Assessment of paddy fields' damage caused by Cyclone Nargis using MODIS time-series images (2004–2013)

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Abstract

The Ayeyarwady Delta in the Bay of Bengal, the rice bowl of Myanmar, depends on natural conditions, especially rainfall. During the dry season, the delta's coastal zone experiences saline water intrusion due to its low-lying topography. On May 2, 2008, Cyclone Nargis made landfall and crossed Ayeyarwady Region and Yangon City, affecting more than 50 townships and causing massive destruction of personal property and natural ecosystems. There is no doubt that Nargis caused an unprecedented large-scale disaster, but there is no objective method to quantify crop yield and salinity damage in the delta post-Nargis. The purpose of this study, therefore, is to clarify the changes in vegetation in paddy fields in the Ayeyarwady Delta using Moderate Resolution Imaging Spectroradiometer data pre- and post-Nargis and determine whether this method can be applied to measure crop and salinity damage. The study used daily composite data at a 250-m resolution (MOD09GQ, collection 6) from 2004 to 2013 and calculated NDVI and salinity indices smoothed by locally weighted regression (Lowess). Based on the results of our studies, NDVI peak value in 2008 was lower by 19% compared to 2007 data, and that the NDVI peak values declined for three straight years since May 2008 when Nargis struck. However, salinity damage evaluation pre- and post-Nargis (using the salinity index equation) showed that soil electrical conductivity did not tend to move up in the post-Nargis dry season (2009), indicating that the decrease in NDVI values was not due to salinity damage.

Keywords Ayeyarwady delta · Cyclone Nargis · NDVI · MODIS · Salinity index

Introduction

Tropical cyclones, which include tropical storms, severe tropical depression, typhoons, hurricanes, and cyclones, threaten lives and property because of their high winds, associated storm surge, excessive rain and flooding. These cyclones have often caused widespread damage to paddy crops in the delta regions, which located in the coastal zones of the high vulnerability to natural disasters.

The Ayeyarwady delta of Bay of Bengal, the rice bowl of Myanmar, has a population of approximately 8 million in an area of 35,032 km² (Driel and Nauta 2014). Three regions

occupy the delta—Ayeyarwady, Yangon and Bago. A total of 2.89 million ha in the delta are favorable for rice cultivation, while some are prone to flooding in the monsoon (Ministry of Agriculture and Irrigation (MOAI) 2015).

A total of 11 severe tropical cyclones hit Myanmar over the last 60 years, only two of which made landfall in the Ayeyarwady delta region. On May 2, 2008, Cyclone Nargis crossed the Ayeyarwady regions and Yangon City, affecting more than 50 townships and causing massive destruction to personal property and natural ecosystems (Aung et al. 2011). Official death toll estimates exceed 146 thousand fatalities making it the seventh deadliest cyclone ever recorded worldwide. Damage estimates at over US\$10 billion made it the most damaging cyclone ever recorded in the Indian Ocean (Fritz et al. 2009).

Rice production in the delta increased significantly from 1976 to 1988 with the implementation of the Paddy Land Development Projects 1 and 2 supported by the World Bank and the Asian Development Bank. The construction of polders provided with embankments, sluice gates, and drainage systems protected the rice farms from seawater intrusion

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(Driel and Nauta 2014). However, the polders degraded and Cyclone Nargis damaged many of the polders, resulting in the uncontrolled entry of seawater and, thus reducing rice yield. Many of the damaged rice areas remain prone to seawater intrusion even in the monsoon season (MOAI 2015).

In contrast, according to the government census statistics, in the paddy-planted area and crop yield in the Ayeyarwady delta, there is no tendency to reduce the area and yield compared to the pre- and post-Cyclone Nargis. The reliability of the statistical data on rice production has been discussed by previous studies (e.g. Matsuda 2009). The previous studies were assumed that the official statistics sometimes had a bias towards achieving the high rice production target set by the government.

Several studies have been conducted on the crop damage and recovery assessment of Cyclone Nargis through the field survey, such as the literature reviews and farmer's interview; however, those studies were conducted 1–3 years after the disaster due to prevent the risk of field survey at the disaster area.

