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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

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Abstract

Multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS) data was used to estimate the spatial distribution of heading date and rice-cropping system employed in the Mekong Delta relative to seasonal changes in water resources in 2002 and 2003. We improved a Wavelet-based Filter for determining Crop Phenology (WFCP) and developed a Wavelet-based Filter for evaluating the spatial distribution of Cropping Systems (WFCS) to the interpretation of MODIS time-series data to determine the spatial distribution of rice phenology and various rice-cropping systems from the seasonal Enhanced Vegetation Index (EVI) data. The findings correspond well the physical characteristics of the cropping system in the Mekong Delta, which have changed over time in response to localized and seasonal changes in water resources. One such example is the double-irrigated rice-cropping system commonly employed in the upper Mekong Delta in the dry season to avoid damage due to the subsequent floods. The shortage of suitable irrigation water and intrusion of saline water in the coastal regions during the dry season has constrained the practice dry-season cropping and has meant that the double- and single-rainfed rice-cropping systems are employed in the rainy season. A triple-irrigated rice-cropping system is used in the central part of the Mekong Delta which is located midway between the flood-prone and salinity intrusion areas. Analysis of annual changes in the rice cropping systems between 2002 and 2003 showed that the triple-cropped rice expanded to the flood- and salinity-intrusion areas. This expansion indicates that the implementation of measures to limit the extent of flooding and salinity intrusion by improved farming technologies and improvements in land management. The heading dates in the upper Mekong Delta in 2003 were earlier than in 2002 by approximately 20 to 30 days. The reasons for this would be due to decreased flood runoff in 2002 compared to 2001, and implementation of government policies regarding early sowing of dry-season crops. Subsequent analysis of the MODIS data confirmed that the spatial distribution of rice-cropping systems was closely related to seasonal changes in river runoff regime in the Mekong Delta.

Keywords: MODIS; Land-use change; Phenology detection; Flood; Salinity intrusion

1. Introduction

The optimal climatic conditions and plentiful water resources of Monsoon Asia enable intensive rice production and the cultivation of multiple crops. The high yields and considerable carrying capacity of the rice-producing regions have supported increases in the Asian population, and the surplus rice production in Thailand, India and Vietnam has enabled these countries to export rice all over the world (FAOSTAT, 2003). The cost effectiveness and considerable size associated with the Asian rice harvest is an important source of nourishment for countries where food self-sufficiency rates are low.

In its third assessment report, the Intergovernmental Panel on Climate Change predicted that average global surface temperatures will increase by 1.4 to 5.8 °C between 1990 and 2100. Moreover, the distribution and intensity of precipitation will change in response to this increase in temperature (IPCC Working Group I, 2001). These perturbations to rainfall will affect river flow rates and flood runoff, which will in turn likely impact upon the amount of available irrigation water. Taken together, these factors are likely to impact upon rice productivity, which is dependent upon bountiful water resources. To evaluate the likely impact of changes in global

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water resources on international rice supply, it is therefore necessary to monitor the dominant rice production areas and determine how changes in water resources affect rice productivity in each area. Vietnam is second only to Thailand in rice exports (FAOSTAT, 2003) and 80% to 85% of the rice exported from Vietnam is produced in the Mekong Delta (Nguyen et al., 2004). Within a global context, given that Vietnam kept 13.8% of global exports in 2003, approximately 11% of those were produced in the Mekong Delta in Vietnam. The high productivity of the Mekong Delta is a consequence of the perennial temperate climate, abundant water resources and organic materials transported by the Mekong and Bassac rivers (Fig. 1; Estellès et al., 2002). The expansion in the areas under rice cultivation has largely been possible due to the influence of these two major rivers. Hoanh et al. (2003) projected future hydrological cycles and food productivity for the lower Mekong River basin for the period 2010 to 2039. Their findings indicate that the maximum and minimum river flows into the Mekong Delta during the rainy and dry season would change by −9% to +1% and −7% to −33%, respectively, with the range in an average monthly river flows being −18% to 0%. This decreased river flow during the flood season would reduce the scale of flooding, and consequently, the supply of organic material to the paddy fields. Furthermore, the decreased river flow in the dry season would provide less fresh water for diluting the influx of salinity, resulting in expansion the areas affected by salinity in parts of the delta near the coast as well as a decrease in the yields of the dry-season crop (Estellès et al., 2002; Nguyen and Ashim, 2001).

We therefore set about to assess the impact of water resource changes in the Mekong and Bassac rivers on rice productivity in the near future. Specifically, we wanted to test the hypothesis of whether rice production in the Mekong Delta is closely related to the seasonal water flow regimes of the Mekong and Bassac rivers. We therefore examined the general relationship between seasonal flows of the Mekong and Bassac rivers and the rice-cropping systems employed in the delta using remote sensing techniques to determine the characteristics of land use in the delta on a large scale.

Specifically, this study describes (i) the application of the Wavelet-based Filter for determining Crop Phenology (WFCP; Sakamoto et al., 2005) to multi-temporal satellite data acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) in 2002 and 2003, and; (ii) an investigation of the relationship between the seasonal change in the flow regime of the Mekong and Bassac rivers and the spatio–temporal distribution of rice phenology and cropping systems.

2. Data and methods

2.1. Study area

We chose the 12 provinces of the Mekong Delta as the study area. These 12 provinces are located at the southernmost edge

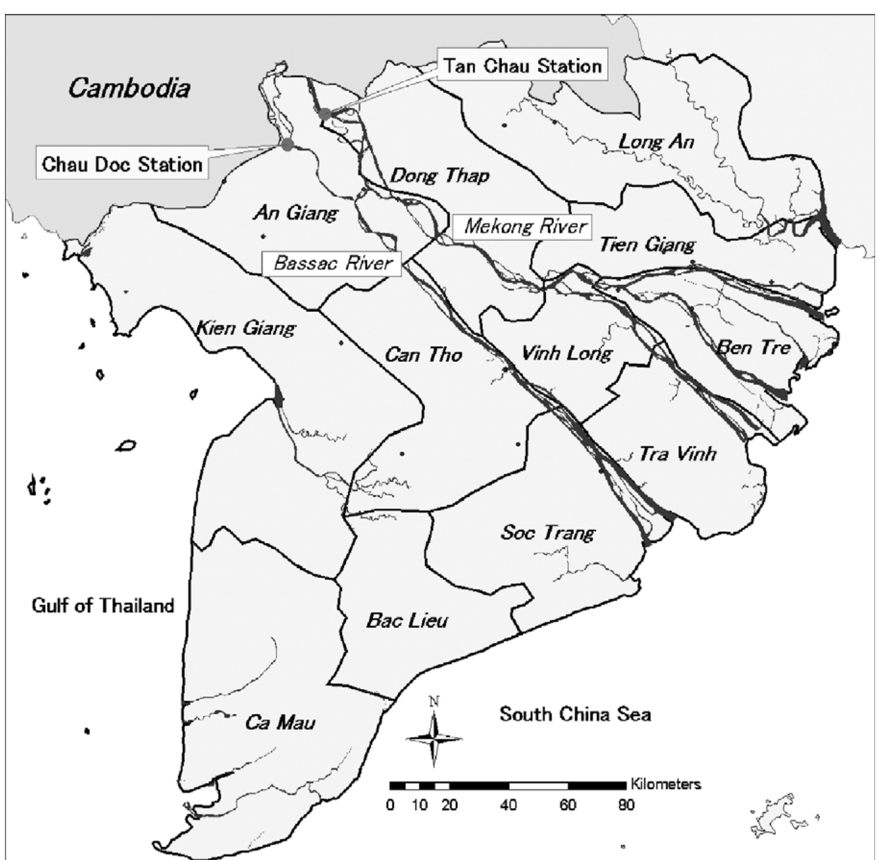

Fig. 1. The Mekong Delta showing provinces and river gauge stations.

of Indochina (Lat. 8.5–11°N, Long. 104.5–106.8°E; Fig. 1). The Mekong Delta is a wide, flat plain characterized by extensive by sedimentation at the mouths of the Mekong and Bassac rivers.

The total size of the study area is approximately 40,000 km^2, more than 70% of which was dedicated to agriculture in 2002 (Nguyen et al., 2004). According to the Koppen classification, the climate of Mekong Delta is characteristic of the savanna type. Seasonal changes in precipitation caused by the monsoon divides the year into well defined dry and wet seasons, with average air temperatures in the coldest months being approximately 18 °C and over (An Giang Statistical Office, 2003; FAO, 1999; Fig. 2A) and rain lasting from May to November. Given that precipitation is concentrated in the rainy season, the Mekong and Bassac rivers overflow their banks in the northern part of the delta every year at this time and means that more than one-third of the Mekong Delta is affected by flooding (Hori, 1996). The decrease in precipitation in December marks the beginning of the dry season, which lasts through April. The monthly average water level at Chau Doc and Tan Chau stations (Fig. 2B; An Giang Statistical Office, 2003) show that the average water level of the Mekong and Bassac rivers reach their annual maxima in September or October, and their minima in around April or May. As shown in Fig. 2B, flood volumes in 2000, 2001, and 2003 were larger than previously recorded (Fujii et al., 2003).

