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Sentinel-1 SAR Time Series-Based Assessment of the Impact of Severe Salinity Intrusion Events on Spatiotemporal Changes in Distribution of Rice Planting Areas in Coastal Provinces of the Mekong Delta, Vietnam

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Abstract: Food security has become a key global issue due to rapid population growth, extensive conversion of arable lands, and declining overall productivity in some areas because of the effects of floods, water shortage, salinity intrusion, and plant diseases. In this study, we analyzed the relationship between the pattern of salinity intrusion and the spatiotemporal distribution of rice cultivation in the winter–spring crops of 2015, 2016, 2019 and 2020 in coastal provinces of the Vietnamese Mekong Delta. Sentinel-1 (S-1) data were used to extract the spatial distribution information of six rice growth stages based on a rice age algorithm. The classification accuracy of rice crop growth stages was found to have an overall accuracy of 85% and a Kappa coefficient of 0.80 (n = 373). For evaluating salinity intrusion effects, salinity isolines (4 g/L) were used to determine the percentage of rice areas affected. Results show that in the years observed to have severe salinity intrusion such as 2016 and 2020, a strong shift in planting calendar was identified to avoid salinity intrusion, with some areas being sown or transplanted 10–30 days earlier than normal planting. In addition, the lack of irrigation water and salinity intrusion limits rice cultivation in the dry season of coastal areas. Further analysis from the S-1 data confirms that the spatiotemporal distribution of rice cultivation is related to the change in government policy/recommendation affected by salinity intrusion. These findings demonstrate the potential and feasibility of using S-1 data to develop an operational rice crop adaptation framework on the delta scale.

Keywords: rice monitoring; mekong delta; spatiotemporal distribution; drought and salinity; synthetic aperture radar

1. Introduction

Rice production plays an important role in world food security, with rice serving as a staple food for more than half of the world's population [1]. Asia, the most populated continent in the world, produces 91% of world rice production and accounts for 70% of world rice exports, primarily from India, Thailand and Vietnam [2]. On the other hand, the Asia-Pacific region is the world's largest rice consumer, with 90% of rice produced in the world [3].

In Vietnam, rice is the most fundamental staple food for most of the 96 million people [4], where rice production holds a crucial role in national food security and rural economy. Rice is a major source of agricultural exportation of Vietnam [4], and is produced mainly at the country's two deltas, i.e., the Mekong Delta (MD) and the Red River Delta (RRD). These two deltas span approximately 4000 and 1000 thousand ha, or 54.2% and 14.4%, respectively, of the total paddy planted area of the whole country [4]. Both MD and RRD are the main agricultural production regions of Vietnam which support large diversity of agricultural systems that endow 70.0% of the rice, 86.3% of the farmed aquaculture, and 64.7% of the fruit production of the country [4].

The climate, hydrology and soil conditions allow farmers in the MD to cultivate two to three crops per year, namely winter–spring (WS), summer–autumn (SA) and autumn–winter (AW), or Dong Xuan, He Thu, and Thu Dong in Vietnamese language, respectively. Among the three seasons, WS contributes the highest rice production in both the deltas. In some areas, during the Mua season, in which traditional rice varieties with a longer maturity period are grown, rice yields are generally low but of high quality. Despite encompassing only 12.3% of the total area of Vietnam, the MD produces 56% of total rice production (compared to 14% from the RRD), and accounts for 90% of the total volume of rice exportation and supports the livelihoods of 80% of the MD population [4]. The major rice cropping systems are single-rice crop, double-rice crop and triple-rice crop (Table 1).

Table 1. The major rice cropping systems of the Mekong Delta (MD).

Cropping System	Seasons	Planting	Area (Units: 1000 ha)
Single-rice crop	Mua (Traditional rice)	Mua: Jul/Aug	Mua 2018: 197.2 [4]
Double-rice crop	Dong Xuan: Winter–Spring; He Thu: Summer–Autumn	Dong Xuan: Nov–Jan; He Thu: May/Jun	Dong Xuan 2019: 1601.5 [4] He Thu 2019: 1565.7 [4] Thu Dong 2019: 724.2 [4]
Triple-rice crop	Dong Xuan: Winter–Spring; He Thu: Summer–Autumn; Thu Dong: Autumn–Winter	Dong Xuan: Nov–Jan; He Thu: May/Jun; Thu Dong: Jul/Aug	

However, the MD of Vietnam is vulnerable to salinity intrusion, exacerbated by drought conditions during the dry season (from November to April) [5,6]. Salinity intrusion in the MD takes place from January to May [6–8], and this period entirely coincides with the WS paddy crop. Other studies argue that climate change-induced sea level rise is among the causes of salinity intrusion by which coastal deltas are the most affected [9–11]. Salinity intrusion may cause abiotic stress on rice and inflicts variable stresses on different growth and development stages of rice to reduce rice yield [12,13].

Under these circumstances, the Ministry of Agriculture and Rural Development (MARD) of Vietnam has ratified a project on the development of rice production in the MD up to 2025, together with the vision for 2030 under climate change adaptation plans [14]. This project aims to decrease the overall paddy planted area in the MD from 4 million ha in 2025 (with a production of 23–24 million tons) to 3.8 million ha in 2030 (with 22–23 million tons). To reduce and adapt to salinity intrusion, the project divides the arable land affected by salinity into two categories: (a) less than 4 g/L and (b) higher than 4 g/L, for which different land use planning will be applied and rice crops will be restructured in different provinces. In areas where salinity is higher than 4 g/L, it is planned to have one paddy crop with brackish water shrimp farms [14]. This ambitious project requires detailed information and sound scientific basis to determine how salinity intrusion affects the spatial pattern and the temporal evolution of rice crops in the MD. In this regard, an indispensable piece of information is the spatiotemporal distribution of the paddy land.

Optical multi-spectral data such as MODIS and SPOT VGT have been used extensively for mapping the spatiotemporal distribution of rice cropping system [15–17], date of planting [18], and monitoring phenological stages of rice during crop season, despite insufficient spatial resolution (i.e., 250 m or more) to observe plant growing processes at the local field scale. Alex et al. [19] and Nguyen-Thanh et al. [20] downscaled MODIS time series imagery based on Landsat data at 30 m resolution in order to map rice crop phenology at high spatial and temporal resolutions. However, optical images are frequently affected by cloud cover. Despite the various techniques [21–23] to reduce cloud effects, the persistent and pervasive cloud cover in tropical monsoon regions like in Vietnam limits the use of optical data, especially during the rainy season. In contrast, microwaves are mostly transparent to atmospheric conditions including haze, rain, snow, clouds, and smoke depending on wavelengths. Radar remote sensing satellites, such as Sentinel-1 and COSMO-SkyMed, acquire imaging data with high spatial and temporal resolutions appropriate for mapping rice cultivated areas [24,25], sowing date [26], and monitoring the number of days after planting [27].