Remote sensing equipment observes a wide area at any one time and regularly observes the same location; therefore, remotely sensed data have recently been used to assess the impact of natural disasters, including cyclone. Satellite remote sensing helps in tracking changes in paddy ecosystem and can assess performance through changes in land use, primary productivity, and phenology (e.g., Kerr and Ostrovsky 2003). Remote sensing-based indices such as normalized difference vegetation index (NDVI) are sensitive to variability in biomass and nitrogen content of crop canopies, reflecting the amount of vegetation and the degree of vegetation vigor. The NDVI theoretically ranges from -1.0 to 1.0 . Several vegetation indices have been used as indirect indicators for assessing and drawing a map of soil salinity distribution. Similarly, a number of researchers have developed different salinity indices to detect and map soil salinity such as normalized difference salinity index and salinity index (Allbed and Kumar 2013).

Many studies are performed in order to assess the vegetation and salinity damage after cyclone using satellite data analysis. For example, Konda et al. (2018) assessed vegetation damage due to Hudhud cyclone based on NDVI using the Landsat-8 satellite image in the southeastern coastal area of India. Goto et al. (2015) evaluated salinity damage to crops due to typhoon 9918 based on NDVI using the Landsat-5 satellite image in Kumamoto Prefecture, south part of Japan. Although these studies using the Landsat satellite image have been just assessed the fractional vegetation or salinity damage at a certain time during pre- and post-cyclone, very few attempts have been made to continuously observe and assess how to recover from the damage of vegetation or salinity after cyclone. On the contrary, time-series satellite data of Moderate Resolution Imaging

Spectroradiometer (MODIS) sensor onboard earth observation satellites like Terra and Aqua are capable of synoptic viewing of inaccessible and protected areas for monitoring the land surface processes with high temporal resolution (Dutta et al. 2015).

There is no doubt that Cyclone Nargis landfall caused the unprecedented large-scale disaster; however, there is no objective evidence of the crop yield and salinity damage of the post-Nargis in the delta. Therefore, the purpose of this study is to clarify the change of vegetation in the paddy fields during pre- and post-Nargis in the delta using MODIS time-series images from 2004 to 2013. That is, our research results lead to one of the objective evidences of the crop and salinity damage caused by Cyclone Nargis.

Materials and methods

Study area

The study area, Labutta township, is in the lower part of Ayeyarwady delta. The area covers the fertile alluvial low land and stands 1.52 m and above the sea level. The total area of Labutta, 300,566 ha, is composed of 99,642 ha agricultural land, 111,544 ha forestland and 85,829 ha non-agricultural land (Seinn Seinn et al. 2015). The major river Ayeyarwady and other rivers Patheingyi, Ywé, and Pyawbwe Rivers are crossing from south to north of Labutta (Fig. 1). The coastal zone of Labutta is crisscrossed by tidal rivers discharging into the Bay of Bengal. The river water is affected by seawater intrusion especially at the end of dry season, or just before the onset of pre-monsoon season. Seawater sometimes reaches as far as more than 100 km from the estuary (Japan International Cooperation Agency (JICA) 2011).

Rainfed rice in Labutta occupied 86% of the total agricultural land. Cropping pattern depends on natural condition, especially rainfall. Farmers start wet season cultivation at the beginning of rainy season (May–June) and harvest at the beginning of dry season (November–December) after drying paddy at the field. Farmers in irrigated area practice dry season paddy between December and April. And, the farmers who have farming land with high moisture contents usually cultivate beans such as black gram, green gram, and groundnuts (JICA 2011). Rice paddy yields in Labutta are slightly higher than the national average and, however, still low overall when compared to the region. Planning Department data show that the rice yield for the dry season crop was 4.89 tons ha⁻¹ in 2014–2015, while the monsoon crop yield was 3.21 tons ha⁻¹, slightly above the national average of 2.56 tons ha⁻¹ (Fee et al. 2017).

Annual riverine floods are most common in Labutta due to intense rainfall at the peak of monsoon. Weather observations over a 30-year period (1988–2017) (observed

Fig. 1 Location of study area (a) and points of field sampling and satellite data analysis (b)

by Department of Agriculture (DOA), Labutta township, 16.1495780° N, 94.7575353° E) showed an annual average rainfall of 3276 mm, and the highest rainfall usually comes in from June to August; particularly, there were large fluctuations in monsoon season (Fig. 2). Monthly rainfall in

May 2008 was 871 mm; this rainfall was 547 mm more than the average on May during 1988–2017. The annual mean temperature is 26.8 °C, the average maximum temperature is 32.3 °C, and the average minimum temperature is 22.3 °C (Myanmar Environment Institute 2017).

