REVIEW

Detection of Yearly Change in Farming Systems in the Vietnamese Mekong Delta from MODIS Time-Series Imagery

Toshihiro SAKAMOTO[1]*, Phung CAO Van[2], Aikihiko KOTERA[1], Khang NGUYEN Duy[3] and Masayuki YOKOZAWA[1]

[1] National Institute for Agro-Environmental Sciences (Tsukuba, Ibaraki 305–8604, Japan)
[2] Cuu Long Delta Rice Research Institute (Omon, Can Tho, Vietnam)
[3] Southern Institute for Water Resources Research (Ho Chi Minh city, Vietnam)

Abstract

This paper briefly introduces an integrated remote-sensing methodology based on MODIS time-series imagery for detecting spatiotemporal changes in Vietnamese Mekong Delta (VMD) farming systems. The integrated methodology consists of six parts, and uses a wavelet-based filter to smooth MODIS-derived time-series indexes (EVI, LSWI, and DVEL) from 2000 to 2008. Through a proposed decision tree using the smoothed indexes, we classified several farming systems, viz., triple rice cropping, two types of double rice cropping, shrimp–rice farming (rotational cropping), and inland aquaculture (monoculture). The MODIS-derived estimate of the total rice-planted area, shrimp–rice farming area, and inland aquaculture area agreed well with statistical data at the province level ($R^2 \geq 0.96$). However, in some provinces, the estimate has a large margin of error, probably because of the mixed-pixel effect due to the moderate spatial resolution of MODIS (250 m). According to the estimated spatial pattern of the farming systems in the whole VMD, inland aquaculture and shrimp–rice farming areas are distributed mostly in the coastal provinces. The areas of the farming systems steadily expanded until 2007, and double rice cropping systems in both upper and coastal regions were replaced by triple rice cropping because of infrastructure improvements. The proportion of the triple rice cropping area peaked in 2005 and then declined steadily over the next 2 years. We discuss the advantage of the proposed methodology for detecting the spatiotemporal changes of land use patterns, especially of farming systems in a regional area.

Discipline: Agricultural environment
Additional key words: remote sensing, flood, saline water intrusion, rice cropping, shrimp farming

Introduction

In recent years, the effects of global warming and rapidly changing oil prices on global food production have become significant worldwide issues threatening global food security. For food exporting countries, the global rise in food prices will be an incentive to increase income through expansion of agricultural regions, improvement of agricultural infrastructure, and intensification of farming systems. For food importing countries, analysis of changes in farming systems can offer insights into future food productivity in exporting countries. Despite the uncertainty in the global food supply, the world population is expected to increase by 9.4% to 12.0% above 2005 levels by 2015[22]. This means that the world demand for cereals will steadily increase in the near future. On the other hand, large amounts of agricultural land have been converted to non-agricultural use: to residential areas and transportation infrastructures in enlarged city zones; and to aquaculture ponds in developing countries in response to increased demands for animal protein and aquatic products for domestic consumption and export to developed countries.

A great deal of information about foreign agriculture is globally distributed through the Internet. We can freely access the statistical data reported by foreign governments and hot topics of agricultural import in on-line

newspapers. However, except for experts in agricultural matters, it is difficult for the public to imagine how the agricultural environments and cropping systems are changing by relying only on brief news articles and the numbers in statistical tables. Official statistical data offer most objective measure of the yearly trend of agricultural productivity on national scale, provide little insight into spatiotemporal information, such as the crop-growing season, the number of crops per year, and land use change. Therefore, remote sensing technology, which provides terrestrial observation data accurately and at low cost, is indispensable to obtaining new perspectives about global food-production areas. In the target area of this study—the Vietnamese Mekong Delta (VMD)—various types of satellite data have been used for monitoring crop growth and environmental changes. Liew et al. (1998) classified the rice cropping systems around Soc Trang province by an index of the change in the backscattering coefficient of ERS-2 Synthetic Aperture Radar data[11]. Tanaka et al. (2003) used special sensor microwave/imager (SSM/I) data for monitoring floods in Tonle Sap and the Mekong catchment. The time-series SSM/I data revealed a phase shift in the flood–drought cycle from 1997 to 1999[20]. Fujii et al. (2003) used 2002 RADARSAT data to reveal the progression of flooding in the Cambodian floodplain of the Mekong River[5]. Tong et al. (2004) classified the land cover pattern in the coastal region of Tra Vinh province by using SPOT4 imagery in order to assess the effects of shrimp aquaculture on mangrove ecosystems[21]. Binh et al. (2005) revealed the land cover changes in shrimp farming from 1968 to 2003 in Cai Nuoc district, Ca Mau province, from aerial, SPOT4, and Landsat/ETM+ images[2]. Haruyama and Shida (2008) visualized the flooding of the Mekong Delta in 1997 and 1998, and prepared a geomorphologic land classification map from JERS-1 SAR data[7]. The freely distributed MODIS time-series imagery offers scope for monitoring crop growing and farming systems. This paper briefly introduces new ideas for using MODIS time-series imagery to monitor the agricultural environment in space and time and reveals yearly changes in the farming systems of the VMD from 2000 to 2007 by using an integrated image-processing algorithm.

Study area

The VMD is located in the southern part of Indochina, at the mouth of the Mekong River (Fig. 1). This area is affected by the Asian monsoon, and there are clear seasonal changes in precipitation between the dry and rainy seasons. According to the Köppen climate classification, the climate of the VMD is classified into savanna and tropical monsoon types. The tropical climate, without risk of low-temperature injury, is suited for multiple rice cropping. Therefore, on farmland with good irrigation drainage management and adequate soil, farmers can raise three rice crops a year with modern rice cultivars that have a short growing period (90–100 days). However, the area eligible for triple rice cropping is geographically limited because of various environmental factors: for example, annual Mekong floods, saline water intrusion, acid sulfate soil, and insects.

In 2005, Vietnam was the world's second largest rice exporter after Thailand[23], as well as the world's largest frozen shrimp exporter[4]. It is particularly worth noting that 80% to 85% of the rice exported from Vietnam is produced in the VMD[13], and that 81% of gross domestic farmed shrimp production also comes from the VMD[6]. Most countries that import Vietnamese rice are developing countries, notably the Philippines and Indonesia. In contrast, most countries that import farmed shrimp are developed, including the EU, the USA, and Japan. Agriculture and fisheries in the VMD play an important role in acquiring foreign currency for Vietnam.

MODIS products

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an optical sensor mounted on the Earth-observing satellites EOS AM and EOS PM, which are
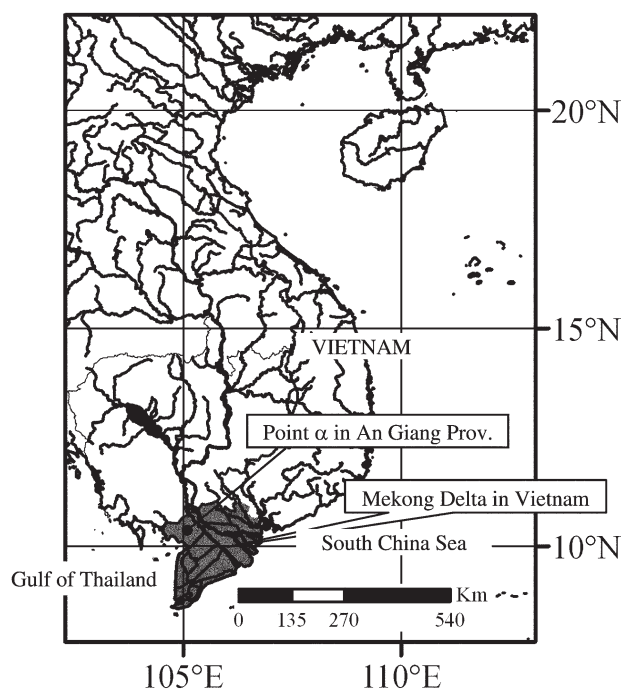