2.2. Satellite and land-use data

2.2.1. MODIS/Terra data and Landsat ETM+ data

The MODIS data were downloaded from the Earth Observing System Data Gateway (EOS, 2004). We used the MOD09 8-day composite data for 2002 and 2003, "MODIS/TERRA SURFACE REFLECTANCE 8-DAY L3 GLOBAL 500 M SIN GRID V004". The resolution of this data is 500 m and the atmospheric correction has already been done (Vermote & Vermeulen, 1999). MOD09 products give the surface spectral-reflectance for seven bands between the optical and short-wavelength-infrared regions. These composite data in-

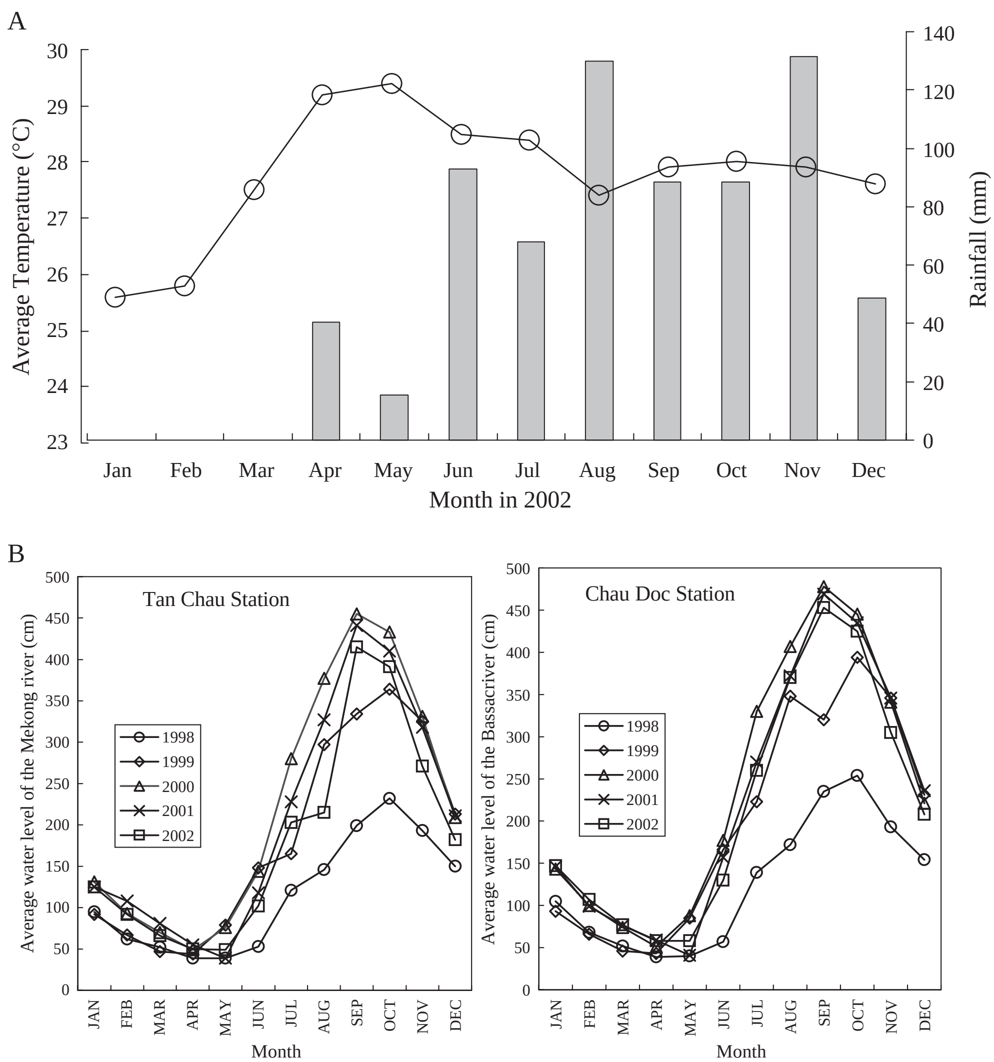

Fig. 2. Hydrometeorological data for An Giang Province. (A) Average monthly air temperature and precipitation in 2002. (B) Average monthly water level at the Chau Doc and Tan Chau stations from 1998 to 2002.

clude the observation date as the day of year (DOY) for each pixel.

LANDSAT 7 ETM+images (path/row: 125/53) were used to validate the details of the estimations of cropping systems. These ETM+images were acquired on 12 January and 13 February 2002.

2.2.2. Land-use data

In this study, we used land-use data for 2002 provided by the Sub-National Institute for Agricultural Planning and Projection of Vietnam (Sub-NIAPP) as the ground reference data for paddy fields in the Mekong Delta (Nguyen et al., 2004, Fig. 3). The land-use data have been updated every a few years and are recorded in vector format. This land-use data was constructed from various data, including LANSAT 7 ETM+ on 7 and 13 February in 2002, the printed map of the agricultural land use in 2002 of 12 provinces at 1/50,000 and 1/100,000 scales produced by the Department of Agriculture and Rural Development of provinces and the Department of Natural Resources and Environment, the digital land use maps in 2000 at 1/250,000 scale of the Ministry of Natural Resources and Environment, and filed survey on May and November in 2002. Then original resolution of the land-use data was 30 m.

We used the land-use data (Fig. 3) to validate the estimated number of rice crops cultivated per year in 2002. The key land-use categories that we selected for analysis were single irrigated-rice and single upland rice, single rainy-season rice, single rainy-season rice and shrimp culture, double irrigated-rice, double rain-fed rice, and triple irrigated-rice crops. In terms of area, most paddy fields in the Mekong Delta are double irrigated-rice crops (with winter–spring and summer–autumn growing seasons), double rain-fed rice crops (with summer-autumn and rainy season growing seasons), or triple irrigated-rice crops (with spring–summer, summer–autumn and rainy seasons). The areas under double irrigated-rice crops were distributed mainly in the middle and upper regions of the Mekong Delta, while double rain-fed rice crops, shrimp farms and single rainy-season rice crops were located near the coastline. The areas under triple-irrigated crops are distributed along with the Bassac and Mekong rivers and not near the coastal areas. The land-use data in 2002 were converted to raster format with a 500 m resolution to facilitate comparisons with results from the MODIS data.

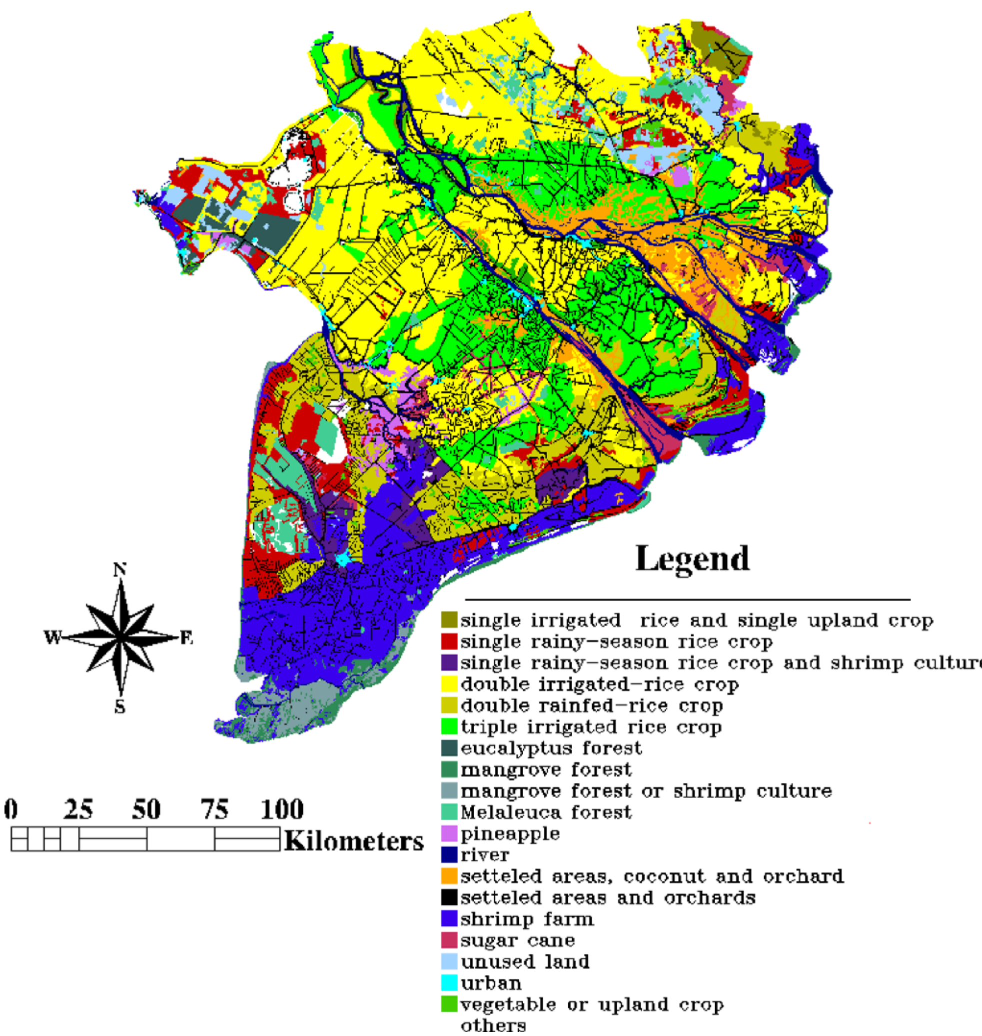

Fig. 3. Land-use map for 2002 (source: Sub-National Institute for Agricultural Planning and Projection of Vietnam).