Fig. 2 Average monthly rainfall in Labutta township during 1988–2017 and 2008 (separately)

Field sampling (ground-truth data)

Soil sampling points were selected paddy fields along the Ywe river, from the river mouth to 65 km inland (Fig. 1b, monsoon crop area). A total of 25 soil samples were collected from the topsoil (0–5 cm) in the dry season (March 2017 and 2018) and rainy season (November 2016 and August and November 2018), respectively. The exact coordinates of each sampling point were registered using a global positioning system (GPS) with an accuracy of ± 5 m. Each soil sample was comprised of four core subsamples that were collected at a distance of 20 m north, south, east, and west of the center sampling point (Allbed et al. 2014). Each sampling point was 0.4–6.5 km away from the river. Each sample was air-dried, ground, filtered with a 2-mm sieve, and stored in a plastic bag until analysis. The electrical conductivity (EC) of a 1:5 soil–water extract ($EC_{1:5}$) was measured by handheld EC meter (ES-71, HORIBA). The $EC_{1:5}$ method has the advantage of simplicity reduced time and cost compared to saturation paste extracts (EC_e) and a strong linear relationship between EC_e and $EC_{1:5}$; however, they vary according to the area of interest. In Japan, the target of salt removal for paddy rice is often set to $EC_{1:5}$ of 0.3–0.7 dS m^{-1} (Crop Science Society of Japan 2012).

In order to compare with the MODIS NDVI time-series data and rice leaf greenness values, the soil plant analysis development (SPAD) values were measured at each soil sampling point, which is registered by GPS, using a SPAD-502 plus chlorophyll meter (Konica Minolta) on July 28–30, 2018, in the monsoon season and November 28 to December 1, 2018, in the post-monsoon season. The field condition at the end of July was a few days to 35 days after transplanting or sowing, almost occupied the water area in the field, and from late November to early December was before harvest of monsoon crop; the conditions of the paddy fields differed depending on the distance from the river mouth. The uppermost expanded leaves on five consecutive plant hills were measured, and the five values were immediately averaged (Shibayama et al. 2012).

Satellite data acquisition and data analysis

The MODIS data were obtained from the U.S. Geological Survey (USGS) through the Earth Explorer tool (<https://earthexplorer.usgs.gov/>). The NDVI satellite dataset used in this study was from the MODIS instrument onboard the Terra satellite. We used daily composite data at a 250-m resolution (MOD09GQ, collection 6) from 2004 to 2013 (5 years before and after Cyclone Nargis landed in 2008, as an intermediate year). The one tile (h27v07, 10–20° N; 91.3887–106.4266° E) of MOD09GQ coverage for Labutta, the same soil sampling points registered by GPS, was accessed from the NASA Land Processes Distributed

Active Archive Center (<https://e4ftl01.cr.usgs.gov/>). The MOD09GQ vegetation product contains quality assessment (QA) data that contain information on the overall usefulness, the pixel reliability on a per-pixel basis. Furthermore, QA contains per-pixel quality flags relating to cloud state, cloud shadow, aerosol quantity, and basic land cover characteristics, such as the land/water, snow, and fire flags (Vermote et al. 2015). Our study extracted high-quality (QA = 00) for 250-m resolution QA of data product quality, cloud state flags (bits 0–1, clear or mixed), and land/water flags (bits 3–5, land or shallow/deep inland water) for data product state QA flags.

The NDVI, which is a nonlinear combination of red and near-infrared (NIR) spectral radiances $(NIR - red)/(NIR + red)$, exhibits a strong relationship with vegetation activity and green biomass. The index is usually employed for predicting vegetation phenology from space (Glenn et al. 2008; Hmimina et al. 2013; Karlsen et al. 2008). The NDVI time series were temporally smoothed by the locally weighted regression (Lowess) smoother as defined by Cleveland and Devlin (1988).