Fig. 1. Study area

commonly known as Terra and Aqua. Terra and Aqua were launched into synchronous sub-recurrent orbit at an altitude of 705 km in December 1999 and May 2002, respectively. The recurrence period of both satellites is 16 days. Terra passes above the equator at 10:30 am from north to south. Aqua passes above the equator at 1:30 pm from south to north. This study used only products acquired by MODIS/Terra, which are freely distributed through the Earth Observing System Data Gateway (EOS[3]). MODIS observes spectral data in 36 bands ranging in wavelengths from 0.4 to 14.4 µm. The spatial resolution varies by band (Table 1). The observation swath of MODIS is so wide (2330 km) that it is possible to observe identical locations nearly every day. However, cloud cover often interrupts land surface observations. The actual data are affected by the atmospheric state and the mixed-pixel effect due to the moderate spatial resolution (250–500 m). This study used MOD09 8-day composite products with 250- and 500-m resolutions, acquired over the last 8 years from day-of-the-year (DOY) 57 in 2000 to DOY 64 in 2008. These products have already been corrected for atmospheric effects, yielding the best possible surface spectral-reflectance data for each 8-day period.

Methodology

In common land-use classification methods using optical satellite imagery, objective pixels are classified by the supervised/unsupervised classification method on the basis of the spectral reflectance characteristics under the assumption that the same land use categories have similar spectral reflectance characteristics. Yet the spectral reflectance characteristics of agricultural lands are continuously changing with crop growth and agricultural management. By using the traditional approach, it would be

Table 1. Description of the MODIS products

MODIS product band name	Nominal resolution	[Wavelength] Description
sur_refl_b01	250 m	[620–670 nm] RED
sur_refl_b02	250 m	[841–876 nm] NIR (near-infrared)
sur_refl_b03	500 m	[459–479 nm] BLUE
sur_refl_b04	500 m	[545–565 nm]
sur_refl_b05	500 m	[1230–1250 nm]
sur_refl_b06	500 m	[1628–1652 nm] SWIR (short-wave infrared)
sur_refl_b07	500 m	[2105–2155 nm]
sur_refl_day_of_year	500 m	DOY, observation date

difficult to identify the slightly different kinds of areas where cropping patterns are the same but cropping schedules are shifted. When classifying farming systems over a wide area spanning several tens of kilometres, it is absolutely essential to extract temporal features of the target farming system from the time-series satellite imagery. Although various methods using satellite data have been proposed for classifying land use patterns and for monitoring natural vegetation and crop growth[1, 10, 14, 26], a systematic approach using time-series MODIS imagery had not been proposed for simultaneously evaluating the spatiotemporal distribution of crop phenology, rice cropping patterns, shrimp farming, flood inundation, and annual changes in the VMD. Therefore, we have proposed new concepts for spatiotemporally monitoring crop growth under the influence of water and environmental fluctuations based on the temporal profiles of three MODIS-derived indexes[15–19]: the Enhanced Vegetation Index (EVI[8]), the Land Surface Water Index (LSWI[27, 28]), and the difference value between the EVI and the LSWI (DVEL). The integrated algorithm for classifying the farming systems of the entire VMD is described in the next section.

Algorithm

The integrated algorithm flow chart is depicted in Fig. 2. This algorithm has six parts.

(A) Preprocessing: Wavelet-based filter for smoothing the temporal profile of the observed three indexes

Part A in Fig. 2 shows the core preprocessing procedure for the time-series analysis. First, routine image preparation is conducted: file format conversions, mosaicking, spatial subsetting, calculating the three indexes (EVI, LSWI, DVEL), building a multi-band file of the indexes, obtaining the reflectance data of the blue band, and combining with 250-m-resolution observation date. The map projection was converted to Universal Transverse Mercator (Zone 48N). EVI, LSWI, and DVEL are calculated from the surface reflectance data of four bands as follows:

$$EVI = 2.5 \times \frac{NIR - RED}{NIR + 6 \times RED - 7.5 \times BLUE + 1} \qquad (1)$$

$$LSWI = \frac{NIR - SWIR}{NIR + SWIR} \qquad (2)$$

$$DVEL = EVI - LSWI \qquad (3)$$

(A) Preprocessing

MODIS 8-day composite reflectance data

500-m resolution / 250-m resolution

Downscaling to 250 m

Changing formats

Blue reflectance (band 3) / Observation date / EVI, LSWI, DVEL

Smoothing process with the wavelet transformation
(mother wavelet: coiflet order = 4)

Noise-reduced time-series data

Smoothed EVI / Smoothed LSWI / Smoothed DVEL

Detecting the local maximal point (EVI ≥ 0.4)

Daily inundated area

Rice heading date

Number of rice crops per year
Growing season of each rice crop

Rice cropping pattern

Total annual inundation days / Start date, end date & duration of annual Mekong floods

(B) Detecting the rice heading season (WFCP)

(C) Detecting the number of rice crops per year and growing seasons (WFCS)

(D) Detecting inundation with MODIS data (WFFI)

(E) Detecting the inland aquaculture area (WFIA)

Maximum value of a year's EVI

Standard deviation of a year's EVI

Total annual inundation days ≥ 110 days and Maximum value of a year's EVI < 0.5

YES / NO

Maximum value of a year's EVI < 0.4

Is there any rice heading date in rainy season?

YES / NO

YES / NO

Masked area (e.g., forest, orchard, unused area)

Ancillary data

Land use map

Administrative boundary

Shrimp–rice farming

Extensive farming

Standard deviation of a year's EVI ≥ 0.1

Number of rice crops per year ≥ 2

NO / YES

Number of rice crops per year ≥ 3

NO / YES

NO / YES

Mixture in flood-prone area

Single rice cropping

Standard deviation of a year's EVI ≥ 0.1

Is there a rice heading date from January to March?

Standard deviation of a year's EVI ≥ 0.1

YES / NO

Inland aquaculture

NO

NO

Mixture (similar to double rice cropping)

Type 1 double rice cropping

Type 2 double rice cropping

Mixture (similar to triple rice cropping)

