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ARTICLE

Impacts of extreme drought on rice planting calendar in Vietnamese Mekong Delta

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Abstract

This research examined the impact of extreme drought on rice planting dates in the Vietnamese Mekong Delta (VMD) region from 2014 to 2018 using the time series of Normalized Difference Vegetation Index (NDVI). The Savitzky–Golay filter method was applied to remove noises and smooth the NDVI time series. Rice planting dates were determined by using the threshold of increasing NDVI to 20% of the amplitude for each season using TIMESAT. The research findings show that the remotely sensed-based sowing batches and the cultivation areas matched the official statistics with an estimated error of less than 12%. In the 2015/2016 extreme drought, the rice planting dates were delayed compared to the neutral years, especially in the winter–spring (WS) and summer–autumn (SA) crops. In general, the WS crop was more affected in the double rice crops than the SA crop in the triple rice crops. The results also pointed out various ecoregions facing different problems that should be addressed to ensure farmers' livelihood, primarily water management. Further research is necessary to understand the combined impacts of drought and changes in sowing dates on rice yield and the vulnerability of different farming models in the VMD.

Keywords Extreme drought · Vietnamese Mekong Delta · MODIS · Rice crop calendar · TIMESAT · Planting date

Introduction

Rice is the principal agricultural production in most countries of South and Southeast Asia and an important primary income source for many households. Viet Nam was the world's third-biggest exporter and fifth-largest producer of rice in the year 2015 (FAOSTAT 2015). The Vietnamese Mekong Delta (VMD) is the most extensive national rice production, accounting for more than 53% of the country's rice areas and more than 80% of exported rice (Nguyen et al. 2004). In the VMD, rice is mainly cultivated in three seasons, including autumn–winter (AW), summer–autumn (SA), and winter–spring (WS). The area of the WS and SA crops gradually increases because they are the most critical crops growing during favorable weather conditions. In contrast, the area of AW crop considerably reduces for other crop categories (FAO 2002). However, the vulnerability of rice production to climate change has increasingly been recognized, especially regarding extremely high temperatures, saline instruction, and drought (Yoshida et al. 2015).

Extreme drought is determined based on several factors. More explicitly, high temperatures with low rainfall or intermittent rain for several months are one of the drought signatures that harm rice production (Korres et al. 2017). Most rice-planted areas are located in regions with temperatures above optimal growth (22–28^{0}C). Therefore, any further temperature increases during the sensitive stages of crop growth adversely affect its normal growth and yield (Krishnan et al. 2011). The severity of extreme climate events, particularly droughts, results in damage to rice planting areas and a reduction in the productivity of crops (Apriyana et al. 2019).

The 2015/2016 drought was one of the worst droughts in history, exacerbated by the El-Niño event (UNDP 2016). Vietnam Meteorological and Hydrological Administration (2017) revealed that the severe drought occurred in the VMD in 2016. Notably, the precipitation at the beginning of the rainy season was low (71.5 mm, 1.4 mm, and 1.8 mm

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in January, February, and April 2016, respectively). The timing of the onset of the rainy season in was also delayed (2,405.7 mm in May), while the recorded average mean temperature was higher (36.3 °C in April; and 36.8 °C in May) compared to other years. It had a significant impact on rice production in the VMD. During the drought, rice planting calendars were disrupted, and rice sowing times were delayed. Delayed sowing can lead to reduced crop yields, as rice has insufficient time to mature before the end of the growing season. Ultimately, it leads to decreased rice yields and higher rice prices, causing food insecurity and threatening the livelihoods of millions of people in the delta (General Statistics Office of Vietnam 2019). As a coastal delta with the vast majority of the population dependent on agriculture, the impacts of extreme climate events on their livelihoods are pronounced and far-reaching (Ho et al. 2021). Therefore, the effects of extreme drought on rice cultivation, especially for sowing time, are of interest to scientists, policymakers, and even farmers.

To date, many climate change and drought studies on the shifting rice crop calendars have been conducted around the VMD (Mainuddin et al. 2013; Deb et al. 2016; Lee and Dang 2018; Kontgis et al. 2019). For example, a study on shifting the rice crop planting calendar to adapt to climate change in the Long Xuyen Quadrangle using the FAO-AquaCrop model was conducted by An (2020). It indicated that the grain yield of WS and SA crops increases in turn by 6.2% and 5.3% when the crop broadcasting calendar (CBC) is delayed from 7 to 14 days compared to the baseline. Meanwhile, the grain yield of AW crop increases by 6.4% when the CBC is shifted 14 days compared to the baseline. Moreover, a research endeavor involving the monitoring of rice growth stages using MOD13Q1 16-day temporal resolution indicated the delineation of rice cropping seasons and the timing of rice planting within the VMD during 2008–2009 through NDVI time series analysis (Minh et al. 2012). They all revealed the shifts in rice cropping seasons and their impacts on seasonal yield trends. However, it has yet identified the sowing date due to limitations on temporal resolution.

Nowadays, the Moderate Resolution Imaging Spectroradiometer (MODIS) MCD43A4 daily product is valuable information for monitoring rice growth. This product uses a combination of spectral bands to derive various biophysical parameters related to vegetation, including vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). These indices are sensitive to changes in vegetation cover and can be used to monitor the growth and development of rice crops. This product provides daily measurements at a spatial resolution of 500 meters, allowing for timely and accurate monitoring of rice crop conditions. Moreover, it is also beneficial for identifying anomalies in rice growth, such as water stress, nutrient deficiencies, and pest infestations (Diem et al. 2021; Sun et al. 2020). Furthermore, the time series of daily MCD43A4 can be processed by TIMESAT, a powerful tool to analyze multi-time data series of satellite images and extract several seasonality parameters, such as beginning, ending, length, and amplitude of growing seasons (Eklundh and Per, 2015).

The study aimed to examine the rice planting calendar in the VMD during the years 2014–2018 by utilizing the TIMESAT software package. Specifically, the investigation focused on extracting the Start of Season (SOS) data during neutral years as well as the 2015/2016 drought period for both double rice crops (DRC) and triple rice crops (TRC). Furthermore, an analysis of SOS changes was conducted at different levels, ranging from an overview of the entire delta to provincial scales, in order to provide a more comprehensive understanding of the spatial variations.

Research methodology

Study area

The Vietnamese Mekong Delta (VMD) is a southern delta of Vietnam (Fig. 1), which ensures food security in the world and Vietnam. With over 40 thousand km^2 stretching over 11 cities/provinces and the primary topography of a flat and fertile plain, VMD is referred to as the “rice bowl” of Vietnam (Diem et al. 2022). Specifically, this region accounts for 54.3% of Vietnam’s total rice cultivation area, annually contributing to 55.6% of the national rice production (Hoang-Phi et al. 2022). As one of the essential deltas with its rice production and ecological significance, VMD is confronting many challenges due to transboundary impacts and climate change related to water management, sea level rise, flood, and drought. The VMD is now under heavy climate change impacts. The delta witnessed the negative impacts of the extreme drought during 2015/2016, which considerably affected rice cultivation and farmers’ livelihood (Nguyen et al. 2021a, b).