We have applied the three salinity indices (SI) proposed by Khan et al. (2005) and Douaoui et al. (2006) in Eqs. (1), (2) and (3), for soil salinity in this study to evaluate a relationship between $EC_{1:5}$ values measured on the ground and the SI values extracted from corresponding pixels.

$$SI1 = \sqrt{B \times R} \quad (\text{Khan et al. 2005}) \quad (1)$$

$$SI2 = \sqrt{G \times R} \quad (\text{Khan et al. 2005}) \quad (2)$$

$$SI3 = \sqrt{G^2 \times R^2} \quad (\text{Douaoui et al. 2006}) \quad (3)$$

where B , G , and R are expressed in reflectance in the blue, green, and red bands, respectively. Surface reflectance is the amount of light reflected by the surface of the earth; it is a ratio of surface radiance to surface irradiance, and as such is unitless, and typically has values from 0 to 1. MOD09's surface reflectance values are scaled by 10,000 and then cast to 16-bit integers, so surface reflectance values in MOD09 files are typically from 0 to 10,000 (Vermote et al. 2015). In the case of SI, obtained SI was divided by 10,000.

Results

MODIS NDVI seasonal pattern

Table 1 shows three-year (2007–2009) MODIS NDVI peak value and ratio of changes at survey points ($n = 25$). The peak value of MODIS NDVI from the river mouth to the point 23.3 km in 2008 decreased by 14.7–24.5% compared

Table 1 Three-year (2007–2009) MODIS NDVI peak value and ratio of changes at survey points ($n=25$)

Distance from the river mouth (km)	NDVI peak (3 years)			Changes (%)	
	2007	2008	2009	2007 versus 2008	2007 versus 2009
2.7	0.330	0.249	0.268	–24.5	–18.8
5.4	0.598	0.458	0.482	–23.4	–19.4
8.4	0.506	0.409	0.428	–19.2	–15.4
10.2	0.453	0.382	0.411	–15.7	–9.3
12.7	0.416	0.348	0.382	–16.3	–8.2
15.6	0.478	0.383	0.433	–19.9	–9.4
19.7	0.571	0.487	0.522	–14.7	–8.6
23.3	0.541	0.444	0.492	–17.9	–9.1
25.8	0.671	0.632	0.649	–5.8	–3.3
28.6	0.703	0.692	0.690	–1.6	–1.8
31.4	0.731	0.709	0.689	–3.0	–5.7
32.8	0.674	0.647	0.633	–4.0	–6.1
34.6	0.781	0.734	0.768	–6.0	–1.7
37.3	0.700	0.674	0.683	–3.7	–2.4
39.1	0.686	0.691	0.657	0.7	–4.2
40.9	0.725	0.698	0.708	–3.7	–2.3
43.9	0.704	0.681	0.692	–3.3	–1.7
46.2	0.780	0.729	0.751	–6.5	–3.7
48.9	0.793	0.809	0.806	2.0	1.6
51.3	0.790	0.788	0.794	–0.3	0.5
53.7	0.778	0.766	0.775	–1.5	–0.4
56.2	0.790	0.765	0.781	–3.2	–1.1
58.9	0.831	0.817	0.774	–1.7	–6.9
62.1	0.798	0.781	0.791	–2.1	–0.9
64.8	0.843	0.845	0.858	0.2	1.8

to 2007. On the other hand, at the point of 25.8 km, which is the next point after 23.3 km, the decreased ratio was 5.8%. It was confirmed that the NDVI peak difference in 2008 was obviously different at the boundary of 23 km. The MODIS NDVI time-series data (original) and the smoothed line by the Lowess smoother from 2004 to 2013 are shown in Fig. 3a and b. These figures show from the Ywe river mouth to 23 km inland at the eight points average of MODIS NDVI (Fig. a), from 23 to 65 km inland at the 17 points average (Fig. b), respectively. During the rainy season from May to November, the number of usefulness MODIS data was much smaller than in the dry season due to the cloudy sky; however, the curve shown in the figures shows the time-series change of NDVI from which noise has been removed by the Lowess smoother, and reproduced the rise of NDVI after rice planting and the peak time near the heading date. The maximum value in the NDVI seasonal change curve was used as the heading date; we estimated the peak date of NDVI value from 2004 to 2013 and calculated the change in NDVI values from 2008 to 2013, using 2007 as the base year (Table 2).