Triple rice cropping

YES

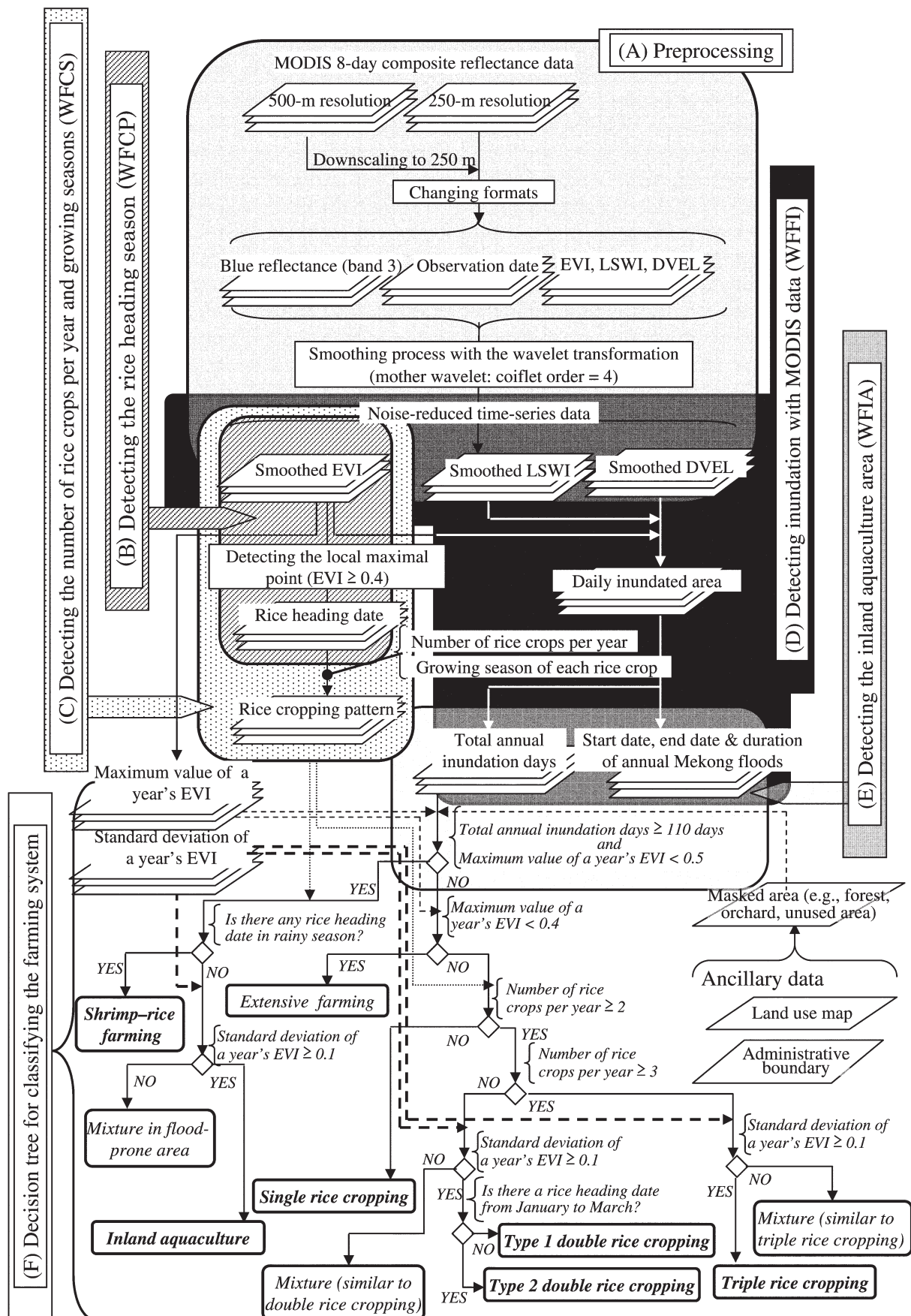(F) Decision tree for classifying the farming system

Fig. 2. Flow chart showing the integrated algorithms of the wavelet-based filter

where NIR, RED, BLUE, and SWIR are the surface reflectance values of each wavelength band (Table 1). We aimed at constructing a farming system map at a resolution of 250 m. Therefore, the BLUE and SWIR surface reflectance data and the observation date at 250-m resolution are produced by re-sampling the 500-m resolution MOD09 product by the nearest-neighbor method.

Figure 3 shows the temporal profile of observed EVI for point α in Fig. 1. Even if the surface reflectance data input is systematically preprocessed with atmospheric correction and 8-day composition, the some time-series index includes noise components, due mainly to cloud cover, viewing angle, the mixed-pixel effect, and the effect of bidirectional reflectance distribution. Before phenological information detection, these noise components should be removed from time-series data input. In other words, it is necessary to extract medium- to long-term seasonal components such as crop growth or flooding from the time-series indexes and remove the short-term noise components. The smoothing process for the observed input data (EVI, LSWI, and DVEL) is conducted as described below. See Sakamoto et al. (2006, 2007) for details[16, 17].

(1) The time-series data of blue-band reflectance, EVI, LSWI, and DVEL for each pixel are arranged daily by observation date. (2) If the pixel value of blue-band reflectance ≥0.2, the pixel is treated as missing data due to thick cloud cover. (3) The missing values in temporal indexes are linearly interpolated from the remaining data. (4) Finally, the linearly interpolated input indexes pass to the wavelet transformation with the specific mother wavelet (coiflet, order = 4). After high-frequency noise (<32 days) is removed from the wavelet-transformed input data, the smoothed index time profiles are reconstructed through the inverse-wavelet transformation. The threshold value (<32 days) in this process was empirically

determined in view of the short rice growing period (90–110 days) and the long waterlogging period (several months) during seasonal flooding and in the inland aquaculture area.

(B) Detecting rice heading season by wavelet-based filter for crop phenology (WFCP)

According to Sakamoto et al. (2005), the EVI value gradually increased with rice growth, and the peaks corresponded well to the rice heading seasons in the statistical data[15]. Sakamoto et al. (2005) named this the wavelet-based filter for detecting crop phenology (WFCP[15]), shown in part B of Fig. 2. The rice heading dates are estimated by detecting local maxima in the smoothed EVI profile in which the smoothed EVI values are ≥0.4.

(C) Detecting number of rice crops per year and growing seasons (WFCS)

In part C of Fig. 2, the number of rice crops per year and the growing seasons are measured from the smoothed EVI data. According to the wavelet-based filter for evaluating spatial distributions of cropping systems (WFCS[16]), the rice-cropping pattern was classified by using only these parameters. Although the rice cropping pattern in this paper is classified using the newly provided decision tree incorporating additional parameters (part F, Fig. 2), this method continues the fundamental concept of classifying multiple rice cropping using the peaks of EVI under the integrated algorithm.

(D) Detecting inundation with MODIS data (WFFI)

Seasonal flooding in each pixel is detected from a combination of smoothed EVI, LSWI, and DVEL in part D of Fig. 2. The surface reflectance value in the short-wave infrared band (band 6), which is applied to the LSWI calculation, is highly sensitive to moisture content.
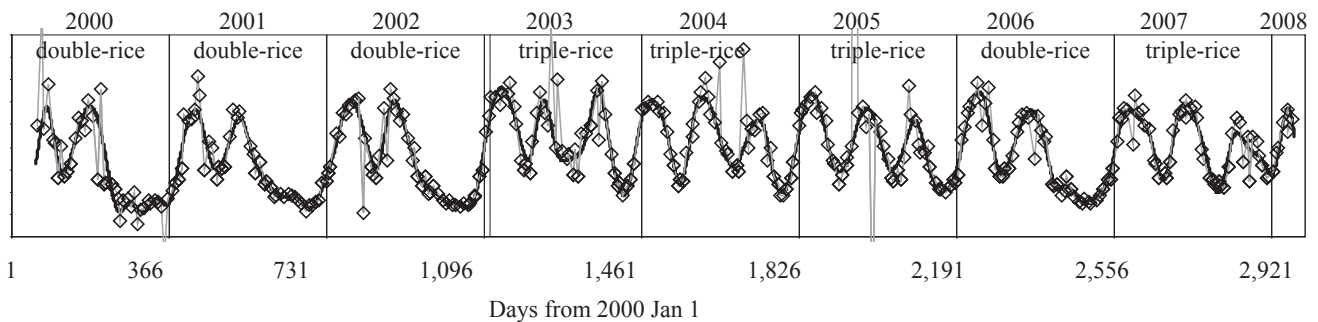

Fig. 3. Time-series EVI data showing change from double to triple rice-cropping systems in 2003
──: Smoothed EVI
─◇─: Observed EVI

Xiao et al. (2002) indicated that the difference between LSWI and vegetation indexes (NDVI or EVI) is effective for detecting flooded paddies[26]. Later, Sakamoto et al. (2007) devised a new approach for spatiotemporally evaluating the magnitude of annual Mekong flooding[17]. The method was named the wavelet-based filter for detecting spatiotemporal changes in flood inundation (WFFI).

The WFFI algorithm classifies the water surface into two categories, *mixture* and *flood*. A *flood* pixel implies that most of a pixel is covered by water. A *mixture* pixel implies that a pixel contains a mixture of water, vegetation, and soil coverage. For example, when rice is in the early growth stages under flooding, the paddy field is classified as a *mixture* pixel. We expect that the paddy fields during the flood season and right after sowing, which are fully submerged, are classified as *flood* by WFFI. The category is discriminated with the following conditions[17].

