and in the upper part of the region that were sown earlier, between DOY 321 and 329 (17-25 Nov 2006), probably due to the early withdraw of flood waters allowing farmers to sow seeds early to avoid rice diseases and improve weed control.

Figure 7 - Spatial distributions of estimated sowing and harvesting progress: (a) sowing date of winter-spring crop in 2006, (b) harvesting date of winter-spring crop in 2007, (c) sowing date of summer-autumn crop in 2007, and (d) sowing date of summer-autumn crop in 2007.

The sowing activity in some areas of Cho Moi and Phu Tan districts was relatively late, between DOY 345 and 353 (12 Nov-19 Dec), because most rice fields in these districts were protected by high dykes that allowed farmers to practice three crops per year. The cropping calendar of the third crop (autumn–winter season) often lasts from Jul-Sep to Oct-Dec,
delaying the sowing progress of the winter-spring crop compared to other districts in the province. The spatial distributions of harvesting dates of this winter-spring crop generally corresponded to the sowing calendar, given that rice varieties of 90-100 days were applied (Fig. 7b).

A similar phenomenon was also observed for the summer-autumn crop. A majority of the study region was sown during DOY 097-105 (4-15 Apr 2007) (Fig. 7c) and harvested between DOY 209-217 (28 Jul-5 Aug 2007) (Fig. 7d). The sowing activity of some areas practicing three crops per year and protected by dykes in Phu Tan, Cho Moi, and Thoai Son districts was approximately one week later, between DOY 105 and 113, compared to other districts where farmers practiced two crops year. Earlier planting helps to avoid unfavorable weather conditions (e.g., storms and heavy rains) at the end of the season, which can potentially effect rice crop yields.

**Rice crop distributions and mapping accuracies**

The mapping results obtained from the classification of the logistic-based smooth time-series sfmEVI2 data for the 2007 winter-spring and summer-autumn cropping seasons indicated comparable spatial distributions of rice (Fig. 8) with the ground reference map collected from the government (Fig. 1). In general, rice in both cropping seasons was spatially concentrated along rivers due to favorable year-round irrigation conditions. Rice cropping was limited in parts of the western region due to unfavorable terrain and soil conditions that were major limiting factors to rice production.

![Figure 8 - Distributions of rice crops in the study area: (a) winter-spring crop, and (b) summer-autumn crop.](image)

Pixel-by-pixel comparisons between the classification maps and the ground reference data using 1,000 pixels (500 for each class) were performed for each cropping season to assess the accuracy of the mapping algorithm. The overall accuracies and Kappa coefficients...
were, respectively, 93.2% and 0.86 for the winter-spring crop and 91.7% and 0.83 for the summer-autumn crop (Tab. 1). In general, a lower accuracy level was observed for the summer-autumn cropping season (May-Jun to Aug-Sep) because it was practiced during the rainy season (May-Oct) when frequent occurrence of cloud cover can reduce the quality of MODIS images, consequently affecting the spectral responses of rice signature sfmEVI2 intensity, thus lowering the classification results.

Table 1 - Results of the classification accuracy assessment.

| Ground reference data | Classification results |
|-----------------------|------------------------|
|                       | Rice  | Non-rice | Total |
| **Winter-spring cropping season** |       |         |       |
| Rice                   | 453   | 47      | 500   |
| Non-rice               | 21    | 479     | 500   |
| Total                  | 474   | 526     | 1000  |
| Producer accuracy (%)  | 90.6  | 95.8    |       |
| User accuracy (%)      | 95.6  | 91.1    |       |
| Overall accuracy (%)   | 93.2  |         |       |
| Kappa coefficient      | 0.86  |         |       |

| **Summer-autumn cropping season** |       |         |       |
| Rice                   | 440   | 60      | 500   |
| Non-rice               | 23    | 477     | 500   |
| Total                  | 463   | 537     | 1000  |
| Producer accuracy (%)  | 88    | 95.4    |       |
| User accuracy (%)      | 95    | 88.8    |       |
| Overall accuracy (%)   | 91.7  |         |       |
| Kappa coefficient      | 0.83  |         |       |