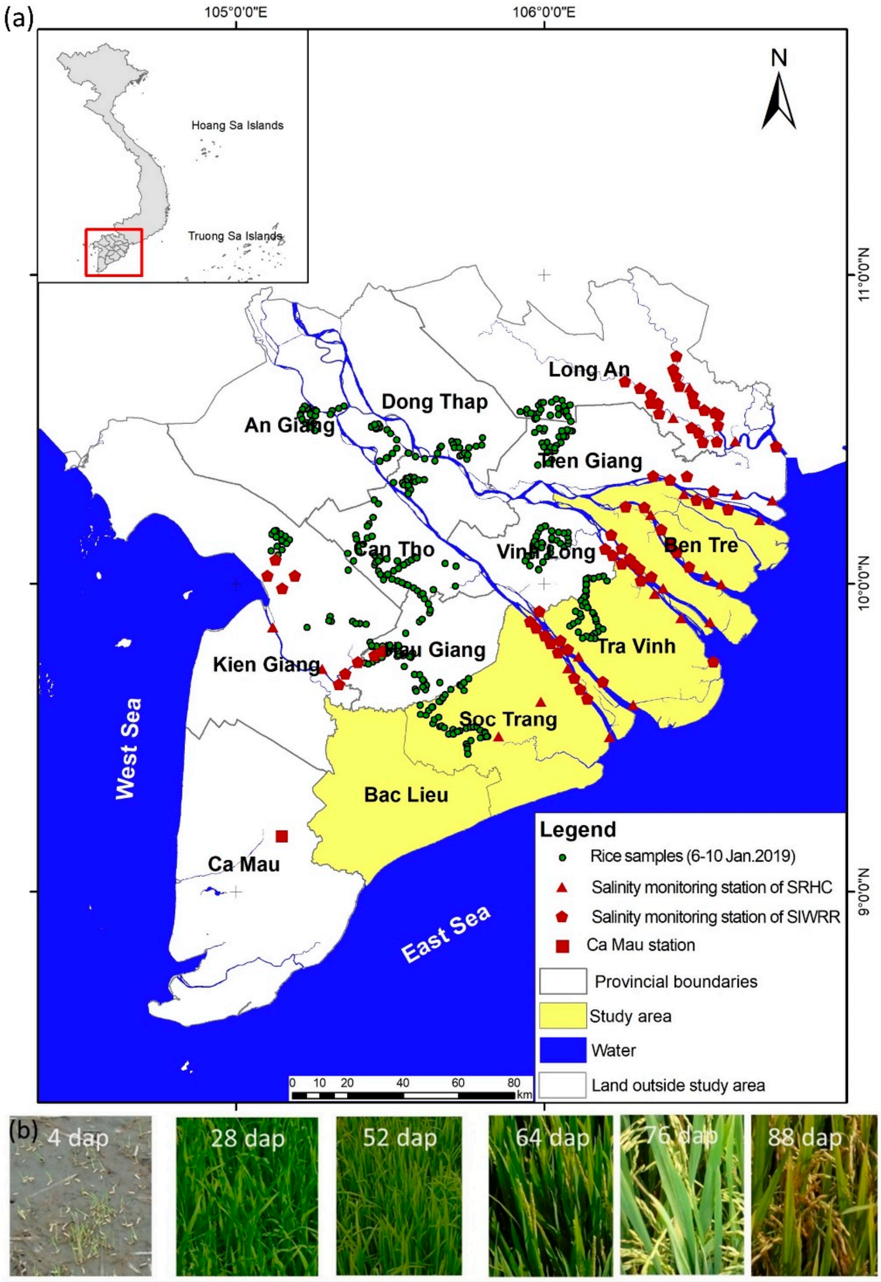
To detect rice pixels and track their phenological status, temporal radar backscatter behavior of the seasonal rice evolution needs to be captured. For this purpose, the wide swath mode of Sentinel-1 data with a high temporal resolution from 12 to 6 days is suitable. Moreover, time–space S-1 synthetic aperture radar (SAR) data have been used to assess the impacts of salinity intrusion on rice cultivation in coastal provinces in recent years. Specifically, we want to test the hypothesis of whether the rice production patterns in the coastal provinces of the MD is closely related to the annual level of salinity intrusion.

The broad aim of the study was to identify the status of rice growth and distribution in the Mekong Delta on a large scale. The specific objectives were the following: (i) to use S-1 multi-temporal data series in extracting distribution information on rice growth stages and using field data to assess the resultant accuracy; (ii) to determine the spatial distribution of the rice-planted area during the WS season under salinity intrusion (2015, 2016, 2019, and 2020) in coastal provinces; and (iii) to determine changes in rice crop calendar and rice cultivation patterns affected by severe salinity intrusion of drought events in 2016 and 2020.

2. Materials and Methods

2.1. Study Area

The Mekong Delta is the delta with the largest area in Vietnam (40,816.4 km^2) [4] and is considered the rice granary of the country. Rice agriculture in the region is facing challenges with the effects of drought and flood [28,29]. Salinity and drought conditions caused limitations and uncertainty about the economic, social, and limited agricultural production of rice in coastal provinces [28,30,31]. Thus, the study area was selected to examine the relationship between salinity drought and rice cultivation in four coastal provinces of Bến Tre, Trà Vinh, Sóc Trăng and Bạc Liêu (Figure 1).



Seeding - transplanting	Tillering	Rebooting Panicle initiation	Booting - Heading	Grain filling	Maturation
Vegetative		Reproductive		Ripening	
0 – 20	20 - 40	40 – 55	55 – 70	70 – 85	85 - 100

Figure 1. Spatial distribution of rice samples in the MD surveyed from 6 to 10 January 2019 (**a**), and six growth stages of the IR50404 rice variety with 95–100 days cycle; (**b**) “dap” is days after planting.

The MD coastal provinces are vulnerable to the effects of salinity intrusion, which is especially severe during the dry season from March to April [7,8]. During the dry season, there is often a high air temperature and low rainfall (Figure 2), and a decrease in the river discharge (Figure 3a), which reduces the ability to repel saltwater from entering the mainland. In particular, some years have serious salinity and drought events that coincide with the annual WS crop (Figure 3b), such as in 2016 due to the effect of El Nino 2015–2016 and the dry season of year 2020 that recorded a decrease from 25 to 60% compared to the monthly mean of discharge in the Mekong River (Figure 3c). Dams upstream of the Mekong affect the water discharge [32], which was clearly lower during the dry season during the post-dam period (1992–2010) compared with the conditions before the dam (1960–1991) [33]. Figure 3b,c also show years with severe drought events such as 2015–2016 and 2020, recording a decrease in the flow of the Mekong river system from the dry season compared to the monthly average. Therefore, this study focuses on how rice cultivation patterns change for 2015, 2016, 2019, and 2020 under the influence of salinity intrusion in coastal provinces.

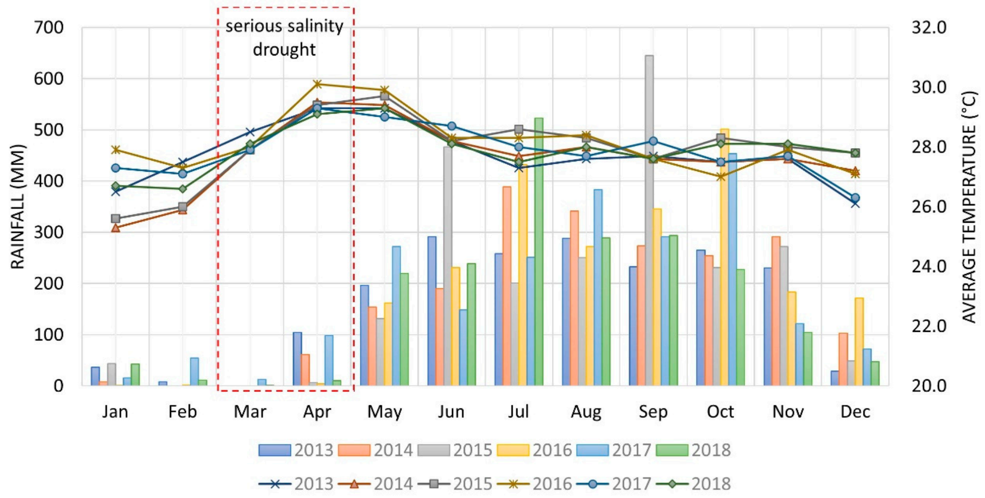


Figure 2. Monthly rainfall (bar chart) and average temperature (line graph) from 2013 to 2018 in Ca Mau hydro-meteorological station (9.18°N, 105.15°E), in the MD. Data source: General Statistics Office [4].

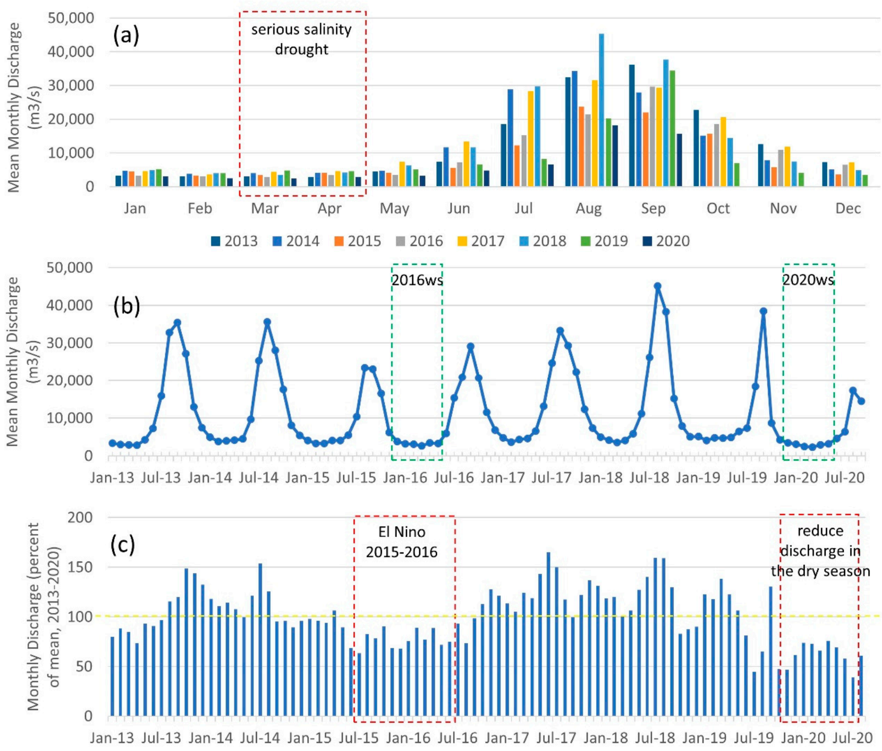


Figure 3. Mean monthly discharge from 2013 to 2020 at Kratie station (12.483°N, 106.016°E) on the Mekong River in Cambodia. In which: (**a**) Mean monthly discharge; (**b**) Series data of mean monthly discharge; (**c**) Monthly discharge (percent of mean). Data source: Mekong River Commission [34].