If condition (4) is satisfied, an objective pixel is classified as *mixture*.

If either condition (5) or (6) is satisfied, an objective pixel is classified as *flood*.

$$\text{Smoothed DVEL} \leq 0.05 \\ \text{and } 0.1 < \text{smoothed EVI} \leq 0.3 \tag{4}$$

$$\text{Smoothed DVEL} \leq 0.05 \text{ and smoothed EVI} \leq 0.1 \tag{5}$$

$$\text{Smoothed LSWI} \leq 0 \text{ and smoothed EVI} \leq 0.05 \tag{6}$$

The start date, end date, and duration of the annual Mekong flood are detected from the longest continuing period of *flood* or *mixture*. The yearly total of inundated days from DOY57 to DOY56 of the next year, including both *mixture* and *flood* situations, is used for the decision-tree classification in part F of Fig. 2.

(E) Detecting the inland aquaculture area (WFIA)

In part E of Fig. 2, pixels indicating inland aquaculture and shrimp–rice farming are detected if the annual total of inundated days (*flood* or *mixture*) ≥ 110 days[19]. However, to avoid the misclassification of rice cropping in flood-prone areas, the pixels whose yearly maximum EVI ≥ 0.5 are not counted as inland aquaculture or shrimp–rice farming areas. This simple method has been named the wavelet-based filter for detecting inland aquaculture (WFIA).

(F) Decision tree for classifying farming systems

The whole VMD is classified into 10 categories by using the decision tree and the various parameters derived from sections A to E above. Some parameters of each discriminant are empirically determined (part F, Fig. 2). Farming systems in 2000 were classified only into inland aquaculture and shrimp–rice farming areas, because the lack of MODIS data before DOY 57 in 2000 makes it difficult to classify multiple rice cropping systems.

As this study focuses on shrimp farming and multiple rice cropping, other areas such as orchards, unused land, and forests are masked by the 2002 ancillary use map[16]. The major farming systems determined by using the integrated algorithm are inland aquaculture, shrimp–rice farming, single rice cropping, type 1 double rice cropping, type 2 double rice cropping, and triple rice cropping. The unique aspects of these farming systems are explained as follows. In this study, inland aquaculture covers fields used only for raising fish or shrimp under extended waterlogging condition. Shrimp–rice farming covers agricultural fields used for shrimp farming in the dry season and rice cropping in the rainy season. Single rice cropping implies that the farmer crops rice once a year. Type 1 double rice cropping implies that the farmer crops rice twice a year, mainly in the rainy season. Type 2 double rice cropping implies that the farmer crops rice twice a year, including in the dry season. Triple rice cropping implies that the farmer crops rice three times a year. These six categories are sufficient for identifying distinctive changes in farming across the whole VMD. Four other categories—mixture 1 (similar to double cropping), mixture 2 (similar to triple cropping), mixture 3 (in annually flooded areas), and extensive farming—indicate that the objective pixels have no discriminating EVI feature, probably because of mixed-pixel effects.

Results and discussion

1. Mekong flood

Figure 4 shows the estimated duration of Mekong flood inundations from 2000 to 2007. The annual and yearly changes of the MODIS-derived Mekong floods showed a similar pattern to the maximum daily-averaged water level at Chau Doc station (Fig. 6)[17]. According to a spatiotemporal comparison between the growing season of the first rice crop and the end of flood inundation in the MODIS-derived results, annual changes in Mekong flood intensity have a strong impact on the rice-cropping season in the upper regions of the VMD[18]. The later the Mekong flood terminates, the later the first rice cropping season starts, because farmers in flood-prone areas must wait until the floodwater level has dropped to appropriate levels (<50 cm) for land preparation and sowing.
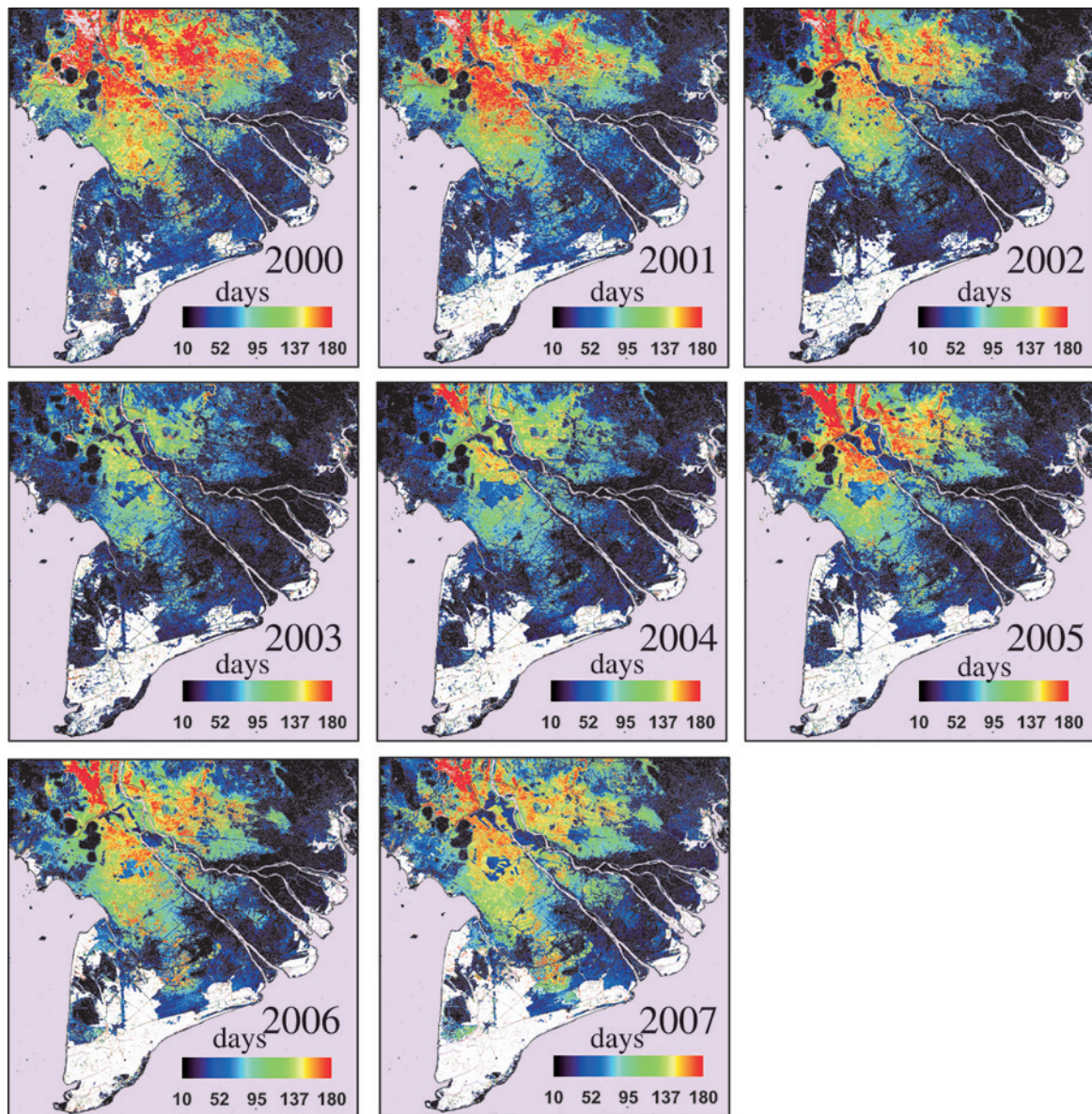
Fig. 4. Estimated duration of Mekong flood inundation cycles
☐: *Inland aquaculture area and shrimp–rice farming*
▨: *Long-term water bodies where the annual total of inundation days is ≥250 days*

2. Yearly change in farming systems from 2000 to 2007

Figure 5 shows the typical temporal profiles of the region-averaged EVI and the areal ratio of the water surface conditions (*flood* and *mixture*) from 2005 to 2008 at 8 sites (each ca. 400 ha). These sampling locations are shown in the map of predicted farming systems (Fig. 6).