Rice crops characteristics in the Vietnamese Mekong Delta

In the Vietnamese Mekong Delta, agricultural cultivation is relatively diverse due to favorable water resources and fertilized soil conditions. However, rice cultivation area mainly depends on the hydrological and climatic patterns of each subregion. Three rice cultivation models in the delta include mono rice crop, DRC, and TRC. Mono rice crop is typically rainfed rice farming in arid regions and rice–shrimp rotational systems along the coast. Rainfed rice farming is deemed to be no longer viable because of efforts to improve

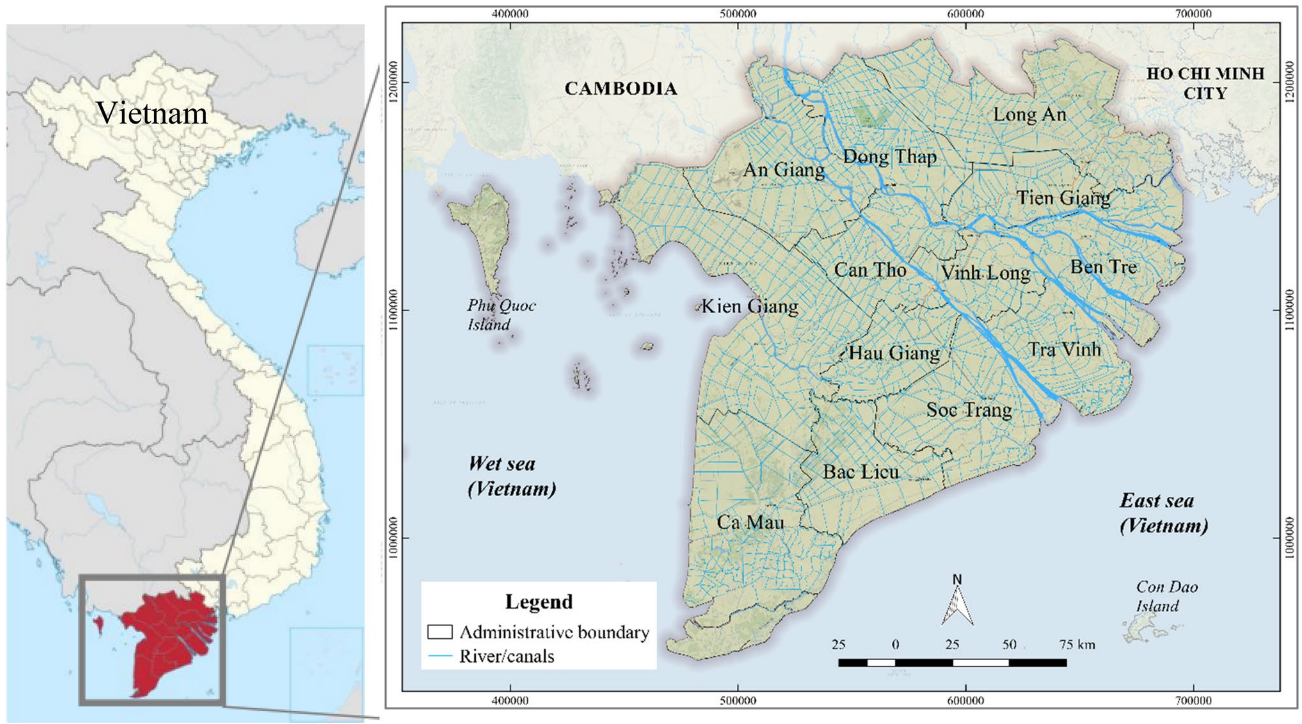

Fig. 1 Location of Mekong Delta in the Southern of Vietnam and thirteen administrative provinces

the irrigation systems entire the delta. The later farming is less affected by saline instruction and drought as rice crop is only cultivated during the rainy season (from August/September to November/December), while the dry season is the primary season for shrimp. The main seasons for rice cultivation in the VMD are winter–spring (WS), summer–autumn (SA), and autumn–winter (AW). The TRC is planted in favorable regions such as inland fertilized regions and subregions with completed irrigation systems, e.g., Bac Lieu, Ben Tre, and Tien Giang (Fig. 2) (Ferrer et al. 2022). Besides, the DRC is usually grown in the two main rice seasons of SA and WS, which are distributed in two unique ecoregions of upstream and coastal areas (e.g., Ca Mau peninsula), with particular difficulties in water resources for the third rice crop. The total rice cultivation area is about 2163 thousand hectares throughout 13 provinces, consisting of 1044 thousand hectares of DRC (except for Vinh Long province) and 1119 thousand hectares of TRC (except for Ca Mau province). Specifically, Kien Giang and Long An provinces lead in DRC with approximately 24% of the total of area each province, while An Giang is the most dominant area of TRC (~20%).

Each rice season is characterized by weather conditions. For example, WS starts from November/December to February/March, SA starts from March/April to June/July, and AW starts from July/August to October/November (Minh et al. 2012; Ferrer et al. 2022). Yet, the specific sowing date for each rice season varies from province to province, which is evenly divided into subregions within an administrative unit due to a combination of terrain, weather, and water conditions, as well as impacts of flooding and saline intrusion.

Datasets

Satellite image of Moderate Resolution Imaging Spectroradiometer (MODIS) is the primary dataset used in this study. We acquired MODIS MCD43A4 product for rice planting calendar analysis. MCD43A4 is a daily product at 500 m resolution, which provides land reflectance information from bands 1–7 adjusted using bidirectional reflectance distribution functions (Schaaf and Wang 2015). At a high temporal resolution of one day, MCD43A4 is appropriate for monitoring and capturing the principal growing stage of rice fields, a plant with a relatively short growth cycle. This research acquired images captured in 1825 single days during 2014–2018 for continuous analyses.

This study also acquired official data on the rice planting calendar and corresponding area for 2014–2018. Besides, rice yield and productivity were also collected for analysis related to drought impacts. These data are aggregated for statistical years at the provincial level and published by the General Statistics Office of Vietnam (GSO 2020). It is considered official data collected using statistical methods

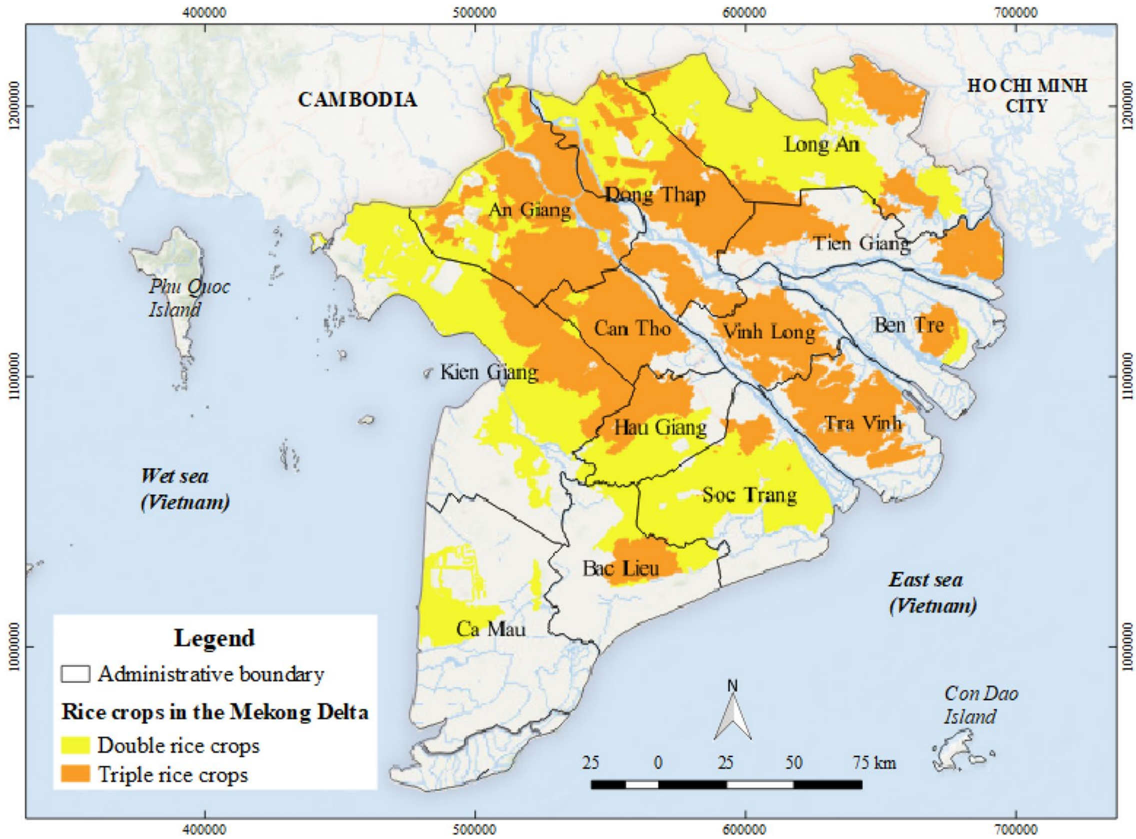

Fig. 2 Spatial distribution of the rice crop seasons in the Vietnamese Mekong Delta

using the bottom-up approach; it therefore achieves high reliability.

Simultaneously, this research also collected meteorological data from 13 weather stations under the National Centre for Hydrometeorological Forecasting (NCHF) located in 11 provinces in VMD. Each province has one corresponding station, except for Ben Tre and Kien Giang having two stations in each province. Two variables of mean temperature (Tmean) and precipitation during the same period of 2014–2018 were acquired as a reference to consider meteorological drought in the VMD.