The consistency between the mapping results of rice cropping areas (derived from the double logistic-based classification of sfmEVI2 data) with the rice area statistics collected from the government at the district level indicated close agreement between these two datasets ($R^2 > 0.9$) (Fig. 9). The results in both cases showed the root mean squared error (RMSE) smaller than 10%, indicating the consistency between the government’s statistics and the rice cropping areas (derived from satellite data). The values of relative error in area (REA) achieved for the winter-spring crop was approximately 2.4%, while that for the summer-autumn crop was 3.3%. The larger REA was observed for the summer-autumn crop due to effects of unfavourable weather conditions during the rainy season. In general, error sources exaggerated the mapping results. For example, in mountainous areas of the Tri Ton district, rice fields were generally small, fragmented, and often mixed with other LUC types, such as upland crops, forests, and orchards planted along roads,
causing rice signatures to be confused with those of other LUC types and leading to misclassification of these rice cropping areas. Moreover, the study region was occupied by dense, small canals with a width smaller than a Landsat pixel. This mixed-pixel issue in districts where small patches of rice fields were mixed with LUC types could complicate the classification process, leading to over-prediction and, consequently, mapping errors.

Figure 9 - District-level comparisons between the classification results and the government’s rice area statistics: (a) winter-spring crop, and (b) summer-autumn crop.

Conclusions

This study investigated phenological events and mapped rice growing areas for the 2007 winter-spring and summer-autumn cropping seasons from the MODIS-Landsat fusion data using STARFM and double logistic algorithms. The data fusion results obtained by comparing sfmEVI2 with Landsat EVI2 data indicated consistency between these two datasets ($R^2 = 0.93$). The double logistic method was applied to the time-series sfmEVI2 data for crop phenology detection. The estimated sowing and harvesting dates compared with those from the field survey data indicated that RMSE values of sowing and harvesting dates achieved for winter-spring crop were, respectively, around 8 and 5 days, and those for summer-autumn crop were around 9 and 12 days. The classification approach based on these phenological events was applied to the smooth the time-series EVI2 data, and a comparison of the classification results with the ground reference data yielded an overall accuracy and Kappa coefficient, respectively, of 93.2% and 0.96 for the winter-spring crop and 91.7% and 0.83 for the summer-autumn crop. These results were reaffirmed by a close agreement between the mapping results and government’s rice area statistics, with overestimated REA values of 2.4% and 3.3% for winter-spring and summer-autumn crops, respectively. This study demonstrates effectiveness of the double logistic algorithm applied to the multi-temporal MODIS-Landsat fusion data for rice crop phenology detection and classification. This method provides quantitative information of rice sowing and harvesting activities and growing areas in the study region useful for crop management and could thus be transferable to other regions for rice crop monitoring.
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References

Bartoszek K., Siluch M., Bednarczyk P. (2015) - Characteristics of the onset of the growing season in Poland based on the application of remotely sensed data in the context of weather conditions and land cover types. European Journal of Remote Sensing, 48: 327-344. doi: http://dx.doi.org/10.5721/EuJRS20154819.

Beck P.S.A., Atzberger C., Høgda K.A., Johansen B., Skidmore A.K. (2006) - Improved monitoring of vegetation dynamics at very high latitudes: A new method using MODIS NDVI. Remote Sensing of Environment, 100: 321-334. doi: http://dx.doi.org/10.1016/j.rse.2005.10.021.

Chen C.F., Huang S.-W., Son N.-T., Chang L.-Y. (2011) - Mapping double-cropped irrigated rice fields in Taiwan using time-series Satellite Pour l’Observation de la Terre data. Journal of Applied Remote Sensing, 5: 053528-053528. doi: http://dx.doi.org/10.1117/1.3595276.

Chen X., Vierling L., Deering D. (2005) - A simple and effective radiometric correction method to improve landscape change detection across sensors and across time. Remote Sensing of Environment, 98: 63-79. doi: http://dx.doi.org/10.1016/j.rse.2005.05.021.

Evenson R.E., Rosegrant M. (2003) - The economic consequences of crop genetic: Improvement programmes. Crop varietal improvement and its effects on productivity: The impact of international agricultural research. CABI Publishing, CAB International, Wallingford, UK. doi: http://dx.doi.org/10.1079/9780851995496.0000.