(1) Rice cropping in the upper region

Type 1 double rice cropping was distributed mainly in the upper VMD, in An Giang, Dong Thap, Long An, and Kieng Giang provinces, from 2001 to 2007. This distribution corresponds with locations where the estimated

duration of Mekong flood inundation is longer than 3 months (Figs. 4, 6). The third rice crop is limited by longer periods of submersion caused by the annual Mekong flood in the upper region of the VMD.

Sites a and b (Fig. 5-1) are located in An Giang province, in the upper VMD. The two large annual peaks of smoothed EVI at site a indicate that double rice cropping is conducted mainly in the dry season. The first rice crop is usually grown from Jan–Feb to Mar–Apr. The second rice crop is grown from Apr–May to Jun–Jul. At site a, most of the paddies located in the flood-prone area are submerged from August to December every year. The
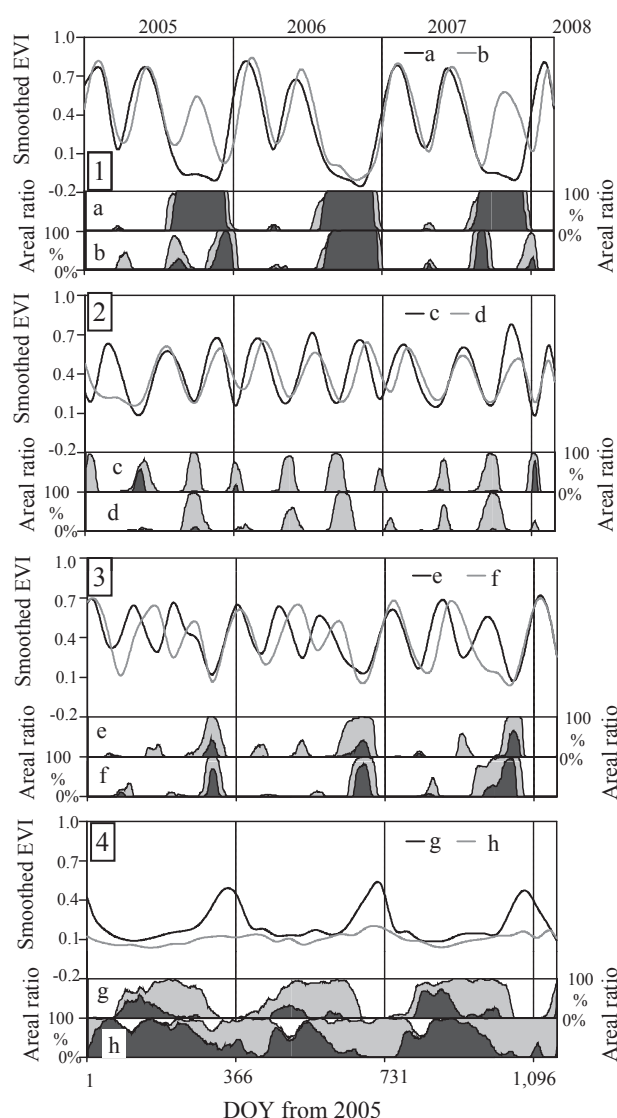
Fig. 5. Regional average of EVI and areal ratio of water-related pixels
☐: Areal ratio of *mixture* pixels
■: Areal ratio of *flood* pixels

darker shaded area of the areal ratio of *flood* pixels in Fig. 5-1 illustrates the annual flood duration. The long flood duration (>3 months; Fig. 4) makes it difficult to grow three rice crops because of the risk that the next year's flood will start before the third crop can be harvested. Site b, in contrast, is also located in a flood-prone area but exhibited additional EVI peaks in the rainy seasons of 2005 and 2007. This site is enclosed by a dike system, and a ring-dike system keeps out surrounding floodwaters in the early flood season. In such areas, the flooding period in the rainy season is shortened (Fig. 4), making it possible to grow the additional third rice crop during the rainy season. This type of triple-cropped area expanded

rapidly until 2005 in An Giang province (Fig. 6), but the situation changed in 2006, when extensive losses occurred owing to an outbreak of brown plant hopper (BPH) the VMD. Nguyen et al. (2007) pointed out that triple rice cropping allows populations of BPH to build up[12]. After this bitter experience, the local government encouraged farmers to conduct a triennial flood fallowing of the third rice crop; in other words, 8 rice crops per 3 years[18]. According to the history of the MODIS-derived triple-cropping areas and our field interviews with farmers in An Giang province in 2007, not every farmer equally followed this triennial flood fallowing during flood seasons[18]. Individual farmers' groups managing the dike system decide whether they grow the third rice crop or use flood fallowing.

(2) Rice cropping in the coastal region

The type 2 double rice cropping system is distributed mainly in the coastal VMD, in Bac Lieu, Soc Trang, Tra Vinh, and Long An provinces (Fig. 6). In this cropping system, both rice crops are grown mainly in the rainy season. In some coastal regions, rice cropping in the dry season is limited by the lack of irrigation water. Large tide amplitudes in the South China Sea and decreased Mekong River flow in the dry season allow seawater to intrude through the canal and river networks, increasing the salt concentration of irrigation water. If irrigation canals in the paddy field zone are affected by the saline water intrusion, the irrigation canals are cut off from the water supply by sluice gates, leaving insufficient fresh water supply.

Sites c and d (Fig. 5-2) are located in Bac Lieu province. In the temporal profile of site d, rice cropping in the dry season was less common before 2006. Because the water quality was improved by the construction of sluice gates, more and more farmers began additional rice cropping in the dry season. The temporal EVI data profile for site c implies that dry-season rice cropping was already conducted in 2005 in this area, ahead of site d. According to interviews with farmers around site d in 2007, the success of neighboring farmers' dry-season crops and recent high rice prices were sufficient incentives for farmers to follow the neighbors' attempts at growing a third rice crop in the dry season, even if they had to pay to rent an irrigation pump[19].