2.2. Data Used

2.2.1. Image Data

Sentinel-1 time series data were used in this study, and they consists of 282 Sentinel-1A and -1B C-band images with ground range detected (GRD) level 1, interferometry wide swath mode (IW), and VH (vertical transmit and horizontal receive) backscatter across a swath width of about 250 km. The images were collected for different years: 1 September 2014–30 April 2015 (33 scenes), 1 September 2015–30 April 2016 (41 scenes) and 1 August 2018–30 April 2020 (208 scenes). Starting from 25 April 2016, we have one image every 6 days instead of 12 days in the earlier time. These images have been processed for the period from 2015–2020 to generate maps of phenological stages and rice-planted areas for the whole MD covering the four coastal provinces of Bến Tre, Trà Vinh, Sóc Trăng and Bạc Liêu selected for this study.

2.2.2. Field Data

Extensive ground truthing was conducted from 6 to 10 January 2019 to validate the spatial distribution of growth stages of the WS rice crop in the same year. Specifically, 238 sample points of rice fields were collected, with information about growth stage, rice variety, sowing/transplanting date and photos, as well as 135 samples over non-rice areas (Figure 1). Random samples across the MD were taken to avoid sampling bias, and farmer interviews were conducted to obtain information on rice varieties. Such information is important to determine rice growth and development stages, since each rice variety has its own growth cycle duration, as listed in Table 2, and a different number of days after planting to reach various growth phases (Figure 4).

Table 2. List of rice varieties recorded in ground truthing mission in the MD from 6 to 10 January 2019.

Rice Variety	Sample Number	Growth Cycle (Day)
IR50404	75	95–100
ML202	50	90–100
Đài Thơm 8	28	90–95
RVT	28	100–105
JASMINE 85	14	100–105
OM5451	11	90–95
ST24	9	103–105
Nếp	6	95–100
Nàng hoa 9	5	95–102
OM4900	3	95–100
Other	9	90–105
Total	238	

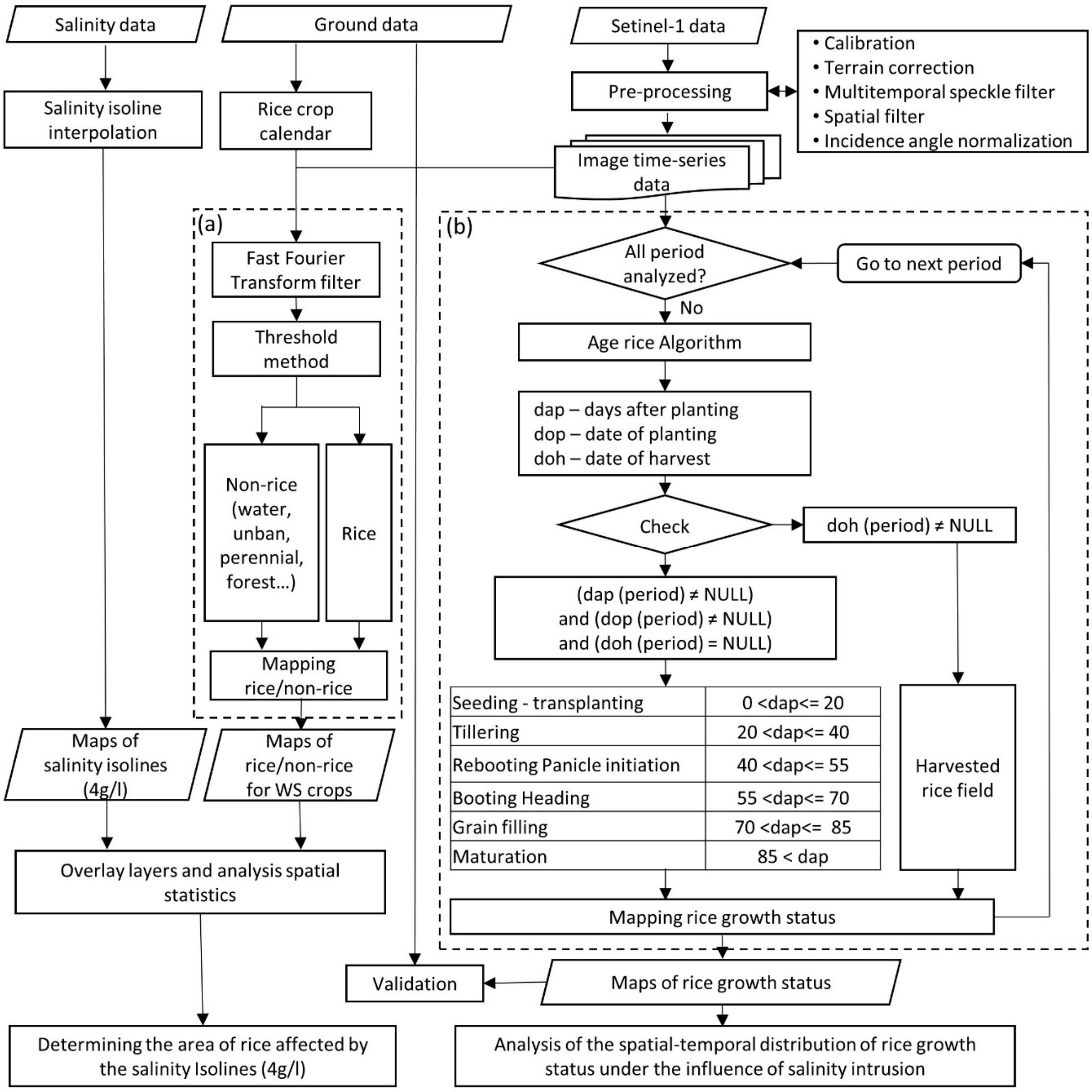


Figure 4. Processing flowchart to evaluate the spatiotemporal distribution patterns of growth stages and rice-planted areas, indicating the mapping algorithm for rice/non-rice (**a**) and rice growth status (**b**).

2.3. Methods

In this study, Sentinel-1 time series data were used to extract information on growth stage distribution and rice-planted areas. The SAR image data were pre-processed before being used for classification. The overall steps performed for better understanding of the behaviors of crop phenology based on the radar backscattering of S-1 data are presented in Figure 4. The rice-growing regions were extracted by the threshold classification method [25,35] (Figure 4a). In addition, this study also established the salinity isolines (4 g/L) using the observed dataset to assess the effect of salinity intrusion on rice-planted areas using GIS analysis tools on QGIS software. The approach is to examine the relationship between salinity-affected rice areas greater than 4 g/L for each province, especially for years affected by severe salinity intrusion such as 2016 and 2020, compared to other years. Moreover, information about the changes on the spatial distribution of rice-growing areas in different years helps evaluate the severity of salinity intrusion impacts.

2.3.1. Sentinel-1 Data Pre-Processing

The data pre-processing used in this study has followed several steps: calibration, terrain correction [36] with 30 m Shuttle Radar Topography Mission digital elevation model (SRTM DEM) (United States Geological Survey Earth Explorer, available online: http://earthexplorer.usgs.gov/), a multitemporal speckle filter [37,38], noise filtering (Gamma filtering, fast Fourier transform and smoothing filter Savitsky–Golay), incidence angle normalization, and finally normalization of backscatter behavior of S-1 IW images using regression analysis [27]. Most of the pre-processing steps were performed using SNAP (Sentinel Application Platform) software, while the noise filtering and the incident angle normalization steps were processed using Python program language.

2.3.2. Growth Stage Information Extraction

This study used the rice age algorithm from S-1 image data proposed by Phung et al. [27] to extract the phenological parameters including the number of days after planting (dap), date of planting (dop), and date of harvest (doh). Biological growth data were extracted for each growing season based on a time series data that are interpolated and smoothed. Although the use of pre-processed data effectively reduces speckle noise, the multi-temporal data of backscatter values still shows significant differences related to morphology or changes in land surface cover. Reducing temporal noise and interpolating data gaps and smoothing out the spatial noise are usually necessary when processing time series data [27].