Fangping D., Gaoli S., Chuang L. (2007) - Seasonal variation of MODIS vegetation indexes and their statistical relationship with climate over the subtropic evergreen forest in Zhejiang, China. IEEE Geoscience and Remote Sensing Letters, 4: 236-240. doi: http://dx.doi.org/10.1109/LGRS.2006.888844.

FAO (2010) - Food outlook: global market analysis. Food and Agriculture Organization of the United Nations, Rome, Italy.

Feng G., Masek J., Schwaller M., Hall F. (2006) - On the blending of the Landsat and MODIS surface reflectance: Predicting daily Landsat surface reflectance. IEEE Transactions on Geoscience and Remote Sensing, 44: 2207-2218. doi: http://dx.doi.org/10.1109/TGRS.2006.872081.

Gaulton R., Hilker T., Wulder M.A., Coops N.C., Stenhouse G. (2011) - Characterizing stand-replacing disturbance in western Alberta grizzly bear habitat, using a satellite-derived high temporal and spatial resolution change sequence. Forest Ecology and Management, 261: 865-877. doi: http://dx.doi.org/10.1016/j.foreco.2010.12.020.

GSO (2010) - Statistical yearbook of Vietnam. General Statistics Office of Vietnam, Vietnam.

Gumma M.K., Thenkabail P.S., Maunahan A., Islam S., Nelson A. (2014) - Mapping seasonal rice cropland extent and area in the high cropping intensity environment of Bangladesh using MODIS 500 m data for the year 2010. ISPRS Journal of Photogrammetry and Remote Sensing, 91: 98-113. doi: http://dx.doi.org/10.1016/j.isprsjprs.2014.02.007.
Hilker T., Wulder, M.A., Coops N.C., Seitz N., White J.C., Gao, F., Masek J.G., Stenhouse G. (2009) - Generation of dense time series synthetic Landsat data through data blending with MODIS using a spatial and temporal adaptive reflectance fusion model. Remote Sensing of Environment, 113: 1988-1999. doi: http://dx.doi.org/10.1016/j.rse.2009.05.011.

Hossain M. (1997) - Rice supply and demand in Asia: A socioeconomic and biophysical analysis. In: Applications of systems approaches at the farm and regional levels. Kluwer Academic Publishers, Dordrecht, Netherlands. doi: http://dx.doi.org/10.1007/978-94-011-5416-1_20.

Intergovernmental Panel on Climate Change (2007) - Climate change: AR4 synthesis report. Cambridge University Press.

Jiang Z., Huete A.R., Didan K., Miura T. (2008) - Development of a two-band enhanced vegetation index without a blue band. Remote Sensing of Environment, 112: 3833-3845. doi: http://dx.doi.org/10.1016/j.rse.2008.06.006.

Julien Y., Sobrino J.A. (2009) - Global land surface phenology trends from GIMMS database. International Journal of Remote Sensing, 30: 3495-3513. doi: http://dx.doi.org/10.1080/01431160802562255.

Le Trong H. (2012) - The rice situation in Vietnam. Asian Development Bank, Manila, Philippines.

Mackay P., Russell M. (2011) - Socialist Republic of Viet Nam: Climate change impact and adaptation study in the Mekong Delta. Asian Development Bank, Manila, Philippines.

Maclean J.L., Dawe D.C., Hardy B., Hettel G.P. (2002) - Rice almanac: Source book for the most important economic activity on earth. CABI Publishing, Wallingford, UK.

Nguyen V.N., Do M.H., Nguyen N.A., Le V.K. (2004) - Rice production in the Mekong delta (Vietnam): Trends of development and diversification. Mekong Rice Conference 2004: Rice the Environment, and Livelihoods for the Poor, Ho Chi Minh City, Vietnam, pp. 15-17.

Pandey S., Byerlee D., Dawe D., Dobermann A., Mohanty S., Rozelle S., Hardy B. (2010) - Rice in the global economy: Strategic research and policy issues for food security. International Rice Research Institute, Philippines.

Richards J.A., Jia X. (2006) - Remote sensing digital image analysis: An Introduction. Springer-Verlag, New York, USA.