In Fig. 3a from the river mouth to 23 km inland, the NDVI peak appeared during October 5–26 every year;

however, the peak in May 2008 appeared on November 2 (Table 2a). The peak after May 2008 has declined for 3 years when the cyclone Nargis attacked. Compared with 2007, the peak difference was –19.0% in 2008, –12.3% in 2009, and –11.7% in 2010. NDVI gradually recovered year by year, and almost recovered in 2011, showed the same NDVI as in 2007. In contrast, in Fig. 3b from 23 to 65 km inland, the NDVI peak in 2008 was slightly lower than that of in 2007, but the decreased ratio was not as high as in Fig. 3a; there has been no remarkable difference ($-2.6 \pm 2.3\%$) when the Cyclone Nargis attacked.

Comparison of MODIS NDVI and measured SPAD

As shown in Table 2, the NDVI peaks of (a) and (b) have a difference of 0.132–0.198 (excluding 2008), and the NDVI peaks of (b) are always high. Table 3 shows the relationship between the measured SPAD and MODIS NDVI analysis at the survey points. The satellite data at the time of the survey used MODIS NDVI average values for the 10 days from November 27 to December 6. The field survey at the end of July was a few days to 35 days after transplanting or sowing, and the survey from late November to early December

Fig. 3 Time-series data of original and smoothed MODIS NDVI during 2004–2013, **a** 23 km inland from the river mouth and **b** from 23 to 65 km inland

Table 2 Peak date and its value of MODIS NDVI and ratio of changes

(a) From the river mouth to 23 km inland				(b) From 23 to 65 km inland		
Year	Peak value	NDVI peak	Changes (%) (2007 as base)	Peak value	NDVI peak	Changes (%) (2007 as base)
2004	17-Oct	0.526		10-Oct	0.663	
2005	26-Oct	0.487		14-Oct	0.636	
2006	23-Oct	0.486		11-Oct	0.647	
2007	5-Oct	0.489	0.0	7-Oct	0.642	0.0
2008	2-Nov	0.396	−19.0	18-Oct	0.625	−2.6
2009	18-Oct	0.429	−12.3	7-Oct	0.627	−2.3
2010	20-Oct	0.432	−11.7	12-Oct	0.614	−4.4
2011	20-Oct	0.487	−0.4	7-Oct	0.636	−0.9
2012	15-Oct	0.490	0.2	5-Oct	0.672	4.7
2013	10-Oct	0.497	1.6	8-Oct	0.629	−2.0

was before harvest. The condition of the paddy fields before harvesting was that 87% of the paddy fields were still growing from the river mouth to 34 km inland (Labutta town, 16.146667° N, 94.761111° E) and 42% from Labutta town to 30 km inland.

Comparing measured SPAD and MODIS NDVI of the river mouth to 23 km inland (a) and 23 km to 65 km inland (b) in Table 3, MODIS NDVI of (b) was 0.14 higher than that of (a); it showed almost the same tendency as the difference between (a) and (b) in Table 2. In contrast, the

Table 3 Relationship between measured SPAD and MODIS NDVI

	Survey date	Measured SPAD	MODIS NDVI
(a) River mouth to 23 km inland	29 Jul. 2018	28.9 ± 3.4	0.36 ± 0.06
	1 Dec. 2018	28.5 ± 2.5	0.41 ± 0.04
Average		29.0 ± 3.0	0.39 ± 0.05
(b) 23 km to 65 km inland	28 & 30 Jul. 2018	30.7 ± 3.6	0.52 ± 0.09
	28 & 30 Nov. 2018	29.5 ± 3.4	0.53 ± 0.07
Average		30.1 ± 3.5	0.53 ± 0.08
(b)–(a)		1.1	0.14

Mean value ± S.D

Fig. 4 Distribution of soil salinity ($EC_{1.5}$) and the leaching ratio at distances from the river mouth in the rainy and dry seasons

difference of SPAD was 1.1, which was within the error range. Besides, no correlation was found between the measured SPAD value and MODIS NDVI ($R^2=0.02$), and no significant difference was found ($p>0.05$).

From the revealed results, it was confirmed that the difference in MODIS NDVI peak from the river mouth to 23 km shown in Fig. 3a and from 23 to 65 km shown in Fig. 3b was not related to SPAD. The data collected by MODIS range within 250 m × 250 m plot. Therefore, it was suggested that the NDVI value becomes low at the measurement points near the estuary, due to the influence of the water area (sea or river) occupying more near the estuary.