The maps were established based on the parameters of crop growth and development phases, such as rice age, dop, and doh for each pixel. The study investigated the backscattering pattern of different rice cultivars and growth cycles. Based from the field survey in the Mekong Delta from 6 to 10 January 2019, rice field samples were collected for different rice cultivars such as: IR50404, ML202, Dai Thom 8, RVT, Jasmine 85, OM5451, ST24, etc., whose growth cycles are mainly from 90 to 105 days (Table 2). Therefore, this study used the growth stage model of a 100-day rice cycle to classify rice growth stages. Six growth stages were classified [39,40] with a 100-day cycle for the major rice cultivars grown in the MD: seeding–transplanting (early stages), tillering, rebooting–panicle initiation, booting–heading, grain filling, and maturation with the rice age thresholds, as shown in Figure 4b.

2.3.3. Validation

To evaluate the classified result of growth stages, the study used field survey data throughout the MD. The accuracy of the classification results was validated with field data which were collected at the same time when the growth stage map was estimated. The effectiveness of the classification method was assessed by confusion matrix [41], overall accuracy and Kappa coefficient [42].

2.3.4. Salinity Isolines

The salinity isolines (4 g/L) were created by using the measured salinity data collected from 88 stations in the MD, including 22 stations from the Southern Regional Hydrometeorological Center (SRHC) and 66 stations from the Southern Institute for Water Resources Research (SIWRR). The locations of 88 salinity monitoring stations are shown in Figure 1a. The sites with salinity concentration of 4 g/L were linearly interpolated from the maximum annual salinity concentration at the nearby monitoring stations. The salinity isoline maps (4 g/L) of 2015, 2016, 2019, 2020 were plotted by connecting the sites of 4 g/L.

2.3.5. Analysis of Spatial Distribution of Rice Growth Status

In this step, the salinity isolines were overlaid on the growth stage and rice-planted area maps for 2015, 2016, 2019, and 2020 of the four coastal provinces, namely, Bến Tre, Trà Vinh, Sóc Trăng and Bạc Liêu. These results were used to obtain the information on spatial distribution changes of growth status and the rice areas of WS crop from 2015 through 2019–2020. The GIS tools used to analyze the spatial distribution of the growth stages during the study period consists of (a) Extract: this tool was used to select features and attributes in a feature class (area, growth status class, crop, year, etc.) based on a query Structured Query Language (SQL) expression or spatial and attribute extraction;

(b) Overlay: this contains tools to overlay multiple feature classes to intersect, erase, union, modify, or update spatial features, resulting in a new feature class (contains attribute information about the area, stage of growth and the area affected by salinity intrusion); and (c) Statistics: this contains tools that perform standard spatial statistical analysis (such as mean, sum, etc.) on attribute data, as well as tools that calculate count and area statistics for overlapping features.

3. Results

3.1. Spatial Distribution of Rice Growth Status

The processing of imagery enabled the classification of the area into different rice growth stages, such as the stages in the MD on 13 January 2019, as shown in Figure 5. The overall accuracy and Kappa coefficient of the classified result of growth stages were 85% and 0.80, respectively (Table 3). To assess the ability to classify the growth stages, Table 3 shows the differences between field data and classified results from satellite image data through the confusion matrix. The results demonstrate that the S-1 multi temporal data have the potential for monitoring rice growth stages in near real time. However, in the early stages of crop growth such as seeding–transplanting (about 0–20 days after planting), the classified results had a large uncertainty, with a user accuracy of 52%. This is because the backscattering of the paddy field at this stage is not significantly changed when the biomass of the rice plant is low.

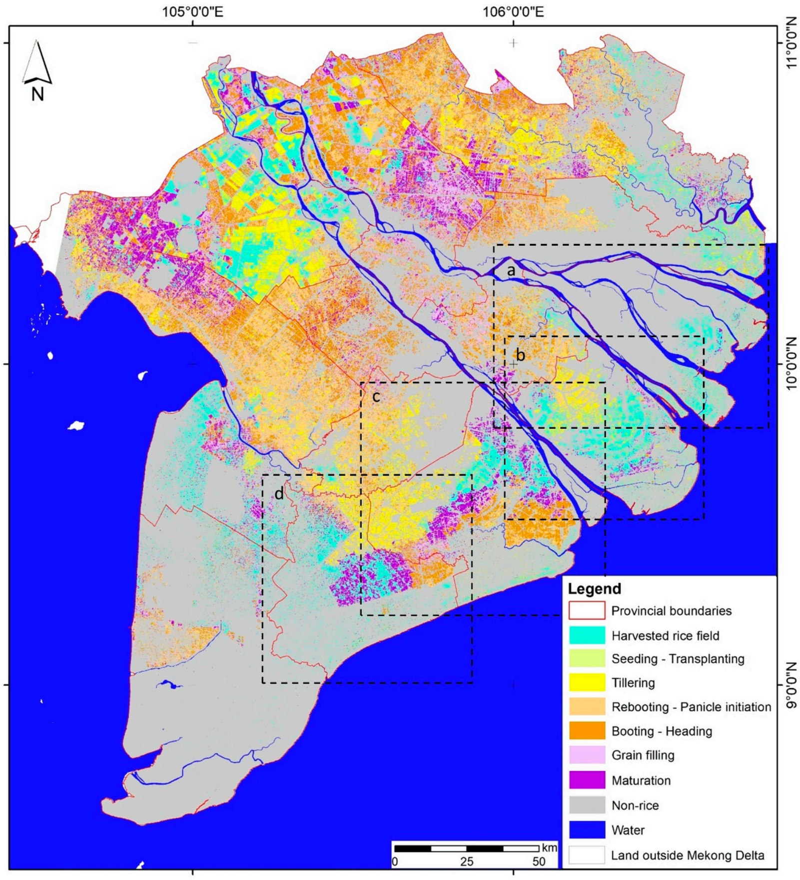


Figure 5. Spatial distribution of rice growth stages in the MD on 13 January 2019. Box a: Bến Tre, b: Trà Vinh, c: Sóc Trăng, and d: Bạc Liêu.

Table 3. Confusion matrix of the classified result of rice growth stages in the MD on 13 January 2019 compared to the field data from 6 to 10 January 2019.

		Truth Data								
		(0)	(1)	(2)	(3)	(4)	(5)	(6)	Total	Producer Accuracy
Classified results	Non-rice (0)	134	9	0	0	0	0	0	143	94
	Seeding–transplanting (1)	1	11	2	0	0	0	0	14	79
	Tillering (2)	0	1	15	5	0	0	0	21	71
	Rebooting Panicle initiation (3)	0	0	3	104	6	0	0	113	92
	Booting–heading (4)	0	0	0	17	32	3	0	52	62
	Grain filling (5)	0	0	0	0	3	12	4	19	63
	Maturation (6)	0	0	0	0	0	2	9	11	82
	Total	135	21	20	126	41	17	13	373	
	User Accuracy	99	52	75	83	78	71	69		

The rice-growing areas in the MD are mostly double- or triple-crop rice. Among the three rice-growing seasons, WS season has the largest rice area when compared to other two rice-growing seasons. The sowing/transplanting dates of the WS season were from mid-November 2018, and the middle of the season was in January 2019. Thus, most of the rice-growing areas had growth stages at tillering and rebooting–panicle initiation. There were also some areas in the coastal provinces that had entered maturation, such as in Sóc Trăng and Bạc Liêu, while Bến Tre and Trà Vinh provinces had just seeded or in the first two stages.

3.2. Change in the Spatiotemporal Distribution of Rice Growth Status

The spatial distribution of growth stages in 2019 for the four coastal provinces is presented in Figure 6. Monthly rice growth status maps were created using the S-1 data series from 1 August 2018 to 30 December 2019. Across the study area, the spatial distribution of growth stages differs between provinces and within each province. The four coastal provinces in the study area adopted either a double- or triple-rice cropping system (Figure 6).