In the eastern part of Soc Trang province, dry-season cropping (triple cropping) expanded similarly from 2001 to 2003 (Fig. 6). It is interesting to note that the triple-cropped area in Bac Lieu and Soc Trang provinces spread out radially in a circle (Figs. 5-2, 6). However, after a huge loss in 2003 because of salinity-contaminated irrigation water, local authorities strongly discouraged dry-season rice cropping in Soc Trang province. A field
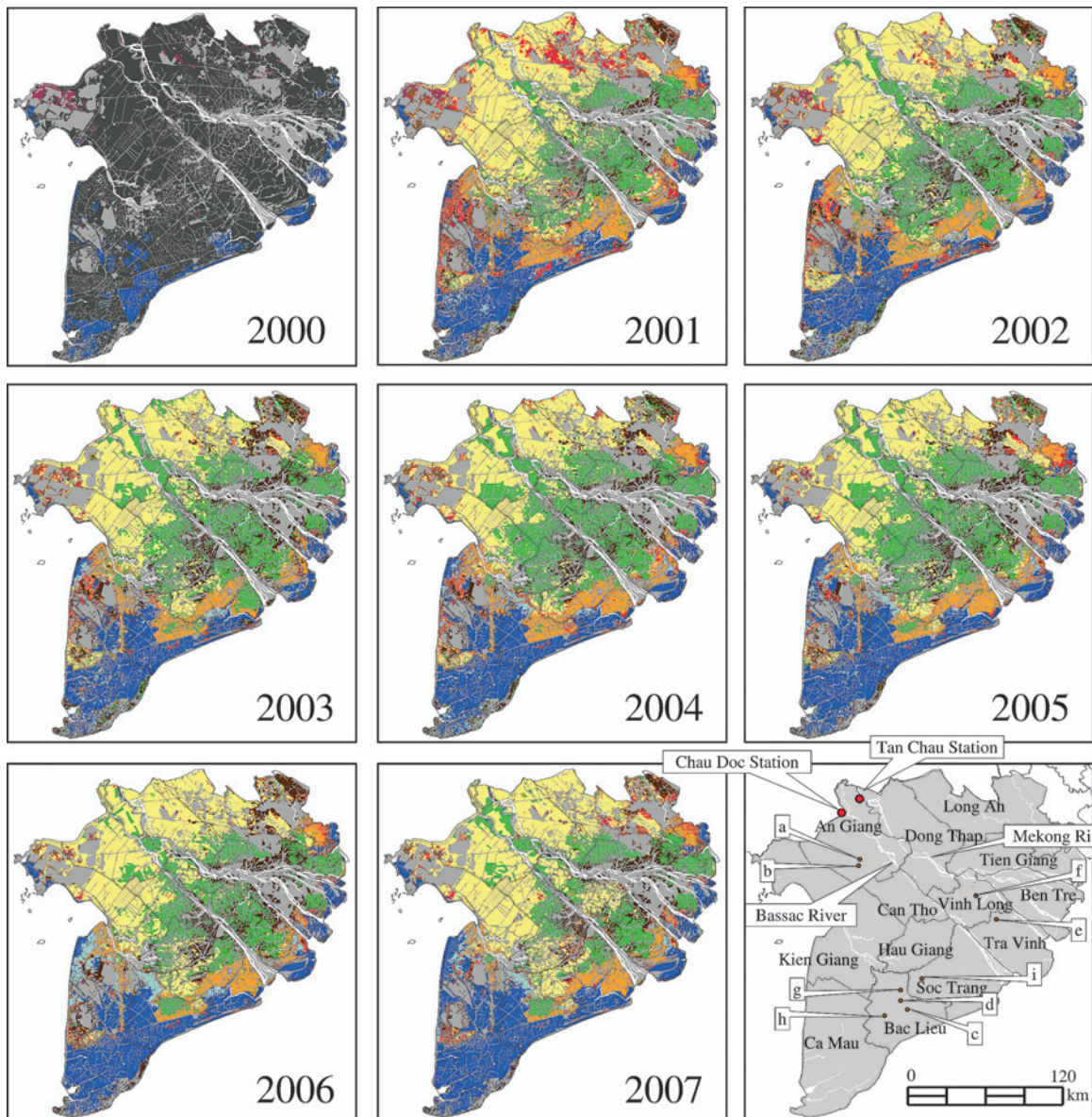
Fig. 6. Classification of results using MODIS time-series imagery

- ■ : Triple rice cropping
- ■ : Type 1 Double rice cropping, mainly in dry season
- ■ : Type 2 Double rice cropping, mainly in rainy season
- ■ : Single rice cropping
- ■ : Extensive farming
- ■ : Inland aquaculture (shrimp farming)
- ■ : Shrimp–rice farming
- ■ : Mixture 1 (similar to double cropping)
- ■ : Mixture 2 (similar to triple cropping)
- ■ : Mixture 3 (in annual flooded area)
- ■ : Masked area

■ : Not inland aquaculture*   * Only for the 2000 results

investigation in February 2008 revealed that dry-season cropping in Bac Lieu province is still expanding, and has begun again in a small part of Soc Trang province. The pioneering farmer who first conducted triple rice cropping in 2001 was motivated by the rice price increase. Both the improvement of water quality and the success of neighboring farmers appeared to play an important role in the enlargement of the triple-cropped area[19].

(3) Rice cropping in the middle region

Between the regions of type 1 double cropping in the upper flood-prone region and type 2 double cropping in the coastal salinity-intrusion region, triple cropping is practiced in Can Tho, Hau Giang, Dong Thap, Ving Long, Tra Vinh, Ben Tre, and Tien Giang provinces (Fig.

6). This middle region is less subject to flood inundation in the rainy season (Fig. 4) and to salinity intrusion in the dry season.

Sites e and f in Fig. 5-3 are located in Vinh Long province. As is shown in the temporal profile for site f (Fig. 5-3), most rice cropping in Vinh Long was changed from triple cropping to double cropping (Fig. 6) in 2007. According to interviews with farmers in 2008, the reduction of the triple rice-cropped area followed the recommendations to conduct a triennial fallow period during the third rice crop after the BPH outbreak in 2006.

In the rest of the VMD, however, the reason why the triple-cropped areas returned to double cropping is not always same as in Vinh Long province. Farmers in Thanh Tri district, Soc Trang province (Fig. 6, **i**), tried to grow a third crop from around 2000 to 2002, but failed to get sustainable rice yields because of too much water in the rainy season as a result of poor drainage. This implies that greater public investment in raising disease- or salinity-resistant rice cultivars is needed for sustainable rice production from the current irrigation system.

(4) Inland aquaculture (shrimp farming)

Although sites g and h in Fig. 5-4 are both used for aquaculture, typical EVI peaks indicating rainy-season rice cropping are evident at site g. Our algorithm divided this shrimp–rice farming system from exclusive inland aquaculture according to the maximum EVI values in the

rainy season (Fig. 2). Because of the mixture of water surface for shrimp farming and rice vegetation in the rainy season, it is difficult to detect smaller-scale shrimp–rice farming areas[19].

The water surface area for aquaculture (including fish ponds and shrimp farms) in the entire Mekong Delta increased continuously from 445 300 ha in 2000 to 717 500 ha (preliminary figure) in 2006[6]. Most of the inland aquaculture area is used for shrimp farming in coastal provinces. The MODIS-derived results indicate inland aquaculture areas and shrimp–rice farming areas in most coastal provinces: Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Kien Ginang, Ben Tre, and Long An (Fig. 6). In these provinces, salinity intrusion hinders rice cropping in the dry season. Conversely, access to brackish water encourages farmers to expand shrimp ponds and earn higher income in the coastal regions. The rapid increase in shrimp farming areas is closely linked with government decision No. 09/NQ-CP in 2000[2]. Given the flexibility of land use regulations and the high market value of shrimp products, shrimp farming quickly spread over coastal areas in the VMD.

Reliability of MODIS-derived farming system estimates

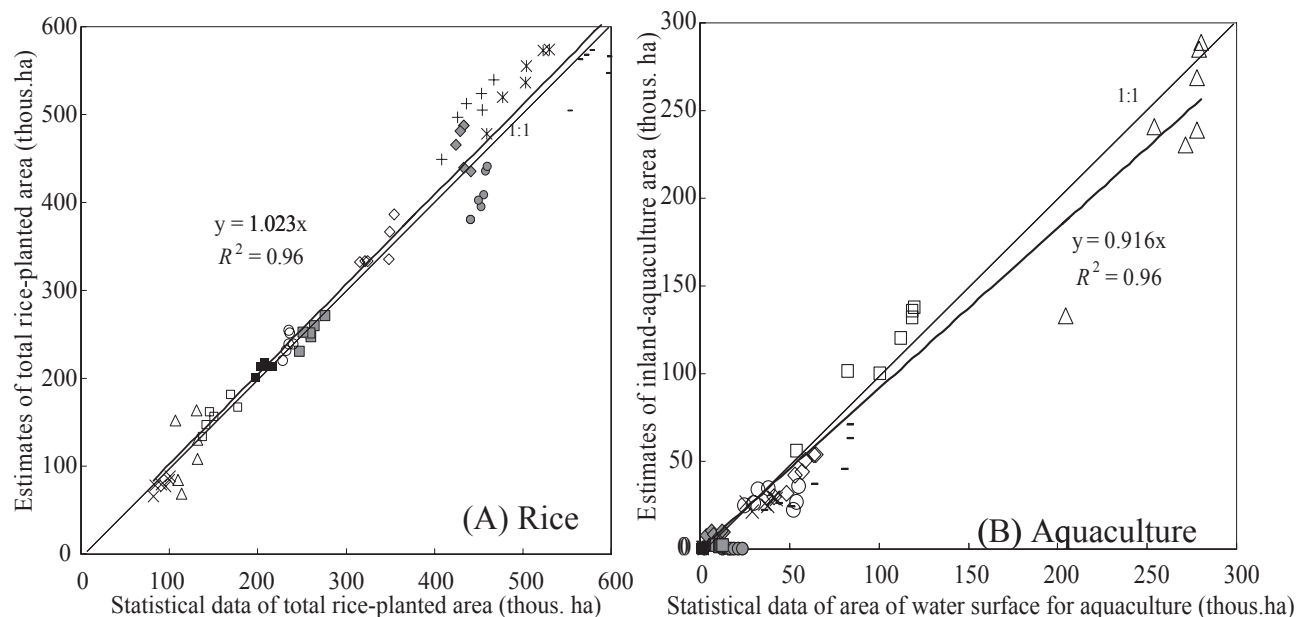Figure 7 compares the MODIS-derived estimates of