2.3. Wavelet-based filter for evaluating the spatial distribution of Cropping Systems (WFCS)

Most previous studies on the detection of cropping systems in the Mekong Delta employed multi-temporal synthetic-aperture radar data acquired by ERS-2 or RADARSAT, and have classified cropping systems based on temporal changes inferred using the backscattering coefficient for paddy fields (Kurosu et al., 1995; Liew et al., 1998; Pham et al., 2003; Ribbes & Le Toan, 1999). Here, we used MODIS data acquired using an optical sensor designed to cover wide areas and estimated cropping systems and rice phenology by analyzing temporal vegetation index data. We applied the WFCP to the original temporal Enhanced Vegetation Index (EVI) data to smooth the EVI time profile (Sakamoto et al., 2005). The principal advantage of using WFCP is that, should EVI be underestimated due to the cloud cover, it can be interpolated by applying wavelet analysis. Accordingly, by scanning the smoothed time profile of EVI data to find characteristic points including maximum point and inflection point, it is possible to detect phenological stages of the rice such as the timing of planting, heading and harvesting. After validating the estimated phenological dates against statistical data derived from 30 test sites in Japan, the root mean square errors of the estimated phenological dates were: 12.1 days for the date of planting, 9.0 days for the date of heading, 10.6 days for the date of harvesting, and 11.0 days for the growing period. Consequently, by detecting the phenological dates of paddy fields on an annual basis we considered it possible to evaluate the spatio–temporal distribution of rice phonological patterns and their associated annual changes in the Mekong Delta. While development of this approach formed the basis of a previous study for detecting the crop phenology using MODIS data and its validation with statistical data in Japan (Sakamoto et al., 2005), this is the first time that WFCP has been applied to reveal the nature of a cropping system in an area the size of the Mekong Delta.

WFCP consists of a three-step process, (1) prescription of multi-temporal MODIS data, (2) filtering EVI time-series data by wavelet analysis, and (3) detecting the peaks on the smoothed EVI time profile to determine the rice-heading date. In procedure (1), the EVI time-series data are calculated. Any EVI data affected by the thick clouds is removed using the reflectance of band 3; data with band 3 reflectance values exceeding 10% are treated as missing values. Subsequent to determining the spectral qualities, the EVI data are arranged by observational date. The missing values between the observed data are substituted with dummy data calculated by linear interpolation. In the second procedure (2), the discrete wavelet transform is applied to the regulated EVI data and high frequency noise components are removed from the time-series data. A smoothed EVI profile is reconstructed through the inverse discrete wavelet transform. In the final step of the procedure (3), the rice-heading dates are detected by identifying the maximum points along the smoothed EVI profile. The smoothed EVI time profile obtained by applying the WFCP is considered to represent the reflectance of the daily rice growth with minimal effects from clouds.

When using the WFCP in the Mekong Delta, we adjusted two parameters from those used in the previous study in Japan (Sakamoto et al., 2005). The first adjustment affected the threshold for regulating the spatial resolution of target pixels in the prescription of the MODIS data (procedure (1)). This was necessary because the spatial resolution of each pixel in the raw data differed depending on the sensor zenith angle. Sakamoto et al. (2005) used sensor zenith angle data to select only those pixels that had a real spatial resolution of less than 750 m. In Japan, given that the size of most agricultural parcels is small relative to the 500-m resolution of the satellite data, such parcels were irregularly distributed especially in the mountainous area. If applied in environments such as Japan, the spatial resolution of target pixels needs to be restricted as EVI calculated with a board sensor zenith angle will be associated with strong neighbor effects. And the Mekong Delta is characterized by the occurrence of thick cloud cover during the rainy season. If the same parameters as those employed in Japan were used for regulating the pixel resolution, then the number of available data during the rainy season would be dramatically decreased in the Mekong Delta as would the accuracy of the WFCP for detecting rice phenology. Consequently, we did not apply a threshold for regulating the spatial resolution in the study area. Instead, it was assumed that the seasonal changes in EVI relative to rice growth would be adequately detected. Given that the distribution of land use in the Mekong Delta is relatively similar and more uniform, combined with the fact that the paddy fields are considerably larger compared to those of Japan, we did not consider it necessary to regulate the spatial resolution of the target pixels in the Mekong Delta.

In addition, the threshold for noise rejection in the EVI time-series data was also altered in this study (procedure (2)). Generally, the duration of growth of paddy rice cultivated in Japan is 130 to 160 days (Ministry of Agriculture, Forestry and Fisheries of Japan, 2003), whereas short-duration rice varieties (80 to 110 days) are widely cultivated in the Mekong Delta (Minh & Kawaguchi, 2002; Nguyen, 2000). It is therefore necessary to retain shorter period elements in the smoothed EVI time profile after noise removal so that the technique can be to account for the short-duration rice variety planted in the Mekong Delta. We therefore eliminated those frequency components with time cycles less than 32 days as these were considered noise components. The mother wavelet used in this study (Coiflet 4) was the same as that applied in the previous study where its application resulted in the best performance for determining rice phenology (Sakamoto et al., 2005). And we named this improved method based on WFCP as a Wavelet-based Filter for evaluating the spatial distribution of Cropping Systems (WFCS).

2.4. Number of rice crops cultivated per year and heading dates in study area

Rice changes its growth phase from the vegetative growth stage to the reproductive growth stage on reaching heading date when the leaves begin to whither and die. According to time-series data for spectral reflectance from paddy fields (Shibayama & Akiyama, 1989), maximum NDVI values are obtained around the heading date. We therefore employed a smoothed EVI time profile on paddy field data as the local maximal point would correspond to each heading date. The heading date of Japanese rice can be estimated with a root mean square error of about 9.0 days detecting maximum point from the smoothed EVI time profile (Sakamoto et al., 2005).

However, because double and triple rice-cropping systems are employed on a wide scale in the Mekong Delta, it is difficult to determine the occurrence of the heading date using only the maximum values on the smoothed EVI time profile in the study area. Consequently, several methods had to be employed to determine the occurrence heading time, the first of which involved selecting those local maximal points with values greater than 0.4. In addition, if the interval between the two probable dates was less than 60 days, it could be possible that the two probable heading dates were misclassified due to the anomalous EVI data around the true heading date. If the EVI data around the true heading date was low and the data was not removed in the prescription of multi-temporal MODIS data, the signature of the smoothed time profile around the heading date would be revealed as two humps. Given that the growing period of rice cultivated in the Mekong Delta should be longer than 80 days, an interval of 60 days between two probable heading dates is unrealistic in terms of rice-growing periods. Therefore, we adopted the date midway between those two dates as the estimated heading date for empirical purposes. Inaccurate assignments like this may have been caused by the occurrence of low EVIs around the heading date due to cloudy days. Finally, the number of rice crops cultivated per year was then defined by the number of estimated heading dates per year.

3. Results and discussion

3.1. Number of crops cultivated per year

3.1.1. Comparison between the estimated number of rice crops in 2002 and land-use data

The number of crops estimated for 2002 and 2003 in the paddy fields of the study area is shown in Fig. 4. The results include the misclassified fields in which the number of crops per year was more than three. These fields were scattered around settled areas, coconut and orchard areas, or settled areas with orchards (Figs. 3 and 4). The overestimation in the number of crops per year may have been due to mixed-pixel effects caused by adjacent land surfaces. The area of these misclassified fields in 2002 relative to whole paddy fields was less than 2.5%. Consequently, given the small size of the area, the fields showing more than three crops per year were excluded from the comparison of spatial patterns between the ground reference land-use data and the estimated data in Fig. 5. Conversely, the paddy fields in which the number of crops was zero were distributed mainly around the single-crop area depicted in the land-use data (Figs. 3 and 5, Table 1), were located near the coastline and were susceptible to increased soil salinities. Therefore, this underestimation of single-cropped areas is related to low EVI values around the maximal points in the smoothed EVI time profile, perhaps owing to poor vegetative growth and vegetation cover.

When the number of crops estimated in 2002 and the land-use data for 2002 were compared (Fig. 5 and Table 1), areas identified as triple-cropped areas in the land-use data were

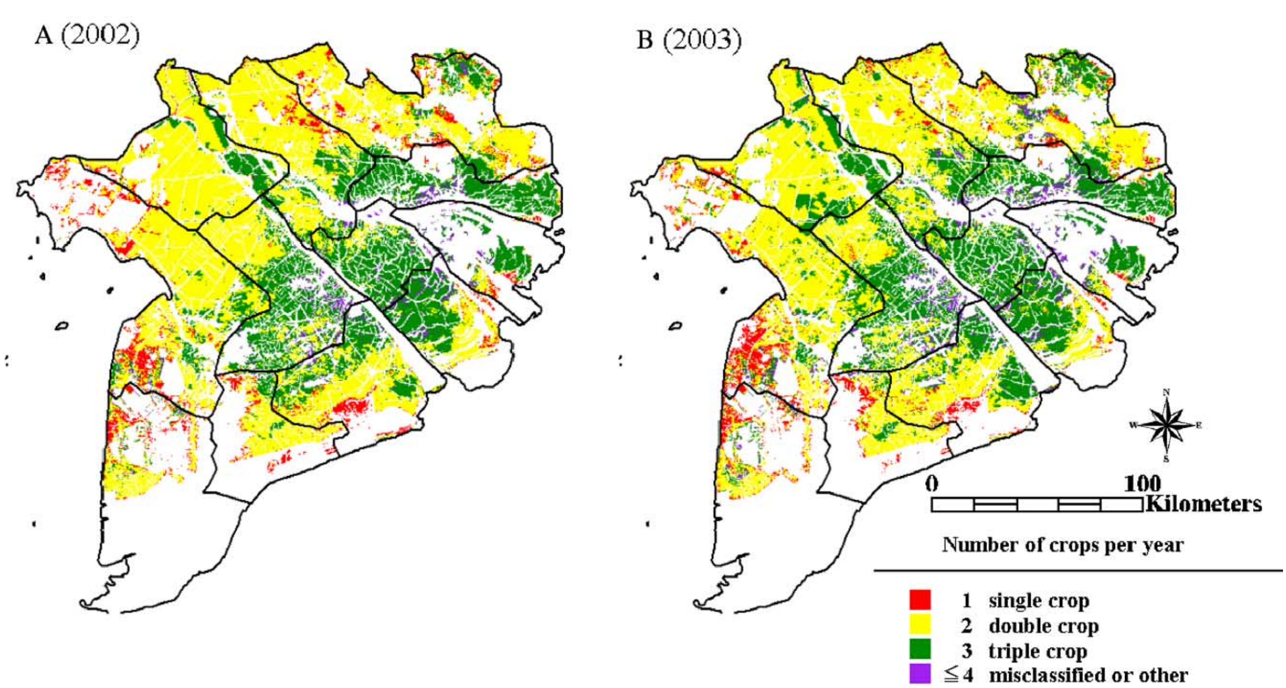

Fig. 4. Estimated number of crops per year in 2002 and 2003.