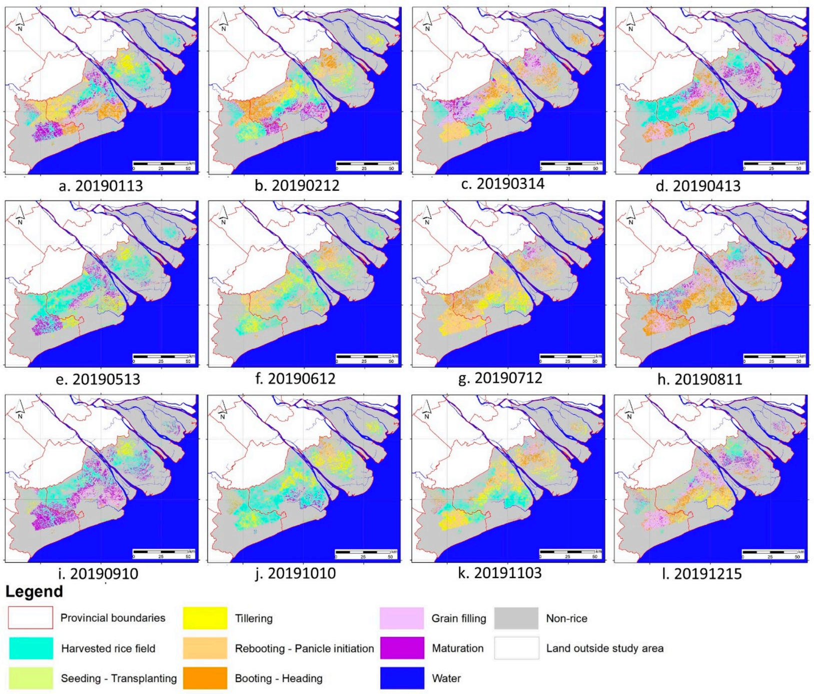


Figure 6. Spatial distribution of the monthly rice growth patterns of 2019 in the study area.

In order to assess the change in the growth stage patterns of each province between 2015–2016 and 2019–2020, spatial distribution maps of growth stages were established for four WS seasons on 3 February 2015 and 10 February 2016 (Figure 7), and 12 February 2019 and 13 February 2020 (Figure 8). Consequently, the WS 2016 and 2020 crops were under unfavorable conditions compared to other years.

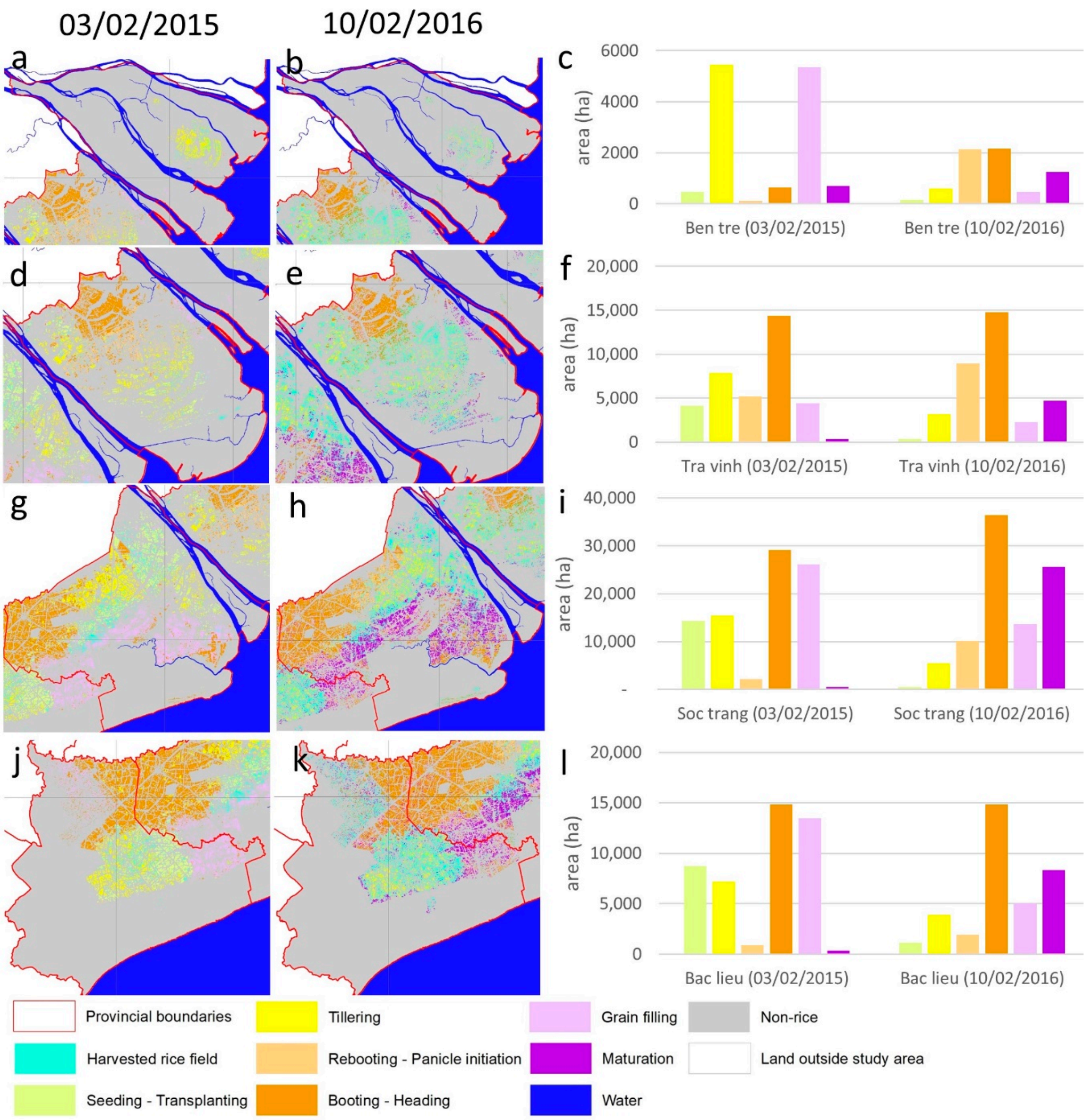


Figure 7. Spatial distribution of growth status patterns of winter–spring (WS) rice in 3 February 2015 and 10 February 2016, and the rice area corresponds to the growth stages in four provinces: Bến Tre (**a**–**c**), Trà Vinh (**d**–**f**), Sóc Trăng (**g**–**i**), and Bạc Liêu (**j**–**l**).