Salinization and desalinization range based on field sampling

Figure 4 shows the distribution from the river mouth on soil salinity ($EC_{1.5}$) in the rainy and dry seasons and the leaching ratio during the rainy season in the study area. The survey location is recorded by GPS and is measured at almost

the same point each time. The leaching ratio was calculated using Eq. (4) on the average value of $EC_{1.5}$ on 2 years dry seasons (March 2017 and March 2018) and 2 years rainy seasons (November 2016 and August and November 2018). The average rainfall during the rainy season (May to November) from 2016 to 2017 was 3466 mm (observed by DOA, Labutta township).

$$\text{Leaching ratio (\%)} = \frac{EC_{1.5} \text{ in dry season} - EC_{1.5} \text{ in rainy season}}{EC_{1.5} \text{ in dry season}} \times 100 \quad (4)$$

Soil salinity was highest near the river mouth in both dry and rainy seasons and gradually decreased away from the estuary. This indicates that the rice-growing areas in the delta are not completely protected against a periodic seawater intrusion even in rainy season. In the dry season, the $EC_{1.5}$ was $9.96 \pm 1.97 \text{ dS m}^{-1}$ at maximum and $0.22 \pm 0.08 \text{ dS m}^{-1}$ at minimum; in rainy season it was $2.67 \pm 0.28 \text{ dS m}^{-1}$ at maximum and $0.12 \pm 0.05 \text{ dS m}^{-1}$ at minimum. This means that the soil EC on the topsoil can be regarded the maximum value as the upper limit in the dry season and the minimum value as the lower limit in the rainy season unless salts infiltrate the ground surface due to storm surge.

The reaching ratio, no matter how large or small of soil EC, was 60–80% up to 46 km from the estuary. These areas are in the range affected by seawater intrusion. In addition, the leaching ratio sharply declined at the upstream side of 46 km with the distance from Ywe river.

Comparison of salinity indices and measured soil $EC_{1.5}$

Table 4 shows the results of applied salinity indices (SI) in the study area. The calculation of SI in MODIS was only for the dry season in 2 years (March 2–6, 2017, and March 10–11, 2018). In our study, salinity data for the rainy season were not considered, because the sky was covered with clouds and the MODIS time-series data were very noisy, and the range of $EC_{1.5}$ was narrow at 2.55 dS m^{-1} (0.12 to 2.67 dS m^{-1}). SI_3 had the highest R^2 ($=0.81$), relatively

Table 4 Applied salinity indices on the study area

Index	Equation	References	R ² (polynomial regression)
Salinity Index 1	$SI_1 = \sqrt{B \cdot R}$	Khan et al. (2005)	0.3034
Salinity Index 2	$SI_2 = \sqrt{G \cdot R}$	Khan et al. (2005)	0.7736
Salinity Index 3	$SI_3 = \sqrt{G^2 + R^2}$	Douaoui et al. (2006)	0.8089

B, G, R reflectance in the blue, green and red bands

Fig. 5 Distribution of measured and calculated $EC_{1.5}$, and SI_3 at distances from the river mouth in dry seasons

good correlation with measured soil EC. The relationship between SI_3 and $EC_{1.5}$ was determined and a regression equation was obtained, as shown in Eq. (5). This equation limits to $0.07 < SI_3$.

$$EC_{1.5} (dS m^{-1}) = 2761.3 (SI_3)^3 - 807.24 (SI_3)^2 + 85.052 (SI_3) - 2.886 \quad (5)$$

Figure 5 shows the distribution from the river mouth on the measured $EC_{1.5}$ for the dry season in two years average, the calculated $EC_{1.5}$ by Eq. (5), and SI_3 calculated by Eq. (3). Although the SI_3 range calculated by Eq. (3) of 1100–1600 has deviated from the measured $EC_{1.5}$, it confirmed and reproduced using Eq. (5). For each point, the calculated $EC_{1.5}$ by Eq. (5) corresponds well with measured $EC_{1.5}$, and the root mean square error (RMSE) was $0.33 dS m^{-1}$. SI_3 was highest near the river mouth in the dry season and gradually decreased away from estuary.