Rice planting calendar identification

The rice planting calendar was analyzed by TIMESAT, which is a software package to analyze time series of satellite images, frequently vegetation indices, to detect seasonal parameters of crop plants (Jönsson and Eklundh 2004). Some of the critical parameters consist of start of season (SOS), end of season (EOS), middle of season (MOS), length of season (LOS), and amplitude. A complete procedure on TIMESAT to extract seasonal parameters comprises three main steps (exclude data preparation): (1) setting up the number of seasons, (2) applying the smooth function, and (3) estimating phenological parameters (Gholamnia et al. 2019; Stanimirova et al. 2019).

Data preparation

A collection of MODIS MCD43A4 in 2014–2018 was processed by a set of preprocessing procedures. The VMD is captured on two MODIS scenes, which have to be combined to get a fully informative scene for every single day. Each image was re-projected to the local coordinate system of WGS84-Zone 48 North (World Geodetic System 1984). The image was then resampled to a 500 m resolution for each pixel to achieve uniformity between the different images in the time series image.

Subsequently, a time series image was constructed for each year, in which each band was constituted by a single normalized difference vegetation index (NDVI) image. The corresponding day of the year (DOY) was also retained for each band as an essential property to identify the planting calendar in the later step. NDVI was adopted because it is a wide-used vegetation index with consistent performance regardless of climate conditions (Nguyen et al. 2021a, b). It therefore can highlight changes in rice during its growing cycle. More explicitly, NDVI recognizes the phenology of green vegetation through different reflectance on red and NIR wavelengths during photosynthesis, as shown in Eq. 1 (Tucker 1979). NDVI values approaching + 1 present healthy and denser vegetation, while NDVI values near 0 present less healthy or sparse vegetation. In contrast, approaching -1 values are frequently non-vegetation features.

$$\mathrm{NDVI} = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where NIR and RED are near-infrared and red wavelengths corresponding to bands 2 and 1 on the MDC43A4 product.

It should be noted that not all pixels were analyzed since they also include other land use and land cover categories such as built-up, aquaculture, or forest. These non-rice pixels were masked using a land cover layer and analyzed from the five-year continuous NDVI time series image to obtain the homogeneous land cover during this period. This study focused solely on DRC and TRC, as single crop system (i.e., rice–shrimp) is less vulnerable to drought because the dry season is the main period for shrimp cultivation.

Start of season (SOS) detection using TIMESAT

Rice is an annual crop that frequently has a three-month growing cycle (i.e., 85–100 days). Therefore, the NDVI values of each crop fluctuate within three months following each rice growth phase. It has the lowest NDVI values at the beginning of the crop at the tillage and sowing stages. Subsequently, the NDVI values continuously increase throughout the transplanting and vegetative growth. It is significantly higher during the reproductive phase when most of the field is covered with dense foliage and branches and reaches the highest value at the flowering stage. After this peak, the NDVI values gradually decrease during grain filling and maturity periods, and it gets another bottom at the end of the season (ripening and harvesting phases) (Tran and Vo 2014; Mosleh et al. 2015). Thus, the variations of NDVI were adopted to identify seasonality parameters.

The NDVI time series image often has noises and uncertainties due to atmospheric effects, data quality, and missing data. These uncertainties have to be solved before they can be extracted from seasonality metrics. This research applied the Savitzky–Golay filter to fit the time series and eliminate potential noises by smoothing the time series. The Savitzky–Golay is the wider-used method in TIMESAT because it can effectively remove random noises while remaining an overall time series signal. Mainly, it follows the within-season variations to better capture the local dynamics of the growing season (Stanimirova et al. 2019; Gholamnia et al. 2019). The fitting model and smoothing are the principal to identify NDVI variations for seasonality parameters.

This study utilized SOS as a critical parameter to assess changes in rice cultivation in VMD, defined as the first significant increase in NDVI as rice growth. Explicitly, the SOS is a DOY when it meets a criterion of the 20%-threshold (Eq. 2) (Eklundha and Jönssonb 2012; Kern et al. 2020). A few other thresholds are used to detect SOS (e.g., 10% or 15%). However, a 20% threshold is frequently applied to avoid uncertainty before foliage development (O'Connor et al. 2012). Each pixel is approximated to a corresponding SOS based on the variation of the NDVI value in the time series and the threshold mentioned above.

$$\mathrm{SOS} = \mathrm{NDVI_{min}} + \left(\mathrm{NDVI_{max}} - \mathrm{NDVI_{min}}\right) \times 0.2 \quad (2)$$

where $\mathrm{NDVI_{min}}$ and $\mathrm{NDVI_{max}}$ are minimum and maximum values of NDVI in a particular time series.

Analyzing changes in rice crop calendar

The SOS pixels were grouped into different periods based on the main planting calendar (i.e., each period lasts two weeks). The study involved estimating and contrasting the proportional area of each sowing period within each planting season across various years, aiming to detect potential changes in the SOS across different sowing batches for each crop. Additionally, this investigation took into account both neutral years and the drought year 2015/2016 to assess the potential consequences of severe drought on rice production. The SOS pixels for neutral years (2014, 2017, and 2018) and drought years (2015, 2016) were composited correspondingly to represent the SOS between neutral and drought years. The composite data are then used for determining the fluctuations of rice planting time. Subsequently, the planted area for each province was estimated in turn for neutral and drought years that expect to highlight the spatial pattern of drought impacts on the SOS. The flowchart of this study is shown in Fig. 3.

Results

Changes in rice planting calendar over 2014–2018

Sowing date conspicuously varies from region to region and even from farmer to farmer depending on many factors, which is even different among farmers within a subregion. Therefore, this study combined the SOS into five (05) sowing batches, each lasting half a month, for conventional assessment and comparison.

Double rice crops (DRC)

The SOS for DRC frequently varies about a month and a half between the regions, starting around mid-November to early January next year for WS and mid-March to early May for

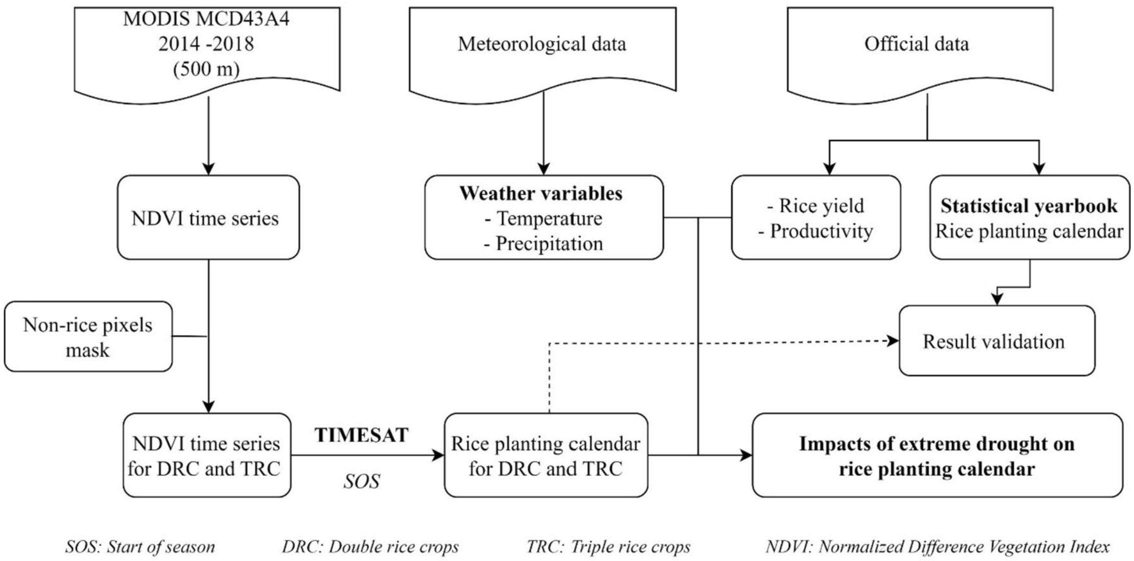

Fig. 3 General flowchart illustrates primary datasets and methodologies within the research to detect impacts of severe drought on SOS of rice cultivation using TIMESAT

SA. Generally, the sowing batches between subregions tend to be early in the upstream and central regions, irrigated by the Mekong River tributaries. Areas far from these primary water sources and close to the coast have a later starting time. These spatial patterns of cultivation time are identical to rice crops (Fig. 4).