Fig. 7. **Comparison between MODIS-derived estimates (A: total rice-planted area from 2001 to 2006; B: inland aquaculture area from 2000 to 2006) and statistical data**

⋇ An Giang	☐ Bac Lieu	✕ Ben Tre
△ Ca Mau	● former Can Tho	+ Dong Thap
— Kieng Giang	◆ Long An	◇ Soc Trang
▨ Tien Giang	○ Tra Vinh	■ Vinh Long

the total rice-planted and inland aquaculture areas with statistical data at the province level[6]. Estimates of both areas agreed well with the statistical data, at $R^2 > 0.96$ over the entire VMD. However, it seems that there are biases in slopes and intercepts by province. The MODIS-derived inland aquaculture areas tend to be underestimated overall. Because this estimation error is attributable to the mixed-pixel effect, due to the moderate resolution of the MODIS sensor (250 m), the MODIS-derived area estimate cannot replace the current practice of the Vietnamese government. Excluding the mixed-pixel effect in the MODIS-derived estimates gives good agreement between the obtained spatial patterns of the multiple rice cropping systems and existing regional land use data[16]. Whereas the statistical data book is not rich in information on land use and land cover, the MODIS-derived estimate contributes to a much better understanding of the spatial distribution of farming systems, filling in the gaps in information about annual changes of land use pattern.

Yearly changes in the proportions of major farming systems from 2001 to 2007 are shown in Fig. 8. The area used mainly for rice production has been reduced since 2002 with the expansion of inland aquaculture and shrimp–rice farming. While agricultural areas producing staple foods for human survival have decreased, aquaculture areas producing products for luxury meals have increased. Additionally, the proportion of triple-cropped areas peaked in 2005 and then declined steadily over the next 2 years. It is interesting that the amount of rice exported from Vietnam also peaked in 2005, and then decreased[23] (Fig. 9). Note, however, that the triple-cropped area is not directly related to the amount of exported rice. Given that 80% to 85% of the rice exported from Vietnam is produced in the VMD and that the difference in yearly total rice production between double- and triple-cropped areas is larger than the yearly rice yield changes from the same double-cropping system, the MODIS-derived yearly changes in the triple-cropped area have the potential to indicate increases or decreases in the rice supply available for export in recent years. The steep international increase in the price of rice is an emergent issue threatening global food security. According to commodity price data published by the World Bank[25], the monthly average price of Thailand's 5% broken rice in
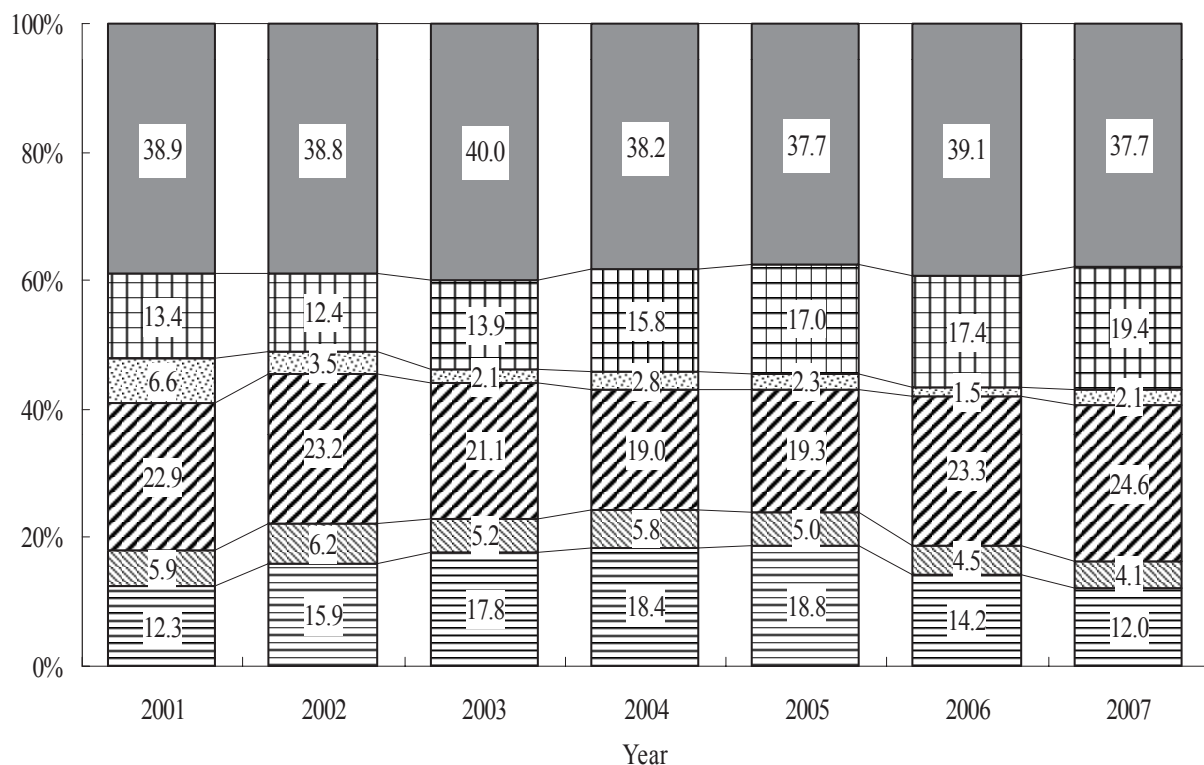

Fig. 8. Annual change in the proportions of major farming systems in the entire Mekong Delta, Vietnam

- ▤ Triple rice cropping
- ▨ Type1 double rice cropping
- ▦ Inland Aquaculture+ Shrimp-Rice farming
- ▩ Type2 double rice cropping
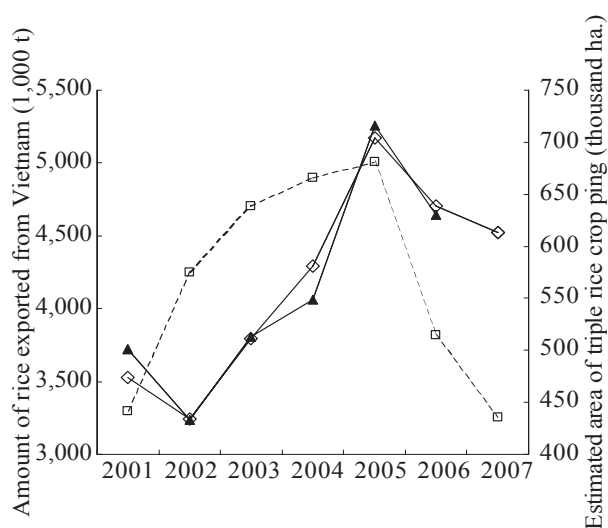- ▧ Single rice cropping
- ▩ Others

Fig. 9. Yearly changes in the amount of rice exported from Vietnam and the MODIS-derived area of triple rice cropping in the VMD from 2001 to 2007

▲—: Total amount of rice exported from Vietnam (source: GSO)

◇—: Total amount of rice exported from Vietnam (source: USDA)

-☐-: Estimated area of triple rice cropping in the whole VMD

May 2008 (USD930/t) was 2.85 times the annual average price in 2007 (USD326.4/t). The Vietnamese government has announced export restrictions to protect its domestic consumers[9, 24]. Although rice production costs increase mostly because of increases in the cost of fertilizer and fuel for irrigation pumps due to the inflating world oil price, the high rice price may create an incentive for some Vietnamese farmers to retry triple rice cropping in 2008.