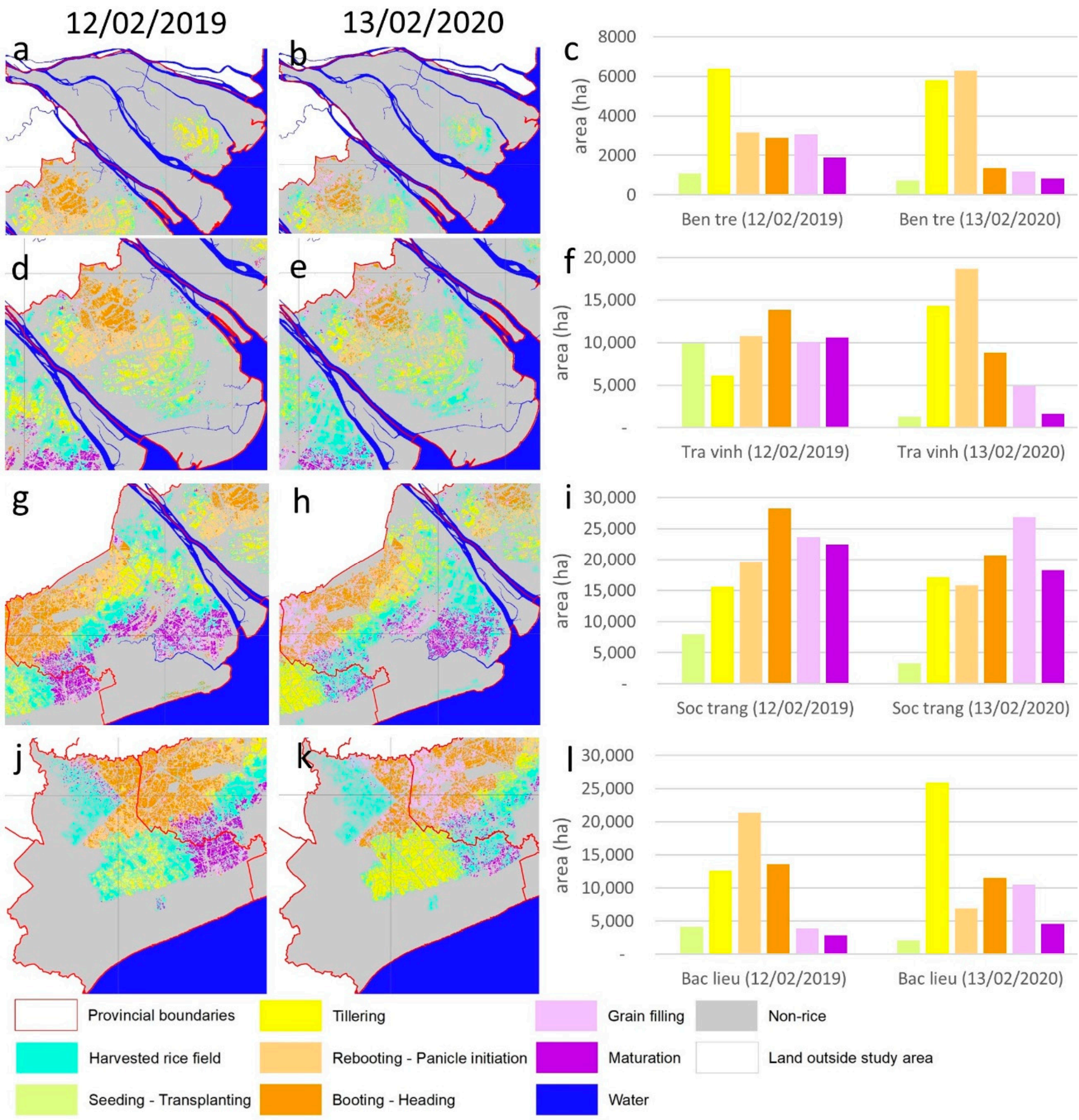


Figure 8. Spatial distribution of rice growth status patterns in 12 February 2019 and 13 February 2020, and the rice area corresponds to the growth stages in the four provinces: Bến Tre (**a**–**c**), Trà Vinh (**d**–**f**), Sóc Trăng (**g**–**i**), and Bạc Liêu (**j**–**l**).

A comparison between the spatial distribution of rice growth stages in the study area on 3 February 2015 and 10 February 2016 is depicted in Figure 7. Bến Tre province was the most affected area by drought and salinity in 2016. During the WS season in 2015, the rice-growing area of more than 5000 hectares was at the tillering stage, while in 2016, most of the farmers in the region adopted earlier sown/transplanted rice following the agro-advisory from the Department of Crop Production (DCP)—MARD. Rice crop during the WS season in 2016 was in rebooting–panicle initiation and booting–heading stages (Figure 7a–c). Similar trends were also noticed in Trà Vinh province, where in the 2015 WS season, around 4000 ha was at the seeding–transplanting stage and 7000 ha at the tillering stage. In contrast, in 2016, WS season, most of the areas in the region were sown/transplanted earlier, so rice crops were in tillering and rebooting–panicle initiation stages (Figure 7d–f). For Sóc Trăng province, a similar phenomenon was also observed in some areas where rice was planted earlier in the 2016 El Niño year (Figure 7g–i), hence, most of the rice-growing areas reached the maturity stage. However, in 2015, around 26,000 ha were at the gain-filling phase. In Bạc Liêu province, around 7000 ha were at the gain-filling stage in 2015, whereas in 2016, rice crop was at the maturity stage

(Figure 7j–l). However, some areas were sown/transplanted later than that in 2015. About 7000 ha were in the seeding–transplanting stage in 2015, while in 2016, they were not planted. Thus, this shows that in 2016, most of the rice-growing areas in the coastal provinces experienced sowing/transplanting about 10–30 days earlier than that in 2015, although some areas did not follow this trend.

The spatial distributions of growth stages on 12 February 2019 and 13 February 2020 in the coastal provinces are displayed in Figure 8. Bến Tre province was highly affected by the salinity and drought of 2020. The area without rice cultivation (about 5000 ha) in 2020 appeared to be much higher than in 2019 (Figure 8a–c), and early sowing/transplanting was also found. Some rice-growing areas were at the tillering stage in 2019, whereas in 2020 rice crop were at the rebooting–panicle initiation stage. For Trà Vinh province, a more uniform planting were observed in 2020, with 70% (more than 33,000 ha) of rice in the tillering and rebooting–panicle initiation stages compared to the previous year (Figure 8d–f). Figure 8d,e also show that some coastal areas also adopted early sowing/transplanting dates in 2020. In 2019 WS season, around 10,000 ha were at the sowing/transplanting stage, while in 2020, due to earlier sowing/transplanting, rice crop reached the tillering stage. Similar rice planting trends were noticed in Sóc Trăng province, where rice crop was transplanted early in 2020 following MARD's agro-advisory about salinity and drought. Around 28,000 ha of rice-growing areas reached the rebooting–panicle initiation stage in 2019, while in the 2020 WS season, most of the rice-growing areas were at the gain-filling stage (Figure 8i). Finally, in Bạc Liêu province, a similar drift was recorded; in the 2019 WS season, approximately 10,000 ha were without rice or at the seeding–transplanting stage, while in 2020, due to early planting, rice crop was at the tillering stage (Figure 8j,k). Thus, the rice monitor with satellite SAR data clearly shows early sowing/transplanting in the WS season of 2020, particularly in Bến Tre and Bạc Liêu provinces and some areas in the remaining two provinces.

3.3. The Effect of Salinity Intrusion on the Rice Area in Winter–Spring Rice Crop

Salinity isolines (4 g/L) in the study area are displayed in Figure 9. The map shows a deep salinity intrusion along the main Mekong River towards the inland direction. The results show that the affected areas were deeper inland for years with severe drought events (2016 and 2020).

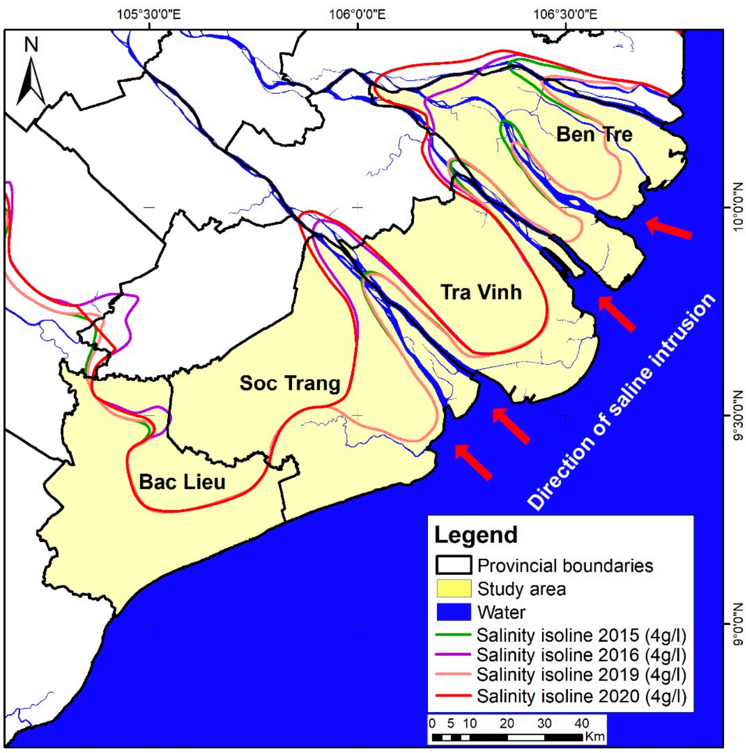


Figure 9. Salinity isoline of the study area in 2015, 2016, 2019 and 2020.

The spatial distribution maps of the WS rice 2015, 2016, 2019, and 2020 in the study area are shown in Figure 10. The maps were created from the S-1 image data collected from 1 November to 30 April and show changes in the rice-planted area over these years. Figure 11a shows that most of the rice area in the four provinces experienced a decline in the years of severe salinity and drought (2016 and 2020) as warned by DCP–MARD [43] when compared to the previous year. In particular, Bến Tre is one of the coastal provinces in the MD that was most severely affected during drought and salinity intrusion years, in which the rice-growing area is cautiously decreasing over the years.