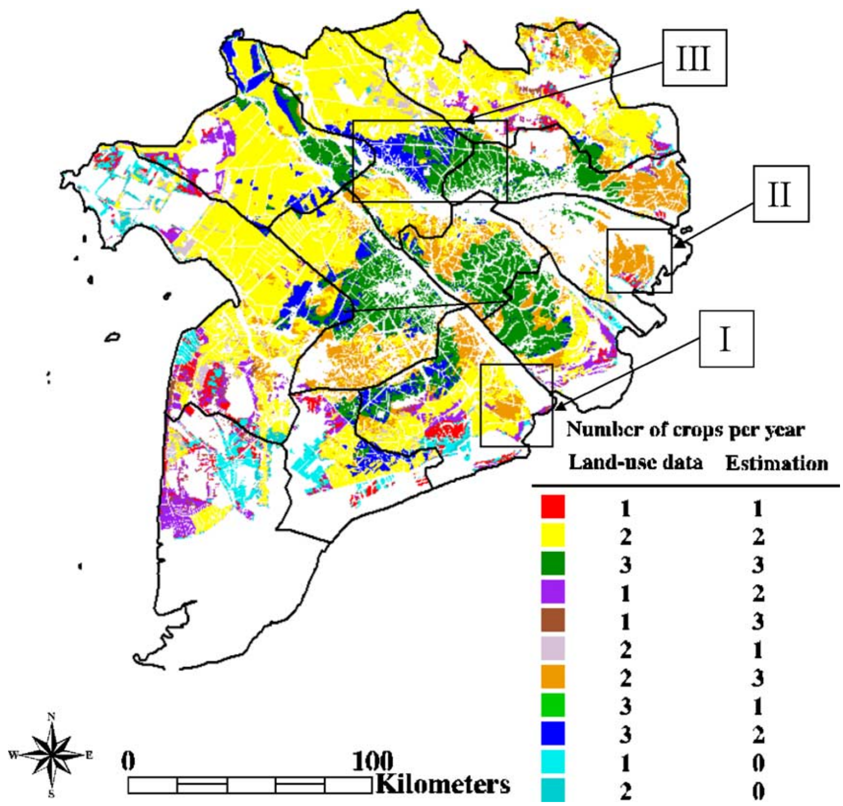

Fig. 5. Comparison of the number of crops per year between the estimate for 2002 and the reference land-use data.

rarely classified as single-cropped areas. On the other hand, those identified as single-cropped areas in the land-use data were rarely classified as triple-cropped areas. Such areas accounted for 0.1% and 1.1% of the total paddy fields, respectively.

From the smoothed EVI time profile, approximately 5.5% of all paddy fields that were overestimated as double-cropped areas were classified single-cropped area in the land-use data. Furthermore, approximately 12.3% of the areas overestimated as triple-cropped area, were classified as double-cropped area in the land-use data. Because the heading dates were defined by the peak EVI values, values of more than 0.4, consideration of the interval between the heading dates, 60 days for restricting overestimation, it is highly unlikely that these entire areas were extracted based on overestimations of the number of crops per year. It is also unlikely that these observations could be attributed to anomalous disadvantageous observation conditions, rather, these observations indicate that the actual number of crops each year was more than that identified in the land-use data. For example, a large part of region I (Fig. 5), classified as being double-cropped based on the land-use data, was estimated as triple-cropped in 2002 from the smoothed EVI time profile. We then further confirmed this finding of this region using LANDSAT ETM+images (Fig. 6B and C).

Table 1
Confusion matrix of the number of crops per year between the amount estimated in 2002 and the land-use data

		Land-use data					Pixel count
		0	1	2	3	≧4	
Estimate for 2002	1	27.2 (%)	25.0	38.0	7.8	1.9	13,857
	2	2.4	5.9	70.0	20.0	1.6	58,422
	3	0.2	0.4	26.8	67.5	5.1	23,025

The target area was located 5 to 20 km inland in the eastern part of Soc Trang Province (Figs. 1 and 6) where coastal areas are affected by salinity intrusion every dry season. Particularly in April or May, a large amount of saline water intrudes into the aquifer from the sea and becomes mixed with the irrigation water, thus inhibiting rice growth in the dry season (Tuong et al., 2003). Therefore, dry-season cropping is impossible in such fields without countermeasures against salinity intrusion, including for example, the use of water sluices or other measures for salt removal (Estellès et al., 2002). For example, as seen in the smoothed EVI time profile (Fig. 6), the area around pixel α was double-cropped; that is, no crops were growing in March and April. Conversely, the area colored orange in Fig. 6A, which includes pixel β, was estimated as a triple-cropped area from the smoothed EVI time profile, but is shown as a double-cropped area in the land-use data. In the Landsat ETM+false color images of the same region (12 January 2002 and 13 February 2002), the land surface indicated by pixel β (Fig. 6) was covered by water in January but was covered by vegetation in February. Therefore, it can be assumed that rice cultivation was performed in the dry-season, from March to April in 2002, and it is surmised that salinity control measures may have been applied in this area. The same interpretation applies to region II (Fig. 5) in the eastern coastal area of Tien Giang Province (Fig. 1) that was triple-cropped in 2002, including dry-season cropping from March through April. Such coastal triple-cropped areas, which were not noted

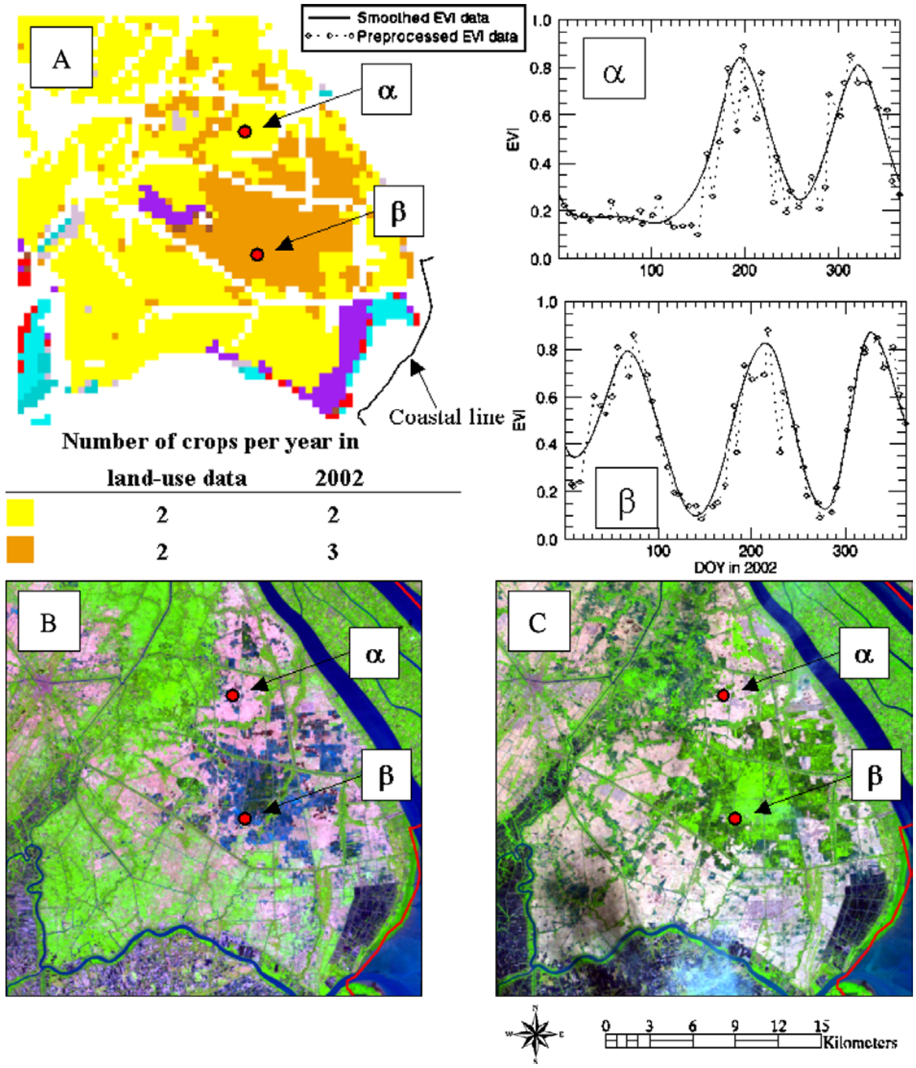

Fig. 6. Validation of the overestimated number of crops in 2002 for the eastern Soc Trang Province. (A) Comparison of the number of crops per year between the reference land-use data and the number estimated from the smoothed EVI time profile in 2002. (B) Landsat ETM+image (R: G: B=Band 5: Band 4: Band 3) for 12 January 2002. (C) Landsat ETM+image for 13 February 2002. Temporal EVI data profiles of pixels α and β are shown in the upper right.

on the land-use data, can therefore be identified by analysis of multi-temporal MODIS data.