The fourth sowing batch (15 December to early January for WS) is a major sowing period entire the delta, which accounts for 34.8% (2017) to 57.9% (2018) of the total planted area. For the SA crop, the main sowing period lasts from mid-April to early May, i.e., 44.9% (2014) to 57.1% (2017). Interestingly, rice cultivation is long traditional farming in Eastern culture, in which farmers use the lunar calendar closely related to tide and water resources. It should be noted that 2014 was a leap year, which affected the SOS of WS (2014–2015) and SA (2015) about 20 days earlier, according to Pham Van Du (2014). These anomalies were detected through 47.6% and 51.3% (2015) of planted areas earlier than in other years for WS and SA in the third batch, respectively (Table 1).

During the 2015/2016 drought, WS and SA experienced the late SOS for about 15 days when quite a few areas continued to sow after the main batch in mid-April. More explicitly, there was a large sowing area in the fifth batch in 2016, i.e., 24.9% (WS, 2016) vs. 2.5% (WS, 2014) and 35.5% (SA, 2016) vs. 10% (SA, 2015). It is deemed affected by the drought and saltwater intrusion during this period that caused a water shortage for soil preparation and sowing like in normal years. The impact of this late SOS has persisted into the following years. However, it has been gradually shortened to the normal state, e.g., the sowing area later than January was only 0.04% (WS, 2018) versus 36.1% (WS, 2017).

Triple rice crops (TRC)

The sowing dates of TRC are divided into five batches for WS (mid-November to early January) and SA (mid-March to early May). The third crop of AW is relatively more simultaneous than the other two crops, which lasts from mid-September to mid-October. In the VMD, WS is the main rice crop in the delta, bringing more income for rice farmers than the other two crops (Can and Xuan 2002; Linh et al. 2013). Therefore, most rice planting area is sown simultaneously, specifically, about 59.8% sowing during the second batch from mid-November to early December. The SOS in WS has no significant difference in spatial patterns over the delta. Yet, the remaining two crops have a distinct spatial division, especially for the AW crop. It is early in the center of the delta, whereas the surrounding regions have a later SOS. These regions are under the influence of two flooding regimes controlling the SOS. In particular, the upstream regions of Dong Thap Muoi and Long Xuyen Quadrangle have seasonally flooded areas of the Vietnam Mekong River delta. In contrast, the coastal regions are influenced by high tides.

The primary season of SA in the TRC frequently starts from mid-March to mid-April, with an accumulative sowing area of above 80%. With respect to the AW crop, the SOS varies from mid-September (center regions) to mid-October (flooded regions), with a total sowing area of approximately 90%, in which it is evenly divided into two subregions.

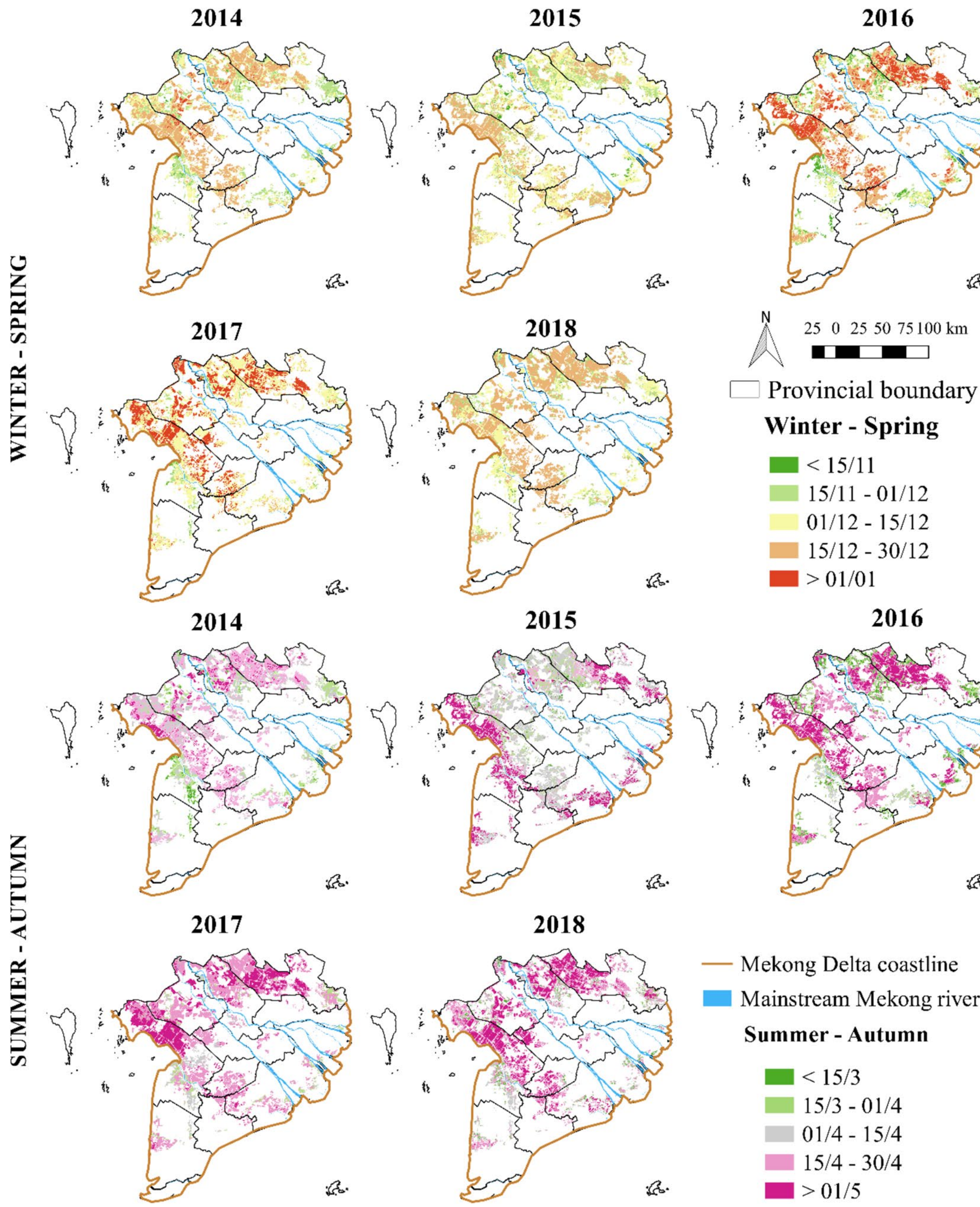

Fig. 4 Map of rice planting calendar for DRC in 2014–2018

Similar to the DRC, a shift of the SOS due to the leap year in 2014 was also observed throughout the three crops, which was earlier than usual.

The impact of the 2015/2016 drought was less significant than the DRC. However, it is challenging to recognize through spatial distribution and planted area for WS and AW crops. This is due to the natural conditions of the area cultivating TRC, which is facilitated by high accessibility to water for cultivation compared to double rice areas. Besides, the SA crop was the most affected season (Fig. 5), with approximately 30% of the rice cultivation area modified to be delayed, extending the SOS until early May (25.9% in 2016 vs. 5.1% in 2015). The affected areas include the eastern coastal regions (Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, and Tien Giang provinces) and An Giang province. Nevertheless, the favorable conditions and complete irrigation systems have assisted these affected areas in rapidly recovering to normal state faster than the DRC (Table 2).