Conclusions

This research introduced a new approach based on MODIS time-series imagery for detecting yearly changes in farming systems in the VMD. The six major farming systems classified using this algorithm are inland aquaculture, shrimp–rice farming, single rice cropping, type 1 double rice cropping, type 2 double rice cropping, and triple rice cropping. Although the MODIS-derived estimates of the total rice-planted area and the shrimp farming area have large margins of error when compared with statistical data, yearly changes in these farming systems were clearly revealed from 2000 to 2007 at a resolution of 250 m. The spatial pattern of multiple rice cropping systems in the VMD is linked to unevenly distributed water resources caused by the annual Mekong flood in the rainy season and salinity intrusion in the dry season. The

multi-year analysis and field survey revealed that double rice cropping systems were replaced by triple rice cropping in some areas in both the upper and coastal regions because of improved environmental conditions due to the ring-dike systems which prevent flooding and the water-sluice gates which control saline water intrusion. Over the entire VMD, estimates showed that the triple-cropped area peaked in 2005 and declined until 2007. Additionally, this yearly pattern of change in the triple-cropped area appears to parallel the change in the amount of rice exported from 2001 to 2007. On the other hand, estimates showed that the inland aquaculture area irreversibly expanded in the coastal regions. The continuous expansion of shrimp-farming area means that the area of cultivable land for staple food is potentially reduced every year. The MODIS-derived estimate clearly demonstrated the spatial distribution of farming systems in the VMD, which changed drastically and widely against the backdrop of strong rice and shrimp exports.

Although the moderate image resolution of MODIS is not always appropriate for the estimation of agricultural land area, the time-series MODIS imagery allows detect the yearly changes in farming systems within a region. The increased world food prices would have similar effects on farming systems in other countries too. Observation of farming systems using MODIS time-series imagery will shed light on this global-scale agro-environmental transformation. We will next apply our study approach to other food exporting countries.

Acknowledgments

References

1. Akiyama, T. et al. (2002) Sustainable grassland management using GIS, GPS and remote sensing data in Inner Mongolia. *In Application on Remote Sensing Technology for the Management of Agricultural Resources*. China Agricultural Scientech Press, Beijing, 13–19.
2. Binh, T. et al. (2005) Land Cover Changes Between 1968 and 2003 in Cai Nuoc, Ca Mau Peninsula, Vietnam. *Environ. Dev. Sustain.*, **7**, 519–536.
3. EOS (2008) NASA earth observing system data gateway. http://edcimswww.cr.usgs.gov/pub/imswelcome/.
4. FAO (2008) FISHSTAT plus. http://www.fao.org/fishery/statistics/software/fishstat.
5. Fujii, H. et al. (2003) Hydrological roles of the Cambodian

floodplain of the Mekong River. *International Journal of River Basin Management*, **58**, 257–266.

6. General Statistics Office of Vietnam (2008) Statistical Data. Statistical Publishing House, Hanoi. http://www.gso.gov.vn/.

7. Haruyama, S. and Shida, K. (2008) Geomorphologic land classification map of the Mekong Delta utilizing JERS-1 SAR images, *Hydrol. Process., 22*, 1373–1381.

8. Huete, A. et al. (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.*, **83**, 195–213.

9. IRRI (2008) The rice crisis: What needs to be done? http://solutions.irri.org/index.php?option=com_frontpage&Itemid=1.

10. Jakubauskas, M.E., Legates, D.R., & Kastens, J.H. (2002) Crop identification using harmonic analysis of time-series AVHRR NDVI data. *Comput. Electron. Agric.*, **37**, 127–139.

11. Liew, S. C. et al. (1998) Application of multitemporal ERS-2 synthetic aperture radar in delineating rice cropping systems in the Mekong River Delta, Vietnam. *IEEE Trans. Geosci. Remote Sens.*, **36**(5), 1412–1420.

12. Nguyen, V.H. (2007) Considering BPH as a factor to adjust the cropping patterns of rice production in the Mekong Delta. *In* CLRRI-IRRI International Conference *Better Rice, Better Environment and Better Life.* Cuu Long Delta Rice Research Institute, Cantho, Vietnam, 83–86.

13. Nguyen, V.N. et al. (2004) Rice production in the Mekong delta (Vietnam): Trends of development and diversification. *In Mekong Rice Conference 2004: Rice the Environment, and Livelihoods for the Poor*, 15–17 Oct, Ho Chi Minh City, 8–18.

14. Saito, G. et al. (2002) Seasonal changes of vegetation index obtained from NOAA/AVHRR data in China and Japan. *In Application on Remote Sensing Technology for the Management of Agricultural Resources*, China Agricultural Scientech Press, Beijing, 13–19.

15. Sakamoto, T. et al. (2005) A crop phenology detection method using time-series MODIS data. *Remote Sens. Environ.*, **96**, 366–374.

16. Sakamoto, T. et al. (2006) Spatio-temporal distribution of rice phenology and cropping systems in the Mekong Delta with special reference to the seasonal water flow of the Mekong and Bassac rivers. *Remote Sens. Environ.*, **100**, 1–16.

17. Sakamoto, T. et al. (2007) Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. *Remote Sens. Environ.*, **109**, 295–313.

18. Sakamoto, T. et al. (2009a) Agro-ecological interpretation of rice-cropping systems in flood-prone areas using MODIS imagery. *Photogramm. Eng. Remote Sens.*, **4**, 413–424.

19. Sakamoto, T. et al. (2009b) Analysis of rapid expansion of inland aquaculture and triple rice-cropping areas in a coastal area of the Vietnamese Mekong Delta using MODIS time-series imagery. *Landscape and Urban Planning*, (in press).

20. Tanaka, M. et al. (2003) Flood-drought cycle of Tonle Sap and Mekong Delta area observed by DMSP-SSM/I. *Int. J. Remote Sens.*, **21**, 1561–1569.

21. Tong, P.H.S. et al. (2004) Assessment from space of mangroves evolution in the Mekong Delta, in relation to extensive shrimp farming. *Int. J. Remote Sens.*, **25**, 4795–4812.

22. United Nations (2008) World Population Prospects: the 2006 revision population database. http://esa.un.org/unpp/

23. USDA (2008) Production, Supply and Distribution Online. http://www.fas.usda.gov/psdonline/.

24. Vietnam News (2008) Ministry urges caution over 2008 rice exports. http://vietnamnews.vnagency.com.vn/show-article.php?num=03ECO200208.

25. World Bank (2008) Commodity Price Data (Pink Sheet). http://www.worldbank.org/.

26. Xiao, X. (2002) Observation of flooding and rice transplanting of paddy rice fields at the site to landscape scales in China using VEGETATION sensor data. *Int. J. Remote Sens.*, **23**, 3009–3022.

27. Xiao, X. et al. (2005) Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. *Remote Sens. Environ.*, **95**, 480–492.

28. Xiao, X. et al. (2006) Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. *Remote Sens. Environ.*, **100**, 95–113.