On the other hand, from the multi-temporal MODIS data, approximately 3.6% of all paddy fields were underestimated as single-cropped areas, and were instead classified as double-cropped areas in the land-use data. In addition, approximately 6.5% were underestimated as double-cropped areas and were classified as triple-cropped areas in the land-use data. The reason for this underestimation was because the peak EVI value at the local maximal point was below 0.4 and was due to aspects such as poor vegetation growth, disadvantageous observation conditions and a mixed-pixel effect. For example, in comparison with the land-use data, the number of crops in region III (Fig. 5) was underestimated as double-cropped areas. The estimated number of crops in 2002 and the MODIS color image of the rainy season (DOY 297–304 in 2002, R: G: B=Band 6: Band 2: Band 1) in this area are shown in Fig. 7. Pixel γ(Fig. 7) was classified as a triple-cropped area in the land-use data, but was underestimated as a double-cropped area from the smoothed EVI time profile, whereas pixel δ (Fig. 7) was classified as a triple-cropped area by both the land-use data and our estimated results. The smoothed EVI time profiles for the two pixels are also shown in Fig. 7. The area around pixel γ(Fig. 7B) was covered with vegetation, and, at around the same time (DOY 297–304), a local maximal point appeared in the smoothed EVI time profile for pixel γ. Therefore, a triple-crop system was probably used in this region. However, this third crop was not detected because the EVI value at the third peak was less than 0.4. Though a lower EVI threshold would facilitate detection of this third crop with a low peak EVI value, it would increase the risk of misidentifying minute fluctuations caused by residual noise as valid data.

3.1.2. Change in the number of rice crops cultivated per year from 2002 to 2003

A comparison of the number of crops in 2002 and 2003 (Fig. 8 and Table 2) shows that the rice-cropping system changed in some areas from being a double-crop system to

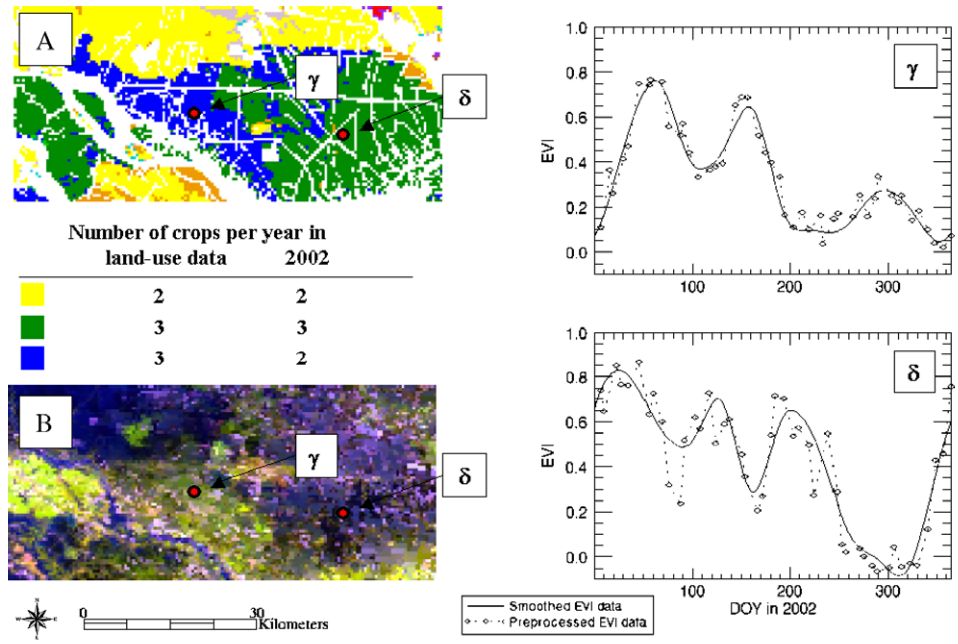

Fig. 7. Validation of the underestimated number of crops in 2002 in eastern Dong Thap Province. (A) Comparison of the number of crops per year between the reference land-use data and the number estimated from the smoothed EVI time profile in 2002. (B) MODIS false-color image (R: G: B = Band 6: Band 2: Band 1) acquired on DOY 297–304 in 2002. The temporal EVI data for pixels γ and δ are shown on the right.

triple-crop system and vice versa. For example, region IV (Fig. 8) was classified as a triple-crop system in 2002, but changed to a double-crop system in 2003. For identifying the causes of these changes in crop-system, we extracted the smoothed EVI profile in 2002 and 2003 and compared these yearly changes with the statistical land use data in region ε; Hong Dan district in Bac Lieu Province, and in region ζ; Thanh Tri district in Soc Trang province (Table 3, Bac Lieu Statistical Office, 2003, 2005; Soc Trang Statistical Office, 2003, 2005). The average daily EVI data in the areas where the crop system changed from triple crop to double crop were calculated in regions ε and ζ, respectively and are shown in Fig. 9. The time profile of the

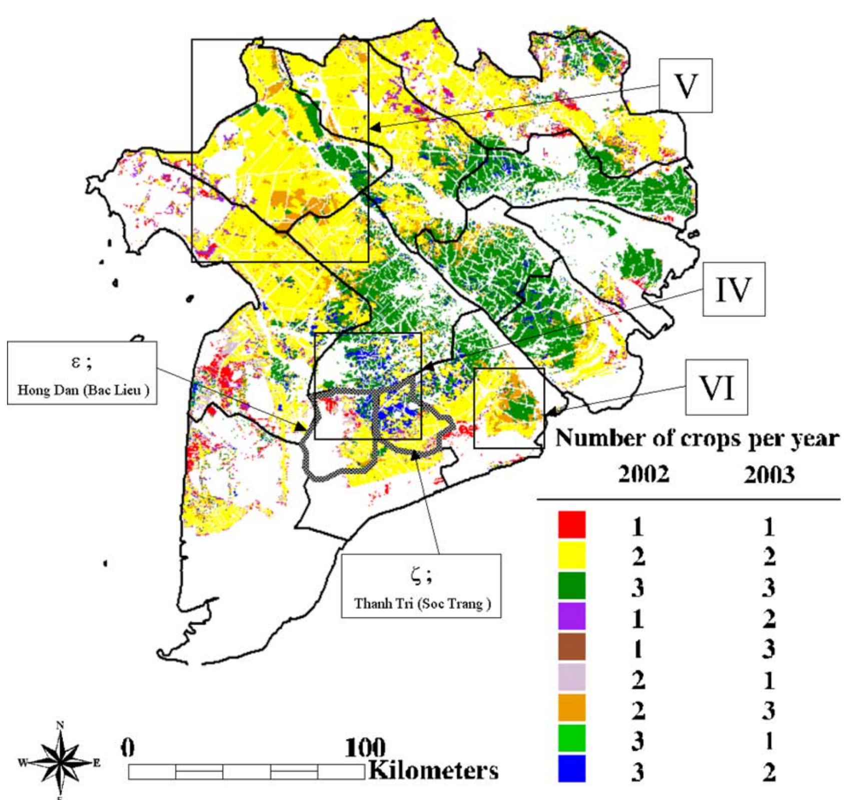

Fig. 8. Comparison of the estimated number of crops per year between 2002 and 2003.

Table 2
Confusion matrix of the number of crops per year between the amount estimated in 2002 and 2003

		Estimate for 2003					Pixel count
		0	1	2	3	≧4	
Estimate for 2002	0	73.5 (%)	17.7	7.0	1.5	0.2	5230
	1	14.8	37.5	39.1	7.3	1.3	6998
	2	0.7	4.3	79.1	14.6	1.2	52,365
	3	0.1	0.7	13.4	78.7	7.1	28,336
	≧4	0.0	0.5	6.7	49.3	43.5	2375

EVI data for region ε in 2003 shows three marked peaks, however, the average EVI values of the second and third peaks in 2003 were lower than that observed in 2002. In region ζ, the yearly change in the EVI time profile was completely different than that obtained for region ε. Though the second crop was performed from April to June and the third crop was performed from August to October in 2002, a peak in EVI values during April to October in 2003 only appeared once. The growing season of the second crop in 2003 is likely to have occurred from May to September. Referring to the statistical land use data (Table 3), the area of summer–autumn paddies and rainy-season paddies in region ε decreased by −51%, −15%, respectively between 2002 and 2003. In addition, the surface area of ponds for aquaculture increased by +47%. In region ζ, the area of summer–autumn paddies and rainy-season paddies were observed to decrease by −11% and −90%, respectively and the surface area of water for aquaculture increased by +21%. With regard to the region ε, the reason why the cropping system was changed from triple crop to double crop would be related to the land use change from rice cultivation to aquaculture and the corresponding mix-pixel effects. Therefore, the lower peak value of the smoothed EVI data for the second and third crops in 2003 was caused by the decline in the estimated number of crops per year in the region ε. In region ζ, it appears that the crop system and growing season were intentionally rescheduled because the area dedicated to rainy-season paddies in the Thanh Tri district was considerably reduced.