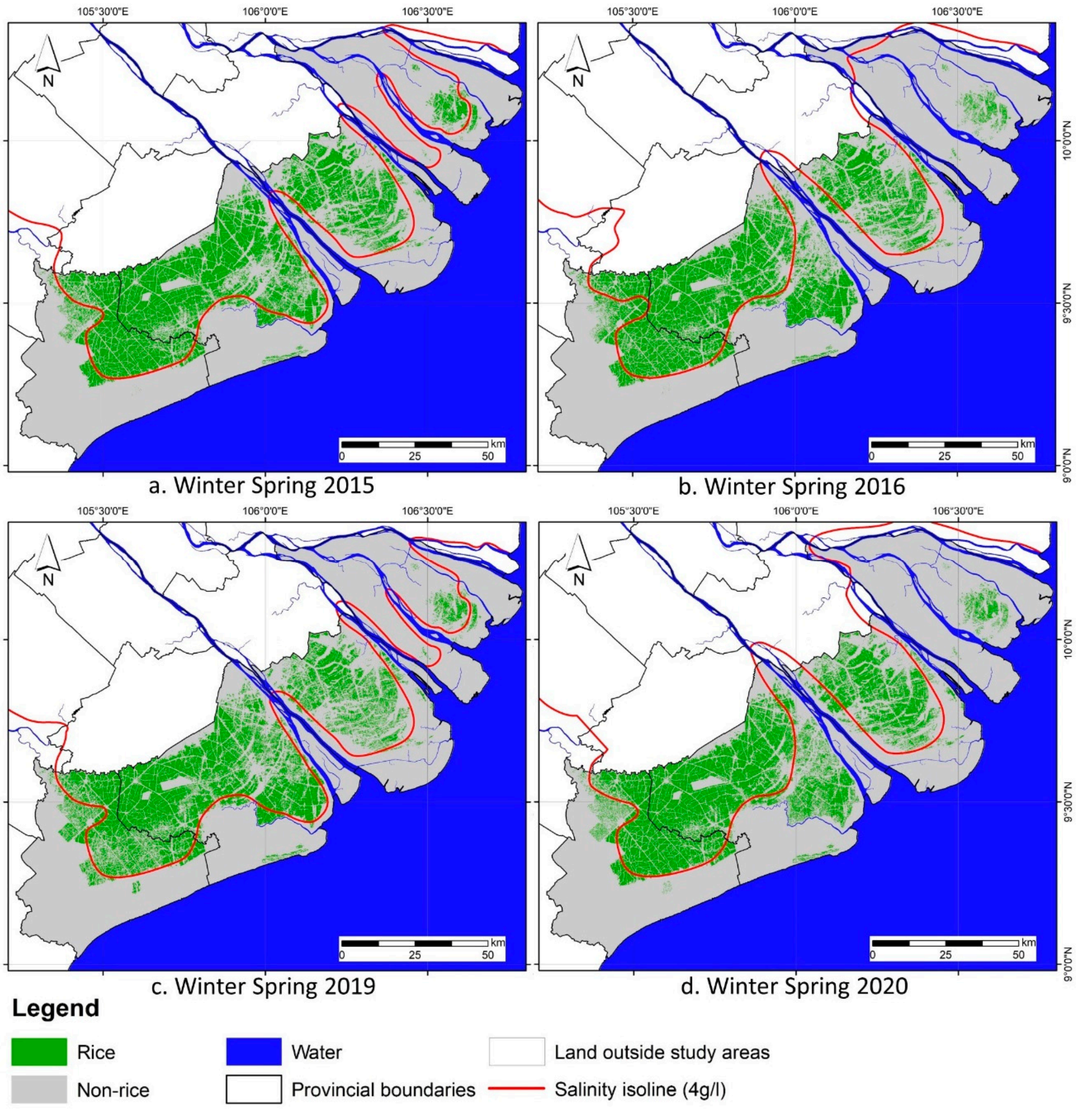


Figure 10. Spatial distribution maps of the WS season with salinity isoline in 2015 (**a**), 2016 (**b**), 2019 (**c**), and 2020 (**d**) of the study area.

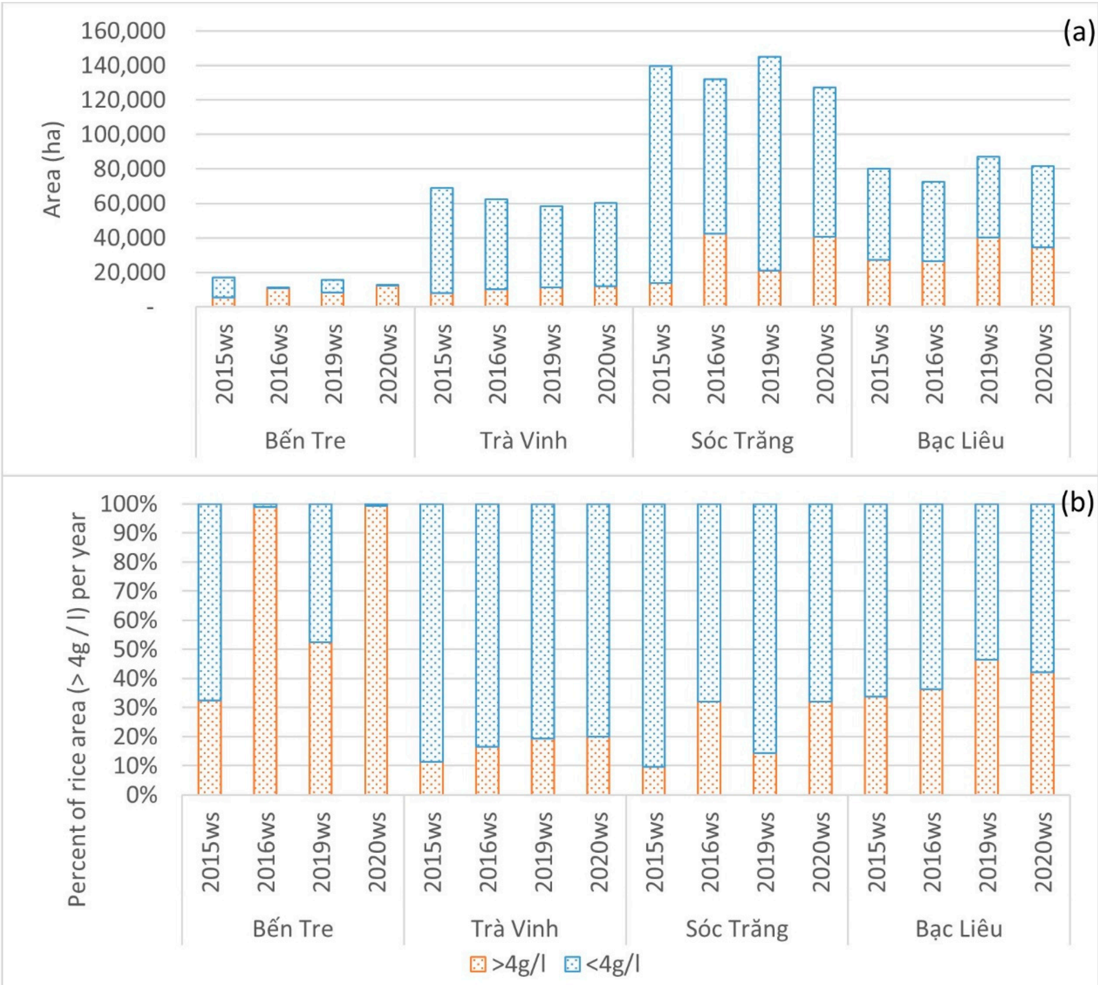


Figure 11. Areas (**a**) and percentage (**b**) affected by salinity intrusion (>4 g/L) in the WS seasons 2015, 2016, 2019, and 2020.

Data analysis allowed us to assess the influence of salinity intrusion on WS seasons for each province, as presented in Figure 11. Figure 11a also shows the rice area affected by salinity (>4 g/L) in 2015, 2016, 2019, and 2020, and the corresponding percentages per year (Figure 11b). The results show that the rice area in Bến Tre province was regularly affected by salinity intrusion (greater than 30%, and in 2016 and 2020 affecting over 95% of the rice-growing area). The rice area in Trà Vinh affected by salinity intrusion was about 17% in 2016 and 20% in 2020. Similarly, the rice area in Sóc Trăng province was also affected by salinity intrusion with less than 15% in 2015 and 2019, and up to 32% in 2016 and 2020. Results indicate that in Bạc Liêu province, around 33–47% of the rice-growing area was affected by salinity intrusion. Unlike other three provinces, Bạc Liêu province displayed an opposite trend in the years 2019 and 2020, in which the area of rice affected by severe salinity intrusion in 2020 was smaller than the previous years. This can be explained by the fact that some areas that were frequently affected by salinity intrusion no longer cultivate rice, so the rice area decreases during the year with the severe drought warned. In summary, results have shown that the provinces in the study area were frequently affected by salinity intrusion and were often affected more widely in severe drought years.

4. Discussion

4.1. Classification of Rice Growth Status

Multi-temporal Sentinel-1 data are important for monitoring rice growth parameters involving rice age, planting and harvest dates due to its ability to guarantee acquisition in the monsoon tropics, where most of the world's rice-growing areas (China, India, Thailand, Vietnam, etc.) are usually covered by clouds [44,45]. The S-1 data are freely accessible in terms of the desired temporal (12 or 6 days) and spatial (20 m) resolutions. Multi-temporal data processing methods are implemented to improve data quality, which significantly reduced spatial and temporal noise [26,27]. This dataset facilitates the pixel-based approach, which is simpler and less time-consuming than other approaches [46]. The method to classify the growth stages in the study, based on the determination of rice age [27], allows an accurate evaluation of changes in the spatial distribution of the growth stages among different rice cultivation regions in near real time. Such information is important for agricultural management agencies.