Table 1 Timing of rice planting area of DRC over the years 2014–2018

Time	Season	Sowing area (Unit: 1,000 ha)					Sowing area (Unit: %)				
		2014	2015	2016	2017	2018	2014	2015	2016	2017	2018
<15/11	Winter-Spring	17.4	23.4	57.8	5.8	5.7	1.8	2.4	5.9	0.6	0.6
15/11-01/12		222.3	210.5	138.0	53.2	148.1	22.6	21.5	14.1	5.4	15.2
01/12-15/12		255.7	466.9	166.8	224.8	255.9	26.0	47.6	17.0	23.0	26.3
15/12-01/01		462.0	276.2	374.6	340.5	564.7	47.0	28.2	38.2	34.8	57.9
>01/01		24.8	3.9	244.2	352.9	0.4	2.5	0.4	24.9	36.1	0.04
<15/03	Summer-Autumn	23.3	20.2	113.7	0.1	33.1	2.4	2.1	11.8	0.0	3.4
15/03-01/04		136.8	92.3	97.9	68.1	46.8	13.9	9.4	10.2	6.9	4.8
01/04-15/04		283.2	503.3	81.6	78.4	189.7	28.8	51.3	8.5	7.9	19.3
15/04-01/05		441.9	153.2	327.0	563.9	477.2	44.9	15.6	34.0	57.1	48.7
>01/05		98.7	211.2	341.1	276.6	233.7	10.0	21.5	35.5	28.0	23.8

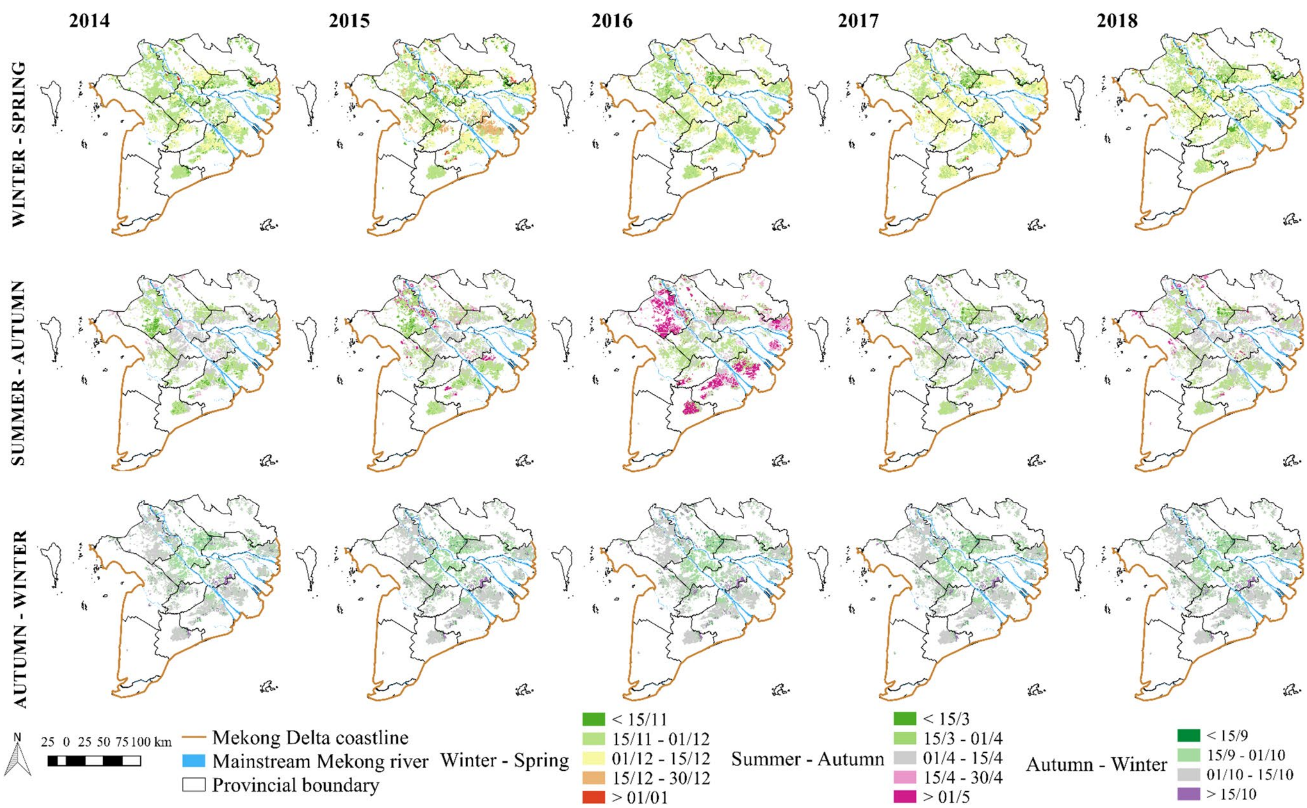

Fig. 5 Map of rice planting calendar for TRC in 2014–2018

Impacts of the extreme 2015/2016 drought on planting calendar

The impacts of the 2015/2016 drought on the rice planting calendar at provincial scale were assessed by comparing the SOS in the drought year against neutral years. The provincial figures are in line with the regional analysis that the SOS of both the WS and SA (DRC) shift from the fourth to the fifth sowing batches (WS) and slightly from the third to the fourth sowing batches (SA). The most affected provinces in the WS crop were Kien Giang (+ 8.29%), Long An (+ 6.23%), An Giang (+ 3.91%), and Soc Trang provinces (+ 3.14%), which experienced the higher planted area during the fifth batch compared to

Table 2 Timing of rice planting area of TRC over the years 2014–2018

Time	Season	Sowing area (Unit: 1,000 ha)					Sowing area (Unit: %)				
		2014	2015	2016	2017	2018	2014	2015	2016	2017	2018
<15/11	Winter-Spring	118.1	146.5	29.0	95.2	140.6	13.7	17.0	3.4	11.1	16.5
15/11-01/12		514.5	272.7	529.7	207.4	327.3	59.8	31.6	61.4	24.1	38.4
01/12-15/12		220.1	329.2	271.4	541.1	352.1	25.6	38.2	31.4	62.9	41.3
15/12-01/01		6.0	95.9	31.8	12.5	30.8	0.7	11.1	3.7	1.5	3.6
>01/01		1.4	18.4	1.2	4.4	1.1	0.2	2.1	0.1	0.5	0.13
<15/03	Summer-Autumn	41.9	27.6	21.6	72.8	11.0	4.9	3.2	2.5	8.5	1.3
15/03-01/04		403.4	453.1	276.8	372.4	360.0	46.7	52.3	32.5	43.2	41.9
01/04-15/04		379.1	300.3	188.3	374.0	414.1	43.9	34.7	22.1	43.4	48.2
15/04-01/05		38.6	41.0	144.0	41.2	53.9	4.5	4.7	16.9	4.8	6.3
>01/05		0.1	44.2	220.5	0.9	21.0	0.0	5.1	25.9	0.1	2.4
<15/09	Autumn-Winter	5.6	51.8	11.5	55.5	61.5	0.6	6.0	1.4	6.5	7.1
15/09-01/10		381.1	550.3	315.3	317.7	279.6	44.2	63.8	39.0	37.0	32.4
01/10-15/10		403.2	234.2	396.3	468.2	508.4	46.8	27.2	49.0	54.5	58.9
>15/10		72.0	25.9	86.3	17.1	13.5	8.4	3.0	10.7	2.0	1.6