Tuong et al. (2003) monitored electrical conductivity at 14 sites and mapped the 7 dS m^{-1} isohalines for February from 1994 to 2000 in Bac Lieu Province. Our region ε is located in the northern part of their study site. The Vietnamese government has built 10 large sluices and numerous smaller ones to protect paddy fields from saline intrusion since 1994. Consequently, the area affected by the salinity intrusion has gradually decreased from the eastern to the western parts of the region (Tuong et al., 2003). Tidal intrusion has been pushed back from the eastern to the western parts of the region using fresh water channeled from the Bassac River and our study regions ε and ζ are located about 50–60 km from the Bassac River. It is considered likely that these regions are very sensitive to the intrusion of saline water from the sea or shrimp fields in the dry season. In addition to this environmental condition, which is a great risk to rice production in the dry season, the land-use change from rice cultivation to aquaculture is likely due to the decrease in the price of rice associated with a general increase in rice production in the whole Mekong Delta. From the point of agricultural management, it would therefore be reasonable for farmers to expand their activities into aquaculture rather than to intensify rice cultivation in areas that are vulnerable to the intrusion of saline water.

In regions V and VI (Fig. 8), double-cropped areas in 2002 changed to triple-cropped areas in 2003. In the MODIS color images for 2002 and 2003 for region V (Fig. 10), the smoothed EVI time profiles for pixels η and θ (Fig. 11A) show that these areas were flooded during the flood season (DOY 241–304) in 2002. However, rainy-season paddy was planted in areas around pixels η and θ during the same time in 2003 (Fig. 11B). One possible reason for this change is that Vietnam government maintains a dike and cannel system for flood control (Kazama et al., 2002). The dikes enclosing the paddy fields prevent flooding of the dry-season rice before harvesting in the early flood season (Hori, 1996; Nguyen, 2000) and enable the farmers to seed the winter-spring and summer-autumn paddy earlier by using pumps for draining flooded water. After the several flood disasters in 2000, the Ministry of Agriculture urged authorities in the Mekong Delta to identify new ways to prevent flood inundation. The Ministry developed a drainage system and improved the dike systems (Disaster Management Unit, 2004). These mitigation policies against flood disasters would help farmers to overcome natural flooding and expand the triple-cropped areas in susceptible regions.

Similarly, in the MODIS false color image (Fig. 12) of region VI (Fig. 8, same as region I in Fig. 5), the orange region shows the areas where the cropping system changed from double-crop system to triple-crop system in 2003. This region forms a circular band around the area of the triple-crop system in 2002 (Fig. 12B, C) and suggests that the area, which has implemented countermeasures against salinity intrusion, was expanding into coastal areas.

3.2. Phenological map

3.2.1. Spatial distributions of heading dates

The spatial distributions of heading dates in 2002 and 2003 are shown at 3-month intervals and categorized into four periods (Fig. 13). Period 1 is from January to March, period 2 is from April to June, period 3 is from July to September, and

Table 3
Sown paddy area and area dedicated to aquaculture from 2001 to 2003 (thousand ha)

District	Land use	2001	2002	2003
Region ε	Spring paddy	9.5	9.5	13
(Hong Dan district in Bac Lieu province)	Summer–autumn paddy	16	21	10
	Rainy-season paddy	14	15	13
	Aquaculture	4.1	8.7	13
Region ζ	Spring paddy	30	36	37
(Thanh Tri district in Soc Tran province)	Summer–autumn paddy	40	42	38
	Rainy-season paddy	7.2	8.5	0.87
	Aquaculture	1.3	1.9	2.3

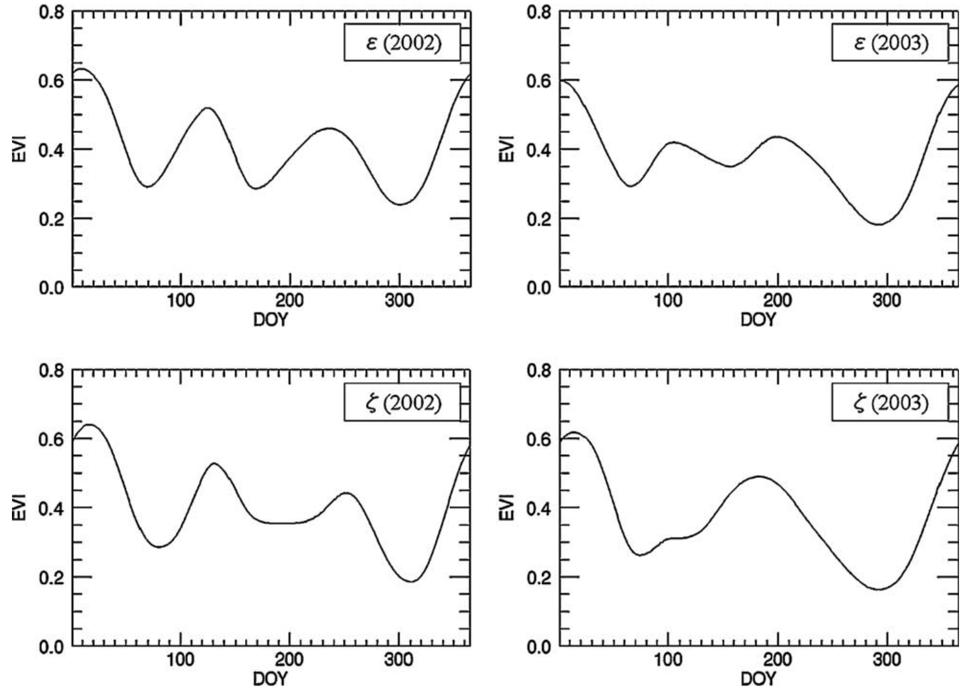

Fig. 9. Average daily EVI data in areas where the number of crops per year decreased from three in 2002 to two in 2003 in the regions ε and ζ shown in Fig. 8.

period 4 is from October to December. During periods 1 and 2, the heading stage appeared mostly in the upper parts of the Mekong Delta, but rarely in the coastal areas. Periods 1 and 2 corresponded to the dry season. Usually in April or May, runoff from the Bassac and Mekong rivers in to the South China Sea are at their lowest. Given that intrusion of saline water due to tidal effects causes the movement of high-density salt into irrigation water, cultivation of rice is difficult in the coastal regions. In contrast, periods 3 and 4 are characterized by the appearance of the heading stage in coastal areas, but rarely in the upper parts of the Mekong Delta. The reason for this is that seasonal floods in periods 3 and 4 inhibit rice cropping in the upper parts of the Mekong Delta and the abundant runoff from the Bassac and Mekong Rivers push back the salinity intrusion. These findings confirm that salinity intrusion and flooding related to seasonal changes in the water flow from the Mekong and Bassac Rivers define the rice-cropping season.

3.2.2. Change in the spatial distribution of heading dates between 2002 and 2003

Comparison of heading dates during periods 1 and 2 between 2002 and 2003 (Fig. 13 a, b, e, f) revealed that the heading dates in 2003 in the upper parts of the Mekong Delta were earlier than those in 2002 by approximately 20 to 30 days. This early heading in 2003 would be related to the combination of a reduction in flood runoff in 2002 and government policy. The flood runoff in 2002 was less than that in 2001. Average water levels observed in September at the Chau Doc and Tan Chau Stations decreased by −26 cm (−5.9%) and −16 cm (−3.4%) compared to the previous year, respectively (Fig. 2B),

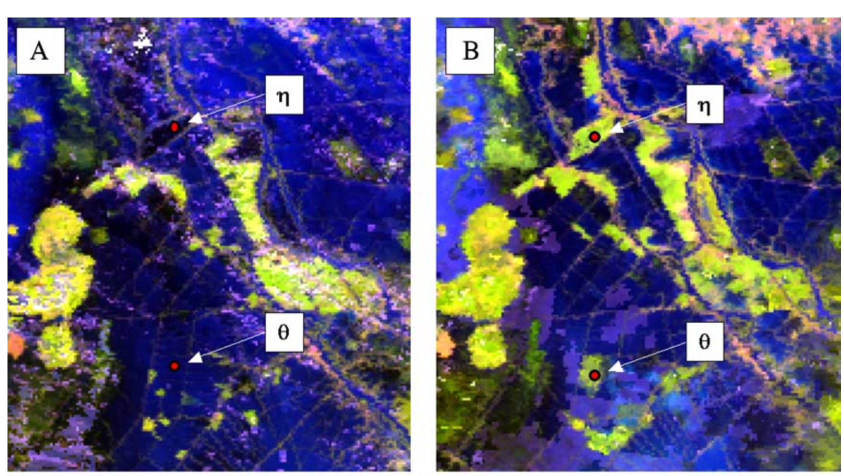

Fig. 10. MODIS false-color images of An Giang Province during the same period (DOY 297–304) in 2002 and 2003. R: G: B = Band 6: Band 2: Band 1.