Soil salinity seasonal pattern

The calculated $EC_{1.5}$ using Eq. (5) and the smoothed line by the Lowess from 2004 to 2013 are shown in Fig. 6. This figure shows from the Ywe river mouth to 23 km inland at the eight points average of calculated $EC_{1.5}$. The calculated SI was spread largely, caused by many clouds at the peak periods (May–June), and the MODIS time-series data were very noisy. The average of the measured $EC_{1.5}$

Fig. 6 Calculated $EC_{1.5}$ changes during 2004–2013 (from the river mouth to 23 km inland)

from the river mouth to 23 km inland shown in Fig. 4 in the dry season was 2.78 dS m^{-1} . It was found from the result that the smoothed line moves upward during the dry season, the peak appeared at the end of May or early June (pre-monsoon season), and it tends to get lower in the rainy season.

The maximum value in the $\text{EC}_{1.5}$ seasonal change curve was used as the heading date; our study estimated the peak date of $\text{EC}_{1.5}$ from 2004 to 2013 and calculated the changes in $\text{EC}_{1.5}$ from 2009 to 2013, using the average of 2005 and 2007 (2.75 dS m^{-1}) as the base year (Table 5). There was no tendency for soil EC to move up in the post-Nargis 2009 in dry seasons. From this result, although the calculation result is noisy, it was confirmed that the soil salinity in the dry season is almost constant even after about 10 years from the Nargis attacked.

Discussions

Crop recovery period caused by cyclone Nargis

We estimated the influence of recovery period by Cyclone Nargis attacked objectively through the MODIS NDVI time-series data analysis from 2004 to 2013. The MODIS NDVI peak of Nargis landed year (2008) was estimated to reduce by 19.0% compared to the previous year, and it was estimated to take 3 years to the recovery (Fig. 3a and Table 2). NDVI is identified as one of the prominent factors indicating the vegetation growth condition and the degree of vegetation cover of an area and it has obvious seasonal variations (Zhao et al. 2004). The relationship between the maximum NDVI value or the summation of the rice NDVI during the rice crop growing season and rice yield has been expressed by an exponential relationship (e.g. Ajith et al. 2017) or a linear relationship (e.g. Aboelghar et al. 2011). Based on the

government census statistics on the rice yield in the Labutta township, although there is no tendency to reduce the yield compared to the pre- and post-Nargis, besides, at the time of our studies we were unable to collect the reliable statistical data on rice yield compared to pre- and post-Nargis. May Phyo Way (2015) found that after Nargis, yield of rice has reduced 19.25% in monsoon rice production through the literature reviews and interview with farmers, which was similar to our study result. May Phyo Way (2015) estimated the reason for the yield reduction in monsoon rice that crop production was risky due to the influence of seawater flooding and pest problem such as rodent and crab, and farmers were not using the resources of land and labor effectively. Besides, UNEP (2009) reported that Nargis caused devastating damage to the environment. Cyclone Nargis destroyed 38,000 ha of natural and replanted mangroves, submerged over 63% of paddy fields, and damaged 43% of freshwater ponds. The impacts of the cyclones have been intensified by earlier damage to the environment, including deforestation and mangroves degradation, over-exploitation of natural resources such as fisheries, and soil erosion.

During our field survey in 2018, we have interviewed some farmers who live from the river mouth to 23 km inland. From those interviews, we got information that it took 3–5 years to recover from the damage caused by Nargis (most often 3 years). In addition, these farmers described that rodent pest problem is still present.

In the field scale survey, Matsuda (2012) reported that although rice yields in some of the affected areas had recovered by the monsoon cropping season of 2009, yields in some of the survey areas along the coast were still less than half that before Nargis in 2010. Besides, Htwe et al. (2013) reported that massive rodent outbreaks occurred in the Ayeyarwady Delta in July 2009 due to the asynchronous planting using different varieties led to an extended harvest period, which provided a longer period of food availability for rodent. Our study using MODIS 250-m resolution does not adequately reflect the individual situation at the micro-level, such as at the village or farm level. However, in the delta, the storm surge caused by Cyclone Nargis destroyed embankments and entered into paddy fields. Under these conditions, conducting a field survey is difficult and risky. At the time of occurred of such an extreme event, our research approach was to understand the actual situation over a wide area using the remote sensing technique.

Estimated factors on decline of NDVI peak from 2008 to 2010

Based on our results, the decline factor in the MODIS NDVI peak in May 2008 was not salt effects caused by storm surge flooding of the cyclone (Fig. 6 and Table 5).