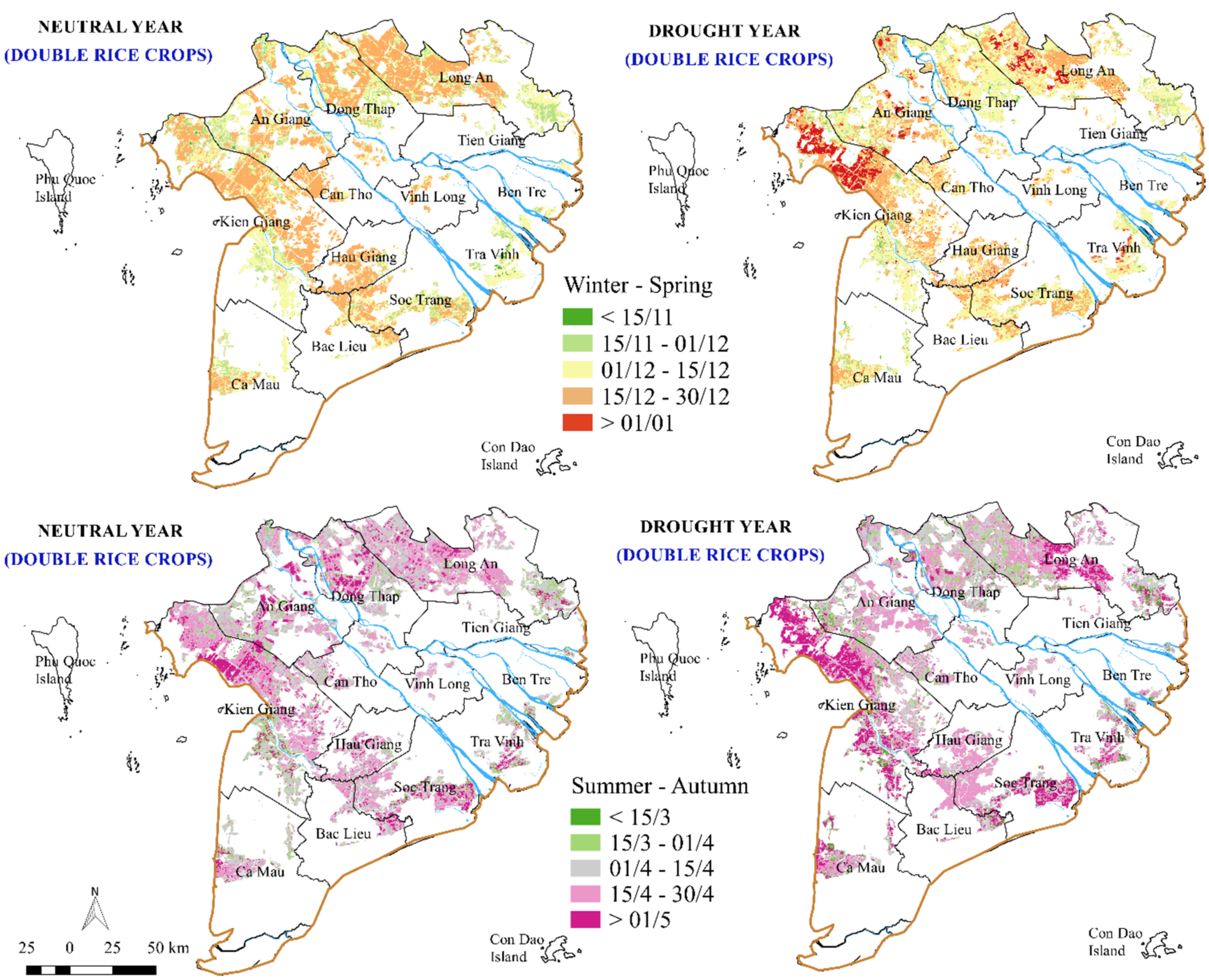

Fig. 6 Map of rice planting calendar in extreme drought and neutral year for DRC

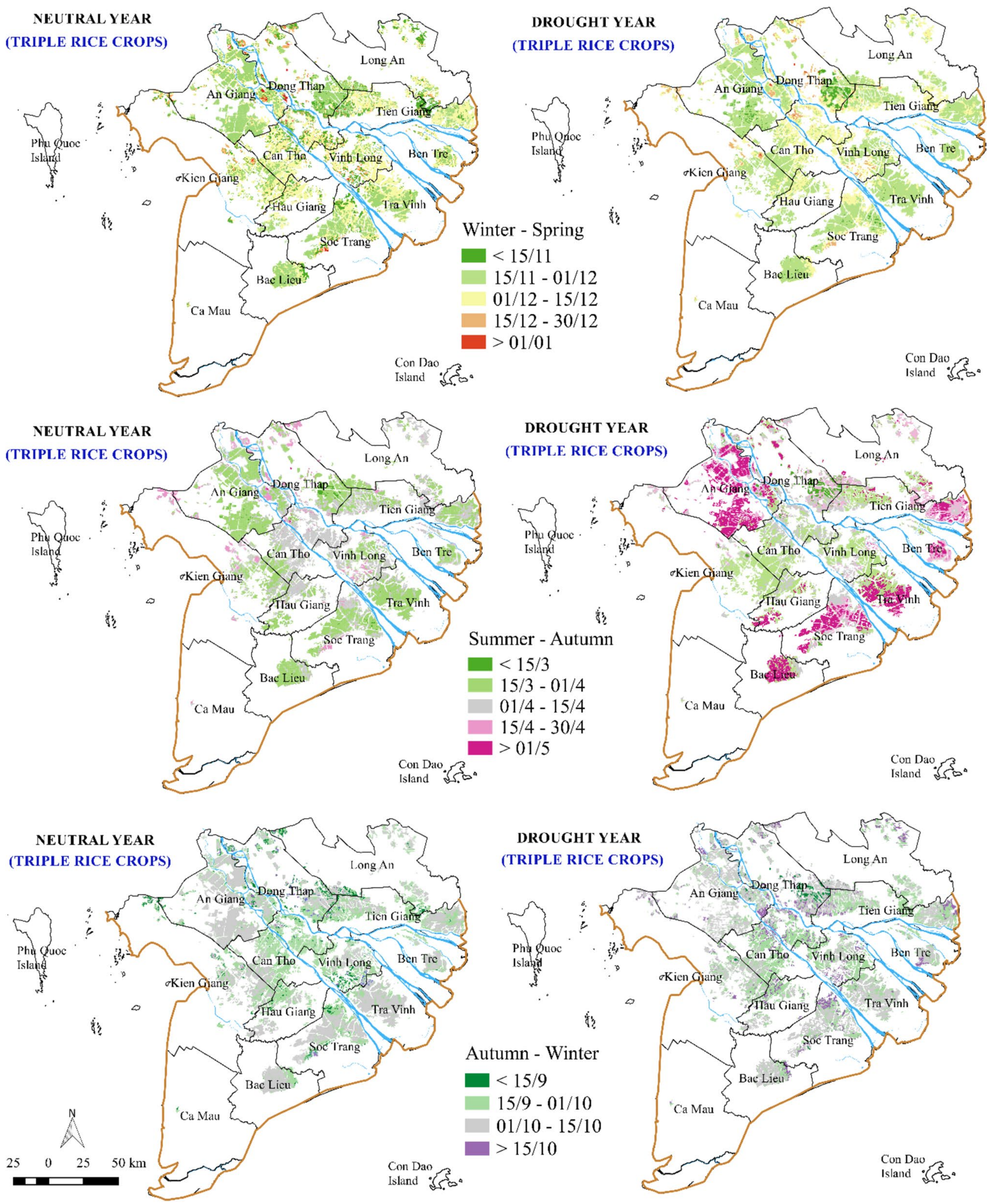

Fig. 7 Map of rice planting calendar in extreme drought and neutral years for TRC

the neutral years (Fig. 6). The provinces of Kien Giang (+ 5.33%), Long An (+ 1.54%), and Soc Trang (+ 1.03%) were still the most influenced provinces for SA crop. In contrast, the remaining provinces (e.g., An Giang, Tra Vinh, Dong Thap, Ca Mau, and Hau Giang) had more moderate impacts than the early provinces.

With respect to TRC, the WS in the drought year started earlier in almost every province, such as Tien Giang (+ 4.72%), Tra Vinh (+ 3.20%), Kien Giang (+ 3.06%), and Vinh Long (+ 3.03%), where the third sowing batch was uniformly concentrated in the second batch (mid-November to early December). During the third crop of AW, the changes in the SOS were relatively negligible compared to other crops. The later SOS was only prominent in Dong Thap, An Giang, and Soc Trang provinces. The most affected crop in the TRC was SA when we could simply observe a large area (pink and dark pink shades in Fig. 7) with a delay of the SOS compared to the neutral years. More explicitly, the provinces of Tien Giang (+ 3.42%), An Giang (+ 2.58%), and Long An (+ 1.74%) experienced a short delay in the SOS. In contrast, the majority of An Giang (+ 10.03%), Soc Trang (+ 4.33%), Tra Vinh (+ 4.03%), and Bac Lieu (+ 2.65%) encountered a more severe delay, which lasted until the fifth sowing batch in early May (see Table 3).

Discussions

Planting calendar based on remotely sensed data versus statistics

The regional planted area acquired from our analysis was compared to the official statistics from the bottom-up approach. Generally, the remotely sensed-based area is smaller than the statistics, approximately 7.0% to 11.4% on average (Fig. 8). It should be noted that the confusion is essentially less than 10%, which is applicable at the delta scale. The adopted MODIS product is at 500 m resolution, which is challenging to identify the isolated and small areas, especially in the coastal region. And, when their sowing times are not simultaneous. Moreover, we found the confusion increases during the SA and AW crops, when the daily optical data of MODIS is relatively influenced by weather conditions during the rainy season (Can et al. 2021; Kuenzer et al. 2013; Leinenkugel et al. 2013). Meanwhile, this research framework effectively captured the sowing dates regardless of planting seasons compared to local observation, which even recorded the impacts of extreme events on rice cultivation. It helps to track the rice crops more proactively and generally at the regional level instead of the traditional statistics that are often costly and labor-intensive.