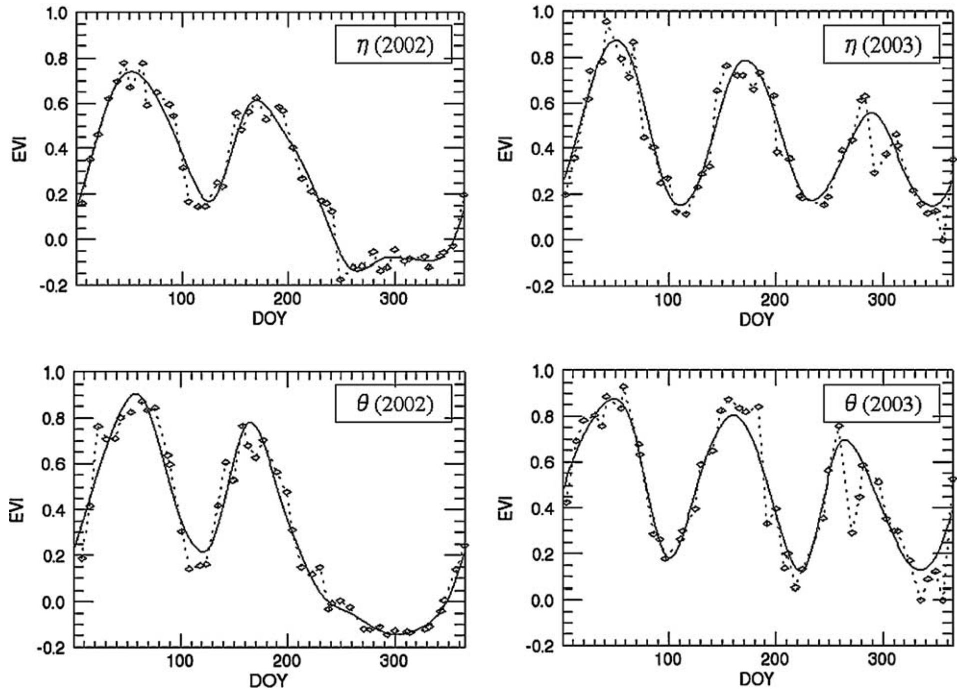

Fig. 11. Temporal EVI data for areas in which the cropping system changed from double in 2002 to triple in 2003. The data refer to pixels η and θ in Fig. 10.

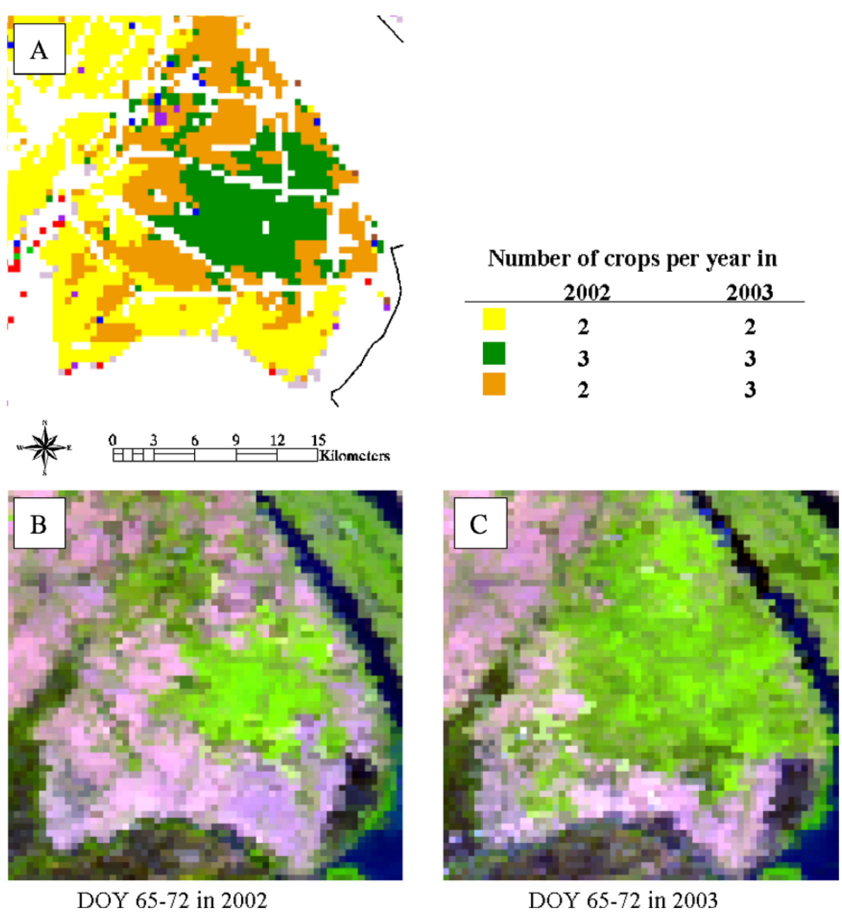

Fig. 12. Comparison of the number of crops per year between 2002 and 2003 in eastern Soc Trang Province (A) and MODIS false-color images for 2002 and 2003 (enlargement of region I in Fig. 5 and region VI in Fig. 8) of the same region. (B) MOIDS 8-day composite image for DOY 65–72 in 2002. (C) MODIS 8-day composite image DOY 65–72 in 2003. R: G: B = Band 6: Band 2: Band 1.

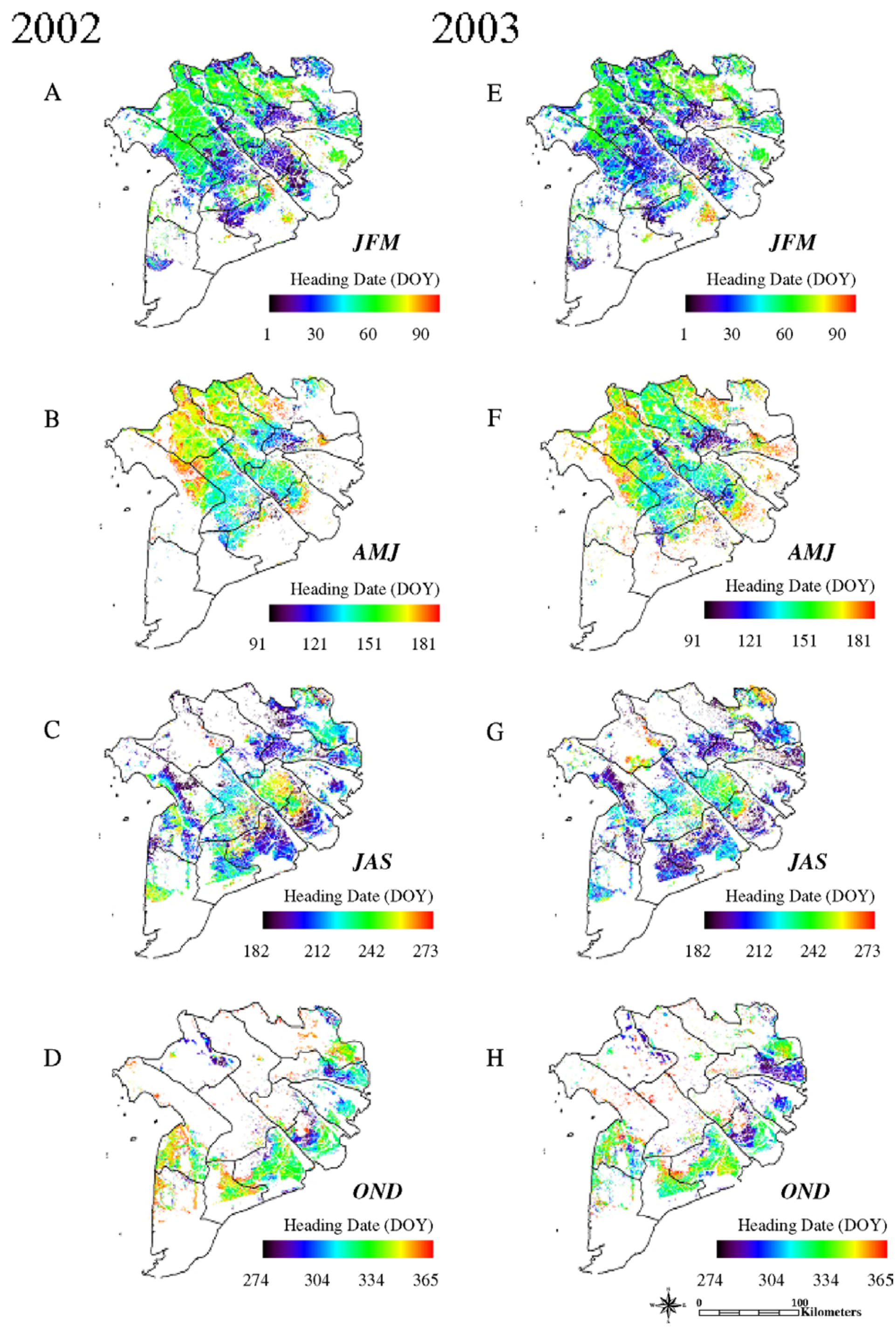

Fig. 13. Spatial distribution of heading dates in 2002 and 2003. The seasonal results for 2002 are shown on the left and those for 2003 on the right: (A, E) period 1 (January, February, March); (B, F) period 2 (April, May, June); (C, G) period 3 (July, August, September); and (D, H) period 4 (October, November, December).

and the water level in 2002 at the Chau Doc station decreased to the 300 cm baseline level 15 days earlier than it did in 2001 (Fig. 14). Fujii et al. (2003) estimated the flood volume of the study area to the south of the Great Lake up to the Vietnam border using a combination of hydrological information and RADARSAT imagery. Their estimation of flood volume during peak flooding conditions in 2002 was 2500 million m^3 (−16.4%), less than in 2001. According to the annual damage assessment report by the Disaster Management Unit (2004), the extent of flooded and inundated paddy areas decreased from 21 thousand hectares in 2001 to 14 thousand hectares in 2002.