Schmidt M., Lucas R., Bunting P., Verbesselt J., Armston J. (2015) - Multi-resolution time series imagery for forest disturbance and regrowth monitoring in Queensland, Australia. Remote Sensing of Environment, 158: 156-168. doi: http://dx.doi.org/10.1016/j.rse.2014.11.015.

Schmidt M., Udelhoven T., Gill T., Röder A. (2012) - Long term data fusion for a dense time series analysis with MODIS and Landsat imagery in an Australian Savanna. Journal of Applied Remote Sensing, 6: 063512-063511-063512-063518.

Son N.-T., Chen C.-F., Chen C.-R., Duc H.-N., Chang L.-Y. (2013) - A phenology-based classification of time-series MODIS data for rice crop monitoring in Mekong Delta, Vietnam. Remote Sensing, 6: 135-156. doi: http://dx.doi.org/10.3390/rs6010135.

Sub-NIAPP (2002) - Land-use map of the Mekong Delta. The Sub-National Institute for Agricultural Planning and Projection, Ho Chi Minh City, Vietnam.

Timmer C.P. (2009) - A world without agriculture: The structural transformation in
historical perspective. American Enterprise Institute, Washington DC, USA.
Tornos L., Huesca M., Dominguez J.A., Moyano M.C., Cicuendez V., Recuero L., Palacios-Orueta A. (2015) - 
Assessment of MODIS spectral indices for determining rice paddy agricultural practices and hydroperiod. ISPRS Journal of Photogrammetry and Remote 
Sensing, 101: 110-124. doi: http://dx.doi.org/10.1016/j.isprsjprs.2014.12.006.
USDA (2012) - Vietnam: Record rice production forecast on surge in planting in Mekong Delta. United States Department of Agriculture, USA.
Vermote E.F., Kotchenova S.Y., Ray J.P. (2008) - MODIS surface reflectance user’s guide. NASA GSFC Terrestrial Information Systems Laboratory, Greenbelt, MD 20771, USA.
Wardlow B.D., Kastens J.H., Egbert S.L. (2006) - Using USDA crop progress data for the evaluation of greenup onset date calculated from MODIS 250-meter data. Photogrammetric Engineering & Remote Sensing, 72: 1225-1234. doi: http://dx.doi.org/10.14358/PERS.72.11.1225.
Watts J.D., Powell S.L., Lawrence R.L., Hilker T. (2011) - Improved classification of conservation tillage adoption using high temporal and synthetic satellite imagery. Remote Sensing of Environment, 115: 66-75. doi: http://dx.doi.org/10.1016/j.rse.2010.08.005.
Xiao X., Boles S., Liu J., Zhuang D., Frohling S., Li C., Salas W., Moore III B. (2005) - Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. Remote Sensing of Environment, 95: 480-492. doi: http://dx.doi.org/10.1016/j.rse.2004.12.009.
Zhang F., Zhu X., Liu D. (2014) - Blending MODIS and Landsat images for urban flood mapping. International Journal of Remote Sensing, 35: 3237-3253. doi: http://dx.doi.org/10.1080/01431161.2014.903351.
Zhang G., Xiao X., Dong J., Kou W., Jin C., Qin Y., Zhou Y., Wang J., Menarguez M.A., Biradar C. (2015) - Mapping paddy rice planting areas through time series analysis of MODIS land surface temperature and vegetation index data. ISPRS Journal of Photogrammetry and Remote Sensing, 106: 157-171. doi: http://dx.doi.org/10.1016/j.isprsjprs.2015.05.011.
Zhang X., Friedl M.A., Schaaf C.B., Strahler A.H., Hodges J.C.F., Gao F., Reed B.C., Huete A. (2003) - Monitoring vegetation phenology using MODIS. Remote Sensing of Environment, 84: 471-475. doi: http://dx.doi.org/10.1016/S0034-4257(02)00135-9.
Zhao H., Yang Z., Di L., Pei Z. (2012) - Evaluation of temporal resolution effect in remote sensing based crop phenology detection studies. In: Li D., Chen Y. (Eds.), Computer and Computing Technologies in Agriculture V. Springer Berlin Heidelberg, pp. 135-150. doi: http://dx.doi.org/10.1007/978-3-642-27278-3_16.

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