SOS differences and Management implications

The meteorological observation for mean temperature (Ta) and precipitation entire the delta in the neutral years against the 2015/2016 drought year (Fig. 9) depicts the severity of the El-Niño event. It is characterized by considerably high Ta and low precipitation from October 2015 to May 2016. Specifically, no rain was observed over the delta from February to April 2016. Therefore, rice cultivation in the whole delta should have been affected. However, only a few provinces/subregions were significantly affected by others (Fig. 8). Hydrological and terrain characteristics of each subregion mainly control these differences. For example, within the DRC, WS is the most affected crop since the early dry season (November), while SA is the most affected crop in the TRC.

Table 3 Sowing area by province ratio in the TRC between drought year and neutral year in the VMD *Unit: (%)*

Unit: (%)

	Province	Triple rice crops														Double rice crops									
		Winter-Spring					Summer - Autumn					Autumn - Winter				Winter-Spring					Summer - Autumn				
		< 15/11	15/11 - 01/12	01-15/12	15 - 30/12	> 01/01	< 15/3	15/3 - 01/4	01-15/4	15-30/4	> 01/5	< 15/9	15/9 - 01/10	01-15/10	> 15/10	< 15/11	15/11 - 01/12	01-15/12	15-30/12	> 01/01	< 15/3	15/3 - 01/4	01 - 15/4	15-30/4	> 01/5
Neutral	An Giang	1.20	11.37	4.00	0.69	0.21	0.17	12.82	3.54	0.92	0.02	7.96	8.60	24.79	15.88	0.09	2.48	4.90	5.40	0.01	0.03	1.28	6.61	3.40	1.58
	Bac Lieu	0.35	2.93	1.02	0.01	0.00	0.02	3.44	0.83	0.02	0.00	0.65	2.17	6.24	0.00	0.01	0.14	1.07	1.45	0.00	0.00	0.09	1.24	0.91	0.44
	Ben Tre	0.23	0.93	1.49	0.13	0.00	0.00	1.55	1.16	0.06	0.00	0.39	2.73	3.07	0.00	0.00	0.16	0.57	0.02	0.00	0.00	0.21	0.45	0.04	0.05
	Ca Mau	0.03	0.00	0.02	0.02	0.00	0.00	0.00	0.04	0.02	0.00	0.39	0.12	0.01	0.00	0.02	0.96	2.10	1.20	0.00	0.00	0.58	2.22	1.02	0.46
	Can Tho	1.31	0.82	4.80	0.34	0.00	0.00	1.99	5.19	0.09	0.00	2.58	12.43	4.13	0.59	0.00	0.04	0.59	2.04	0.00	0.00	0.14	1.64	0.73	0.18
	Dong Thap	3.51	4.21	3.72	1.53	0.18	0.44	5.08	6.19	1.40	0.04	27.45	18.22	7.53	50.00	0.07	2.16	5.31	4.92	0.00	0.03	1.00	6.31	3.51	1.64
	Hau Giang	0.71	0.79	3.11	0.23	0.00	0.01	2.01	2.76	0.07	0.00	3.53	6.65	3.78	0.00	0.00	0.23	0.98	3.27	0.00	0.00	0.11	1.98	2.10	0.28
	Kien Giang	1.08	2.24	3.95	0.82	0.02	0.00	3.96	2.95	1.21	0.00	11.04	7.25	8.58	8.24	0.08	3.43	9.70	12.18	0.00	0.08	2.51	8.79	9.66	4.28
	Long An	1.94	1.46	1.92	0.56	0.02	0.10	2.38	2.98	0.55	0.00	16.36	6.18	4.85	6.47	0.02	3.20	6.30	11.55	0.00	0.01	1.37	9.41	8.49	1.81
	Soc Trang	1.52	4.19	3.45	0.42	0.05	0.00	6.03	3.07	0.43	0.00	9.15	7.77	11.01	10.59	0.02	1.43	3.62	3.24	0.00	0.03	0.59	3.49	2.83	1.38
	Tien Giang	2.06	2.29	6.49	0.37	0.03	0.00	5.13	5.88	0.23	0.00	6.41	14.24	9.65	4.71	0.00	0.27	0.50	0.12	0.00	0.00	0.13	0.55	0.16	0.05
	Tra Vinh	0.29	3.85	3.75	0.07	0.00	0.01	5.83	2.12	0.01	0.00	0.45	3.73	11.67	0.00	0.19	0.65	2.32	0.04	0.00	0.01	0.64	1.70	0.31	0.54
	Vinh Long	1.29	0.81	4.39	0.76	0.02	0.00	2.39	4.20	0.69	0.00	13.65	9.93	4.70	3.53	0.00	0.06	0.27	0.60	0.00	0.00	0.02	0.43	0.48	0.00
Drought	An Giang	0.87	13.60	2.48	0.45	0.02	0.14	1.29	1.87	3.50	10.05	0.14	8.34	20.99	12.49	0.20	0.93	6.83	0.87	3.91	0.52	1.10	4.92	5.83	0.52
	Bac Lieu	0.06	3.53	0.68	0.00	0.00	0.00	1.12	0.50	0.00	2.65	0.00	2.23	6.33	2.31	0.01	0.03	1.51	0.06	1.14	0.15	0.03	0.85	1.35	0.40
	Ben Tre	0.29	2.00	0.74	0.01	0.00	0.00	0.45	0.42	1.23	0.70	0.00	2.85	3.04	3.16	0.01	0.02	0.66	0.02	0.07	0.09	0.02	0.30	0.29	0.07
	Ca Mau	0.00	0.02	0.04	0.01	0.00	0.00	0.02	0.04	0.00	0.00	0.00	0.10	0.04	0.14	0.10	0.02	2.63	0.59	1.10	0.35	0.19	1.41	1.52	1.02
	Can Tho	0.00	3.66	3.65	0.05	0.00	0.00	4.91	2.28	0.04	0.09	0.00	13.14	3.48	8.30	0.00	0.04	1.58	0.04	1.05	0.02	0.22	1.27	1.10	0.12
	Dong Thap	1.87	3.37	6.35	1.43	0.09	1.92	2.66	5.35	2.57	0.70	1.92	11.28	12.37	19.87	0.15	0.09	9.50	0.98	1.87	0.58	1.11	6.35	4.14	0.57
	Hau Giang	0.02	2.83	1.93	0.02	0.00	0.00	2.56	1.40	0.02	0.86	0.00	6.86	3.46	5.93	0.01	0.12	2.06	0.02	2.30	0.01	0.10	1.54	2.59	0.32
	Kien Giang	0.01	5.30	2.14	0.68	0.02	0.13	5.74	1.64	0.54	0.18	0.13	8.57	9.05	6.56	0.24	4.41	9.91	1.87	8.29	0.68	1.59	6.08	5.92	9.61
	Long An	0.01	2.79	2.87	0.23	0.00	0.17	1.60	1.38	2.29	0.50	0.17	6.75	5.44	8.40	0.07	1.76	11.58	1.35	6.23	0.78	2.00	8.12	6.97	3.35
	Soc Trang	0.00	6.39	2.70	0.29	0.00	0.08	0.89	2.28	1.91	4.33	0.08	6.33	10.64	12.03	0.04	0.05	4.76	0.56	3.14	0.09	0.23	2.63	3.28	2.41
	Tien Giang	0.20	7.01	4.02	0.16	0.00	0.07	3.57	2.44	3.65	1.79	0.07	16.15	9.00	11.40	0.01	0.01	0.62	0.08	0.17	0.07	0.04	0.36	0.32	0.11
	Tra Vinh	0.04	7.04	0.81	0.00	0.00	0.00	3.00	0.48	0.61	4.03	0.00	6.03	11.17	1.33	0.05	0.23	2.41	0.27	0.45	0.32	0.18	1.36	0.97	0.61
	Vinh Long	0.00	3.84	3.03	0.37	0.00	0.03	4.71	2.03	0.55	0.02	0.03	11.38	4.98	8.09	0.09	2.48	4.90	5.40	0.01	0.03	1.28	6.61	3.40	1.58