Table 5 Peak date and its value of calculated EC and ratio of changes (from the river mouth to 23 km inland)

Year	Peak date	EC value	Changes (%) (average of 2005 and 2007 as base)
2004	30-May	2.82	
2005	2-Jun	2.77	
2006	n/a	n/a	
2007	3-Jun	2.73	0.0
2008	n/a	n/a	–
2009	29-May	2.58	– 6.2
2010	30-May	2.44	– 11.3
2011	5-Jun	2.54	– 7.6
2012	30-May	2.74	– 0.4
2013	4-Jun	2.46	– 10.5

In the dry season, little or no rainfall in the delta, and the downstream flow of freshwater becomes very low. Therefore, during the dry season period, soil salinity level became highest through evaporation in low land fields. According to our field survey results, salts accumulate in the dry season up to 46 km from the estuary due to saline water intrusion; however, 60–80% of salts are leached due to rain in the rainy season (Fig. 4). This event is constantly occurring. JICA (2011) reported that the cyclone struck the Ayeyarwady Delta on May 2–3, 2008, which was just before the wet season paddy cultivation started. It is considered that there was no agricultural crop plant growing on the surface of the paddy land; however, the surface soil was almost saturated by the considerable amount of rainfall. The rainfall water was stored for several months on the surface of the paddy field for the monsoon season, the leaching was accelerated, and the salt concentration has remarkably reduced. After landing in Cyclone Nargis, the rainfall in Labutta was 2451 mm during monsoon season (May–September) in 2008. Cyclone Nargis came at the end of the dry season (pre-monsoon); seawater intrusions were washed out by the following rainy season. As the salt leaching in the paddy field during monsoon season, FAO (1985) and Rasel et al. (2013) have reported that the rainfall during monsoon seasons reduce the surfaces soil salinity in the southwestern coastal zone of Bangladesh that is located about 800 km away from Ayeyarwady delta.

Therefore, it seems reasonable to conclude that the major factors on the decline of NDVI peak from 2008 to 2010 were attributed to the massive destruction to personal properties (home, crop, livestock, etc.) and main infrastructure (transportation, marketing, etc.). These are likely to be followed by the destruction of mangrove forests, seawater flooding, and pest outbreaks (rodents and crabs). The loss of assets and destruction of communication networks have resulted in the non-functioning of a majority of rural markets and limited supply of basic goods and services (FAO 2008).

Conclusion

Lower delta, like the Ayeyarwady Delta, has permanently or seasonally under influence of seawater intrusion; it is highly vulnerable to disasters such as storm surge caused by cyclones. In this study, it is the first time that satellite data analysis has objectively clarified the crop damage recovery period in the delta caused by Cyclone Nargis. In other words, we used daily composite data at a 250-m resolution (MOD09GQ, collection 6) from 2004 to 2013, and we calculated NDVI and salinity index (SI) smoothed by locally weighted regression (Lowess). The MODIS NDVI peak value in 2008 was lower by 19.0% compared with 2007 data,

and that the NDVI peak values declined for three straight years since May 2008 when Nargis struck.

In the dry season, salts accumulate up to 46 km from the estuary due to saline water intrusion; however, 60–80% of salts are leached due to rain in the rainy season. This event constantly occurs unless an extreme event occurs. However, we indicated a relationship between $EC_{1.5}$ values measured on the ground and the SI values extracted from corresponding pixels, and we evaluated salinity damage for pre- and post-Nargis (using SI equation) and showed that soil EC did not tend to move up in the dry season post-Nargis (2009), indicating that the decrease in NDVI values was not due to salinity damage. Although the calculated SI was spread largely, caused by many clouds during rainy seasons, and the MODIS time-series data were very noisy, it seems reasonable to conclude that the major factors on the decline of NDVI peak from 2008 to 2010 were attributed to the socio-economic factors such as massive destruction to personal properties (home, crop, livestock, etc.) and main infrastructure (transportation, marketing, etc.), and subsequent agroecological factors such as mangrove forests destruction, seawater flooding, and pest outbreaks (rodents and crabs).

In contrast, there are two cyclone seasons in the north Indian Ocean, namely the pre-monsoon (May) and the post-monsoon (October–November). The storm surge caused by the cyclone landed in the pre-monsoon will be leached out by rain in the rainy season, so salinity damage will not have a serious problem in the delta. In contrast, the cyclone in the post-monsoon, it will be estimated that salt will accumulate because no rainfall can be expected until the next year's rainy season. We need to clarify this hypothesis as a matter of further discussion.

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