Generally, optimal sowing dates depend largely on water availability and it is thought that the best conditions are when the soil is moist but the field is not flooded (Sipaseuth et al., 2001). Consequently, prolonging field inundation increases the moist condition during harvesting of the summer–autumn paddy and causes a delay in planting the winter–spring paddies (Reiner et al., 2004). Given that flood inundation in 2002

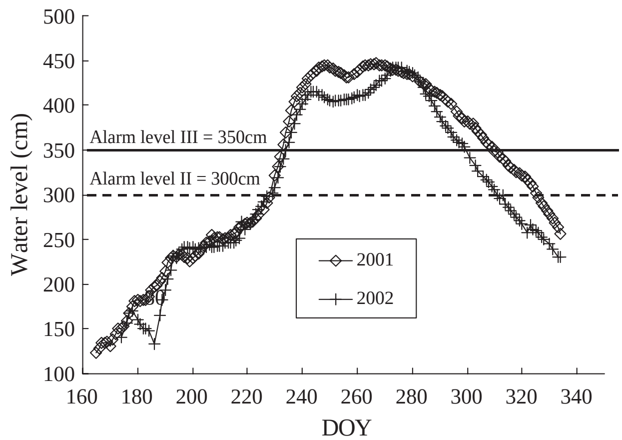

Fig. 14. Time-series rainy-season water-level data at the Chau Doc station in 2001 and 2002.

ended earlier and the appropriate time for sowing was also earlier than the previous year, it was possible for farmers to sow the following winter–spring paddy early in 2003. In addition to the good conditions for early sowing in 2003, the government improved rural infrastructure and accelerated crop restructuring to accommodate the floods (Disaster Management Unit, 2004). The government policies encouraged early seedling winter–spring and summer–autumn paddies to facilitate early harvesting before flooding (Neefjes, 2002; Tinh, 2003; UN/ISDR, 2004). The farmers from vulnerable areas in the Dong Thap province sowed the summer–autumn rice crop 15 to 20 days earlier than usual in 2003 (personal communication). Therefore, we assumed that the decreased amount of flooding and the earlier termination of flood season in 2002 accelerated the drainage of flooded areas before the dry season in 2003. Furthermore, the combination of favorable soil moisture for early sowing combined with the government incentive for early sowing provided farmers with the opportunity to bring the growing season forward. As a result, the earlier heading dates detected during periods 1 and 2 in 2003 would reflect the actual situation of earlier sowing.

3.3. Rice cropping patterns in the Mekong Delta

Rice cropping patterns were classified according to the estimated heading dates (Fig. 15). Heading dates were classified into 3-month intervals and categorized into four periods. The four periods were same as those depicted in Fig. 13. For example, the legend "1–2" in Fig. 15 means that two heading dates were estimated, one in period 1 (January to March) and one in period 2 (April to June) in this area. The major cropping patterns could be characterized as being of five types: "1–2", "1–2–3", "3–4", "1–3–4", and "1–3". Based on estimations of heading date, these cropping patterns accounted for 79.7% in 2002 and 74.4% in 2003 in the Mekong Delta. These cropping patterns were distributed in a fan-like pattern that spread outward from the headwaters of the Mekong and Bassac rivers in the upper part of the Mekong Delta to the coastline. The "1–2" double-cropped area was distributed in the inundated areas of the upper part of the delta, the "1–2–3" triple-cropped area in the central parts, and the "3–4" double-cropped area along coastal areas of the Mekong Delta. The "1–3" double-cropped area was distributed in the west and northeast of the "1–2" double-cropped area and the "1–3–4" triple-cropped area occurred in coastal areas or in

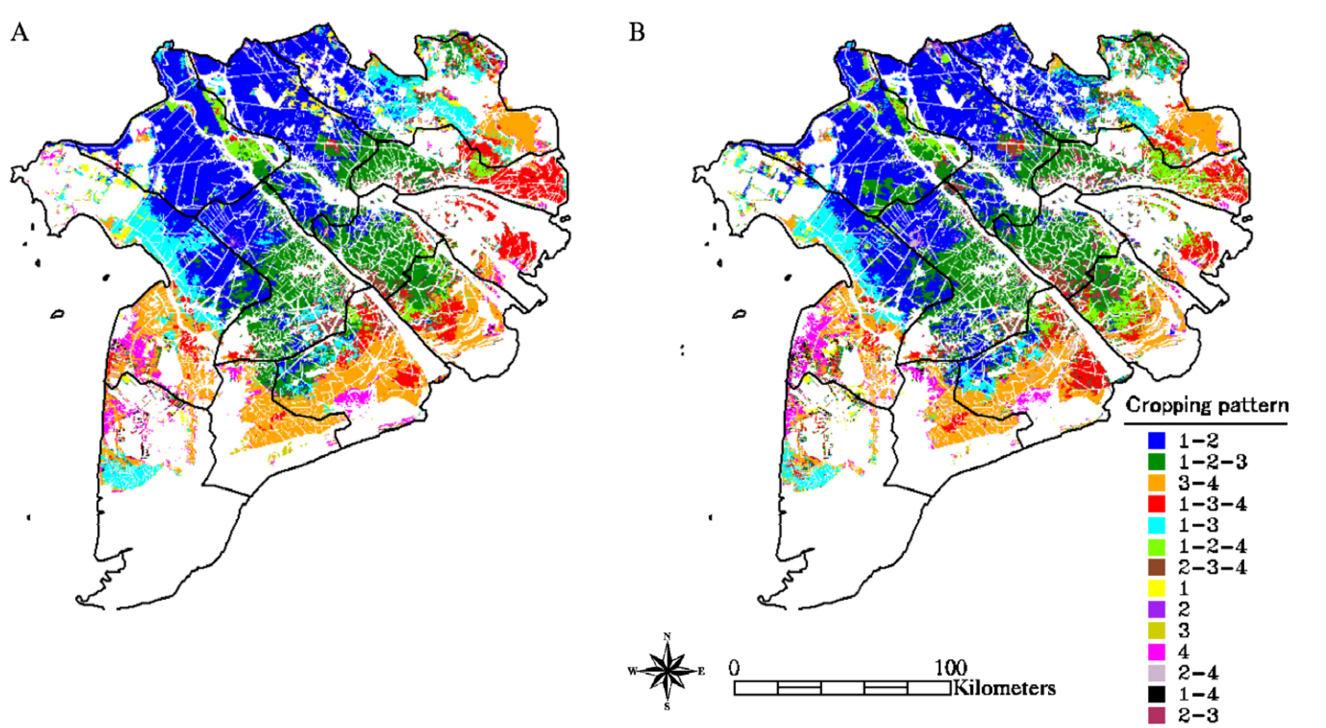

Fig. 15. Spatial distribution of cropping patterns in 2002 (A) and 2003 (B). Cropping patterns are described according to the estimated heading seasons (see Fig. 13). For example, the legend "1–2" means that two heading dates were estimated, one in period 1 (January to March) and another in period 2 (April to June).

marginal areas between the "3–4" double-cropped area and the "1–2–3" triple-cropped area.

These characteristics of spatial distributions in rice-cropping patterns provide valuable information about the relationship between the location of a paddy fields and the cropping system that is being used. In the upper part of the Mekong Delta, flooding limits rainy-season cropping (periods 3 and 4), while salinity intrusion in the dry season limits rice cultivation during periods 1 and 2 in coastal areas. The central part of the Mekong Delta is located between these areas and is dominated by alluvial soil without acid and saline constraints. Given that the paddy fields in this region can be irrigated throughout the year and because the risk of inundation is low, the "1–2–3" triple-crop system can be employed here.

The spatial distribution of cropping patterns (Fig. 15) makes it easier to understand the meaning of the land-use changes in regions V and VI in Fig. 8. Fig. 15 shows that the dry-season crop became practicable, and the cropping pattern could be changed from "3–4" to "1–3–4" in region VI. In the southern and northeastern parts of An Giang Province (region V in Fig. 8), rainy-season cropping became possible in some fields, and the cropping pattern tended to change from "1–2" to "1–2–3".

4. Conclusion

We applied WFCS, which was improved in the basis of WFCP, to multi-temporal MODIS data to accurately estimate the spatio–temporal distribution of rice phenology, the number of rice crops per year, and the cropping patterns in the Mekong Delta. We succeeded in locating triple-cropped areas that were not identified in the reference land-use data for 2002. Our findings suggested that the distribution of cropping pattern depended on whether fields were located in the upper, central, or coastal areas of the Mekong Delta. Furthermore, cropping pattern was also found to be dependent upon the quality and quantity of water resources, variations in which occurred in response to the seasonal fluctuations in runoff from the Mekong and Bassac rivers. In the upper part of the Mekong Delta, double-crop systems were dominant, with the growing season occurring from January to June to avoid flood damage. Double-crop systems were also prevalent in the coastal areas, however, the growing season in these areas occurred from July to December when salinity intrusion was ameliorated by the high water flows in the Bassac and Mekong rivers. In the central part of the Mekong Delta, triple-crop systems were employed because the threat of flooding and salinity intrusion is low. Comparison of spatial cropping patterns employed between in 2002 and 2003 revealed that the effects of flood damage and salinity intrusion were partially overcome in some areas and that the available area for cultivation was expanded from 2002 to 2003. It was also possible to identify those areas where the number of crops per year was increased from two to three. We estimated that the heading dates during the first half of 2003 in the upper part of the Mekong Delta occurred approximately 20 to 30 days earlier compared to the first half of 2002. The earlier heading dates observed in 2003 could be attributed to an earlier termination of the flood inundation in 2003 and the promotion by government of earlier sowing in winter–spring or summer–autumn paddies for the purpose of flood mitigation. These results enabled us to conclude that the cropping systems and rice phenology in the Mekong Delta are highly dependent upon the seasonal flows of the Mekong and Bassac rivers.

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