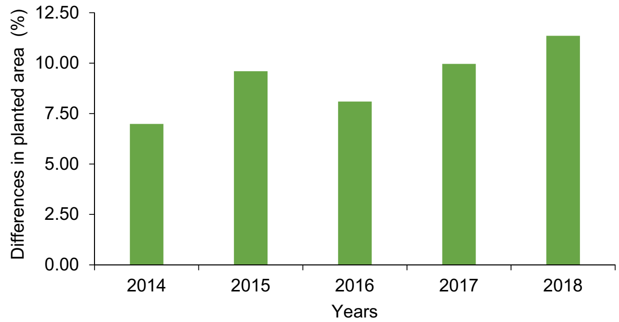

Fig. 8 Differences in the planted area between official statistics and interpreted by remotely sensed data

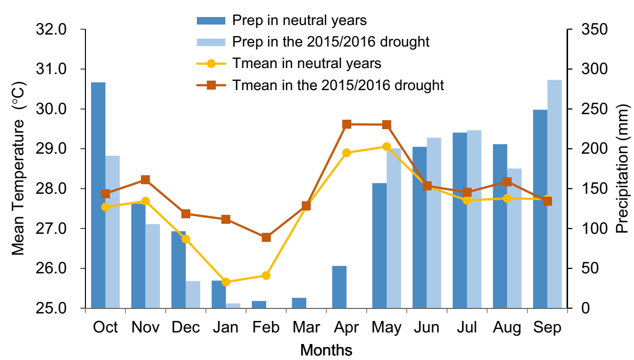

Fig. 9 Mean temperature (Tmean) and precipitation (Prep) in the VMD during the 2015/2016 drought versus neutral year average

In essence, the DRC areas embrace the TRC, which has many difficulties accessing freshwater for rice farms and is affected by the saline intrusion. Therefore, these regions confront the delay in SOS earlier than the TRC. The TRC adjacent to the DRC is the next region facing a delay in SOS due to water stress during the dry season when the drought amplifies water shortage in these regions. The affected regions include coastal and inland upstream areas in An Giang and Long An provinces, with relatively high terrain and far from the mainstream. It contributes to delineating the VMD into three ecoregions (Fig. 10) based on hydrological characteristics and drought vulnerability, including region I—brackish coastal region (Bac Lieu, Soc Trang, Tra Vinh, Kien Giang) with high exposure to drought and saline intrusion, region II—central freshwater region (Can Tho, Vinh Long, Hau Giang, Dong Thap) with low drought impact, and region III—the inland upstream region (An Giang, Dong Thap, and Long An) with potential drought impact.

It is necessary to have appropriate visions and strategies for each region, especially for the upstream and brackish areas. The critical issue is completing irrigation systems for the frequent drought areas in these two regions to ensure enough water for rice production. In coastal areas, the dyke systems need to be strengthened and improved to maintain the current freshwater areas for rice cultivation in the context of increasing saline intrusion due to climate change for the long-term goal of food security. Meanwhile, the immediate objective is to ensure the livelihood of rice farmers in these regions, where spontaneous agricultural restructuring is likely to happen. The reason is that rice cultivation profit is much lower than other brackish models. Therefore, the water conflict (brackish vs. freshwater) is relatively possible. For example, the conflict over water sources for shrimp and rice farmers on the west coast of VMD is a typical case. In the upstream areas where drought often occurs, integrated water management water-saving technology, such as alternate wetting and drying method (AWD), needs to be widely applied to use water resources rationally. This is an urgent issue for the delta because we are facing climate change and the transboundary water source problem for the Mekong River that affects the water resources downstream.

Conclusion

This research applied MODIS MCD43A4 product and TIMESAT tool to detect the SOS of rice cultivation in the VMD. The remotely sensed-based sowing batches and planted areas extracted from the SOS are appropriate to the sowing periods recorded by official statistics. Although the planted area from this study is smaller than the official data, about 7.0% to 11.4%, it is applicable at the regional level with coarse resolution data of MODIS. The DRC was supposed to be more affected during the WS crop versus the SA crop for the TRC. The distribution of the most affected areas depicts ecoregions entire the delta, facing different problems that need to be effectively solved to ensure the farmers' livelihood, primarily water management.

Although this study verified the applicability of MODIS data for monitoring rice production at the delta level, questions and research potentials were also raised. Firstly, the statistics showed that the corresponding yield in the drought year was significantly reduced compared to neutral years, and this effect persisted into the following year. However, this yield decline may be due to the combined impacts of drought and changes in sowing date, which changes the normal growing period of the crop compared to the normal years. Therefore, it is necessary to have further studies on their effects on rice yield. Socially, the DRC deems more affected and slowly recovered than the TRC. However, we do not have enough evidence to confirm in this study. In addition, the livelihoods of farmers

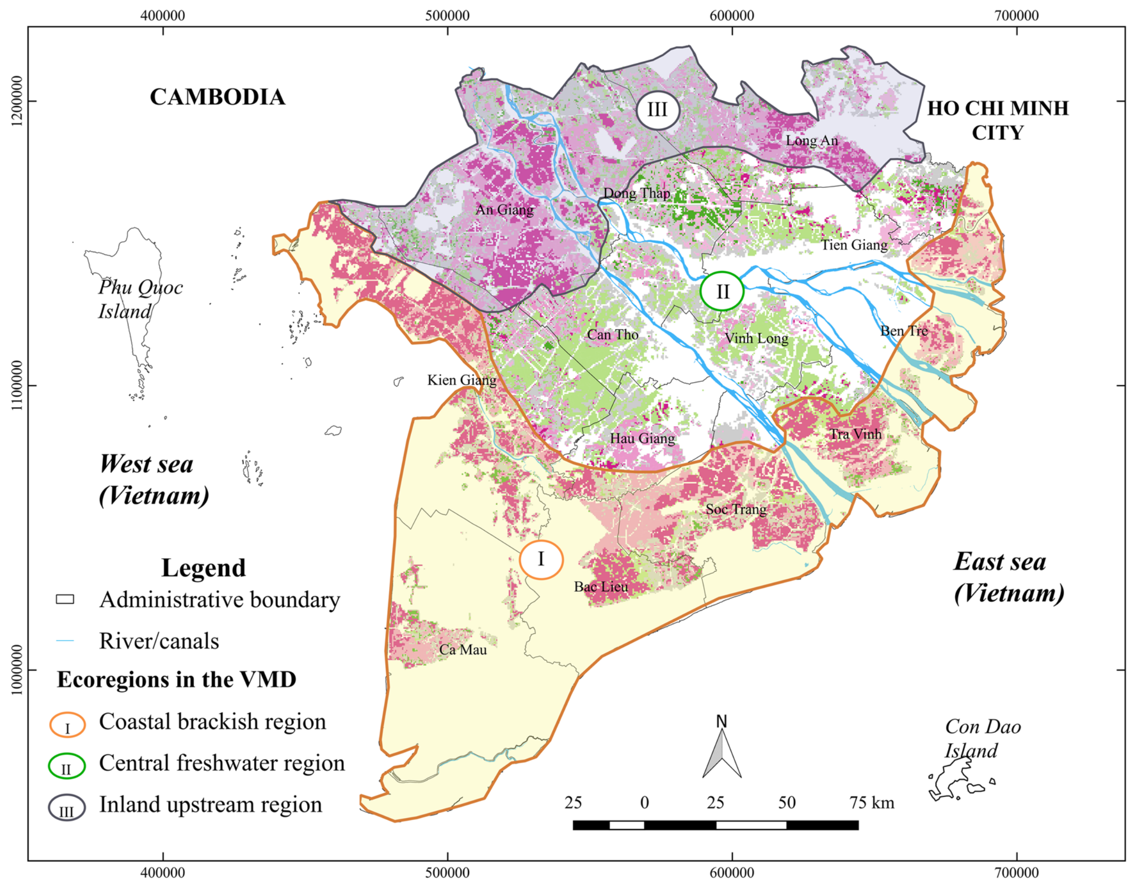

Fig. 10 Three ecoregions in VMD according to rice crops calendar analysis

corresponding to each model may also be significantly affected, so understanding the vulnerability of each model can also be studied. It together with technical solutions will contribute to the sustainable development of rice production in the VMD.

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