The results of this study show a more detailed classification of the rice growth stages through S-1 multi-temporal data analyses when compared with other research results in terms of quality and consistency. Prior studies [26,47] used multi-time X-band radar data to analyze growth status (phenology) to determine flooding/transplanting dates, in which high accuracy was obtained. Ze et al. [48] classified four growth stages of rice crop (including transplanting, vegetative, reproductive, maturity) using a threshold method on RADARSAT-2 fully polarized data with an overall accuracy of 86.2% (n = 30). Subsequently, Phung et al. [27], analyzed the current status of rice growth to estimate the age of rice, date of sowing/transplanting and harvest date from S-1 C-band data. In this study, the classification of growth stages using the S-1 data series for a large area obtained better results for six stages with an 85% overall accuracy and a Kappa coefficient of 0.80 (n = 373). This proves that the method of classifying growth stages based on S-1 C-band multi-temporal data series with a VH polarization can be practically applied to large areas.

4.2. The Effect of Salinity and Drought Events on Changes in the WS Rice

The intrusion of saline water by tidal action causes the movement of high-density salt into irrigation water [7], leading to the salinization of agricultural land, and making rice cultivation very difficult in coastal areas. Such a situation is more severely affected during the dry season when rainfall decreases and river flows are insufficient to repel the saline water, a phenomenon characterized by the appearance in the dry season in coastal areas, but rarely in the upper part of the MD. In addition, the upstream dams influence the discharge through water control [32,33], such as storing water during the rainy season in order to ensure the normal operation of power generation during the dry season [49]. However, it may also impair downstream discharge and irrigation water resources during dry season [33,50]. In particular, the decrease in discharge in the downstream of the Mekong River corresponds to the severe salinity and drought situation in 2020 (Figure 3c), although there is no effect of El Nino. The highest monthly salinity is usually in March or April of the dry season in the MD [8], so in the years with high salinity and drought warned (such as 2016), local managers recommended farmers to harvest earlier in the WS rice crop before the salinity and drought hit their peak. The coastal provinces experienced sowing/transplanting at about 10–30 days in 2016 earlier than in 2015, especially in Bến Tre and Sóc Trăng, although some areas did not record this phenomenon.

The study of Kaustubh et al. [51] showed the possibility of continued warming in Southeast Asia in 2016 with strong connection to the El Nino phenomenon, in which these extreme events can be predicted quantitatively a few months in advance, and therefore may increase the preparedness of the area to be affected. By the time of the WS season in 2020, according to the National Oceanic and Atmospheric Administration (NOAA), it was also predicted that the hottest phenomenon in the history will result in severe salinity. Thus, the Department of Crop Production recommended early sowing for the WS crop of 2020 [43], where localities were sown 10 to 30 days earlier than the previous WS crops.

This has been found in the spatial distribution maps of the rice growth stages on 12 February 2019 and 13 February 2020 in the four provinces. Similar to the year 2016, some areas were sown/transplanted earlier in the WS crop of 2020 than that of the previous year 2019, mainly in Bến Tre and Bạc Liêu and the areas in the remaining provinces. There was a trend of early sowing/transplanting in these two provinces, which can be explained by the affected rice area (>4 g/L) in 2019—it was 52% and 47% in Bến Tre and Bạc Liêu, respectively. Recommendations were the main reason why farmers changed their crop calendar under salinization. In addition, the economic benefits of farmers had been reduced due to the decrease in or loss of rice productivity when affected by the previous years' drought, which made many farmers follow the recommendations of managers to avoid the impact of salinity and drought. Findings from the analysis of changes in spatial distribution patterns of growth stages in the study area have confirmed that salinity intrusion had direct or indirect effects on changes in rice crop calendar in coastal provinces of the study area.

The impact of salinity intrusion on the arable land for rice cultivation has been clearly demonstrated, which causes restrictions on rice production in coastal areas. One of these impacts is limiting the ability to grow rice, reduce productivity or damage rice, leading to a difference in the rice cultivation area between years, especially in the recorded years affected by severe salinity intrusion such as 2016 and 2020. This is because rice is known as a crop that is particularly sensitive to the salinity of arable land [52,53]. Salinity data greater than 1 g/L may begin to affect rice yield [52]. According to the MARD report [14], using a threshold of 4 g/L is considered as the rice production threshold. Salinity that reaches this threshold often noted that many poor-tolerant rice varieties could stop growing or dying in the MD region [54]. This study used the salinity isoline (4 g/L) to determine the affected areas. The map showed a deep salinity intrusion along the main land-based Mekong River in Vietnam, particularly in the three provinces of Bến Tre, Trà Vinh and Sóc Trăng (Figure 9). Bến Tre and Sóc Trăng recorded an increase in the area of rice affected by salinity intrusion in 2016 and 2020 (Figure 11). In particular, Bến Tre was most affected by salinity intrusion in the year of severe drought; in particular, the affected area (>4 g/L) in 2016 and 2020 was over 95% of the total rice area.

In order to ensure normal rice production and limit the effects of salinity intrusion, certain models of rice cultivation have been changed, such as shifting rice sowing/transplanting date to adapt to environmental changes [43]. Recommendations and policies are in place to ensure that limited rice area is less affected by salinity and drought for rice growth. The incentive not to plant rice in areas with high salinity in the WS season can also be carried out to limit crop failure, thus allowing farmers to avoid negative economic impact. Typically, Bến Tre province showed that the area of rice regularly in the affected area has a high salinity of >4 g/L in the dry season, so the managers encouraged farmers to not cultivate rice in the WS crop. In the areas where salinity intrusion often reduces rice productivity or dies, farmers will not plant rice because of low profits. This has led to changes in the livelihoods of affected households, requiring the need for land-use conversion to increase profits in the rural area. As a result, it has caused pressure to reduce the area of rice cultivation in Bến Tre province over the years, from 17,200 ha (2015) to 13,892 ha (2019) of WS rice-growing land according to the General Statistics Office [4]. Thus, we found a certain relationship between the percentage of the area of rice affected by salinity and drought and rice area of the following years. If the percentage is high for many years, it will cause a decrease in the rice area the following year.

To reduce the effects of salinity intrusion, agricultural managers in Bến Tre advised farmers not to grow WS rice in 2020. However, some areas were still planted with rice, but the sowing/transplanting date was made earlier to reduce the effects of salinity and drought (Figure 8a,b). Rice agriculture is a long-standing tradition of the locals, and rice cultivation can still have advantages in terms of sustainability of production, low investment costs, and economic benefits. However, the current situation of salinity intrusion is causing certain pressure on the rice cultivation pattern and livelihoods of coastal households. This could be a driving force for changes in the WS crop calendar or land-use conversion of the affected areas, which is important information for managers.

This study has shown the potential of multi-temporal SAR data in spatial distribution monitoring of rice growth stages. The multi-temporal analysis results showed changes in the crop calendar and rice area under the influence of strong salinity intrusion for the years when severe drought occurred. The classification method for determining the phenological stages was based on the rice cultivation pattern specifically for the MD. The method can be adapted to other areas after the calibration and verification steps are carried out with the local conditions pertaining to such areas (e.g., the RRD), especially for areas with a rice cultivation pattern using different rice varieties in different growth cycles. This study also demonstrates the ability to monitor the rice growth stage, as well as the change in the status of agricultural crops, using the C-band SAR time series data, which is in accordance with previous studies [48,55]. In this study, more detailed monitoring of spatial distribution for various regions across the study area showed differences in crop growth between rice fields in each region. This is because of different rice farming conditions in each region, such as irrigation systems, dikes and environmental conditions, the possibility of saline water intrusion and local policies/recommendations. Therefore, the method that takes advantage C-band SAR time series data for monitoring the rice growth status is essential for areas with different growth status changes on a large scale.

5. Conclusions

Multi-temporal Sentinel-1 data were used to determine the spatiotemporal distribution of rice growth stages in four coastal provinces of the Mekong Delta in Vietnam. We successfully identified areas with different growth stages from the VH polarized SAR data. The results show that the distribution of rice growth stages depends on crop calendar in each coastal province of the study area. Furthermore, the distribution of growth stages in the years that were strongly affected by salinity intrusion (2016 and 2020) shows a distinctive change in the crop calendar, which was earlier than that of the previous year, in order to reduce the impact of salinity intrusion. This is clearly shown by the results of the growth stages in February each year of the WS crop in coastal provinces, reflecting the avoidance of the effects of higher salinity intrusion in March and April of the years strongly affected by salinity intrusion. The results show that many areas of the WS crop of 2016 and 2020 were planted with rice 10 to 30 days earlier when compared to the previous year. Especially in Bến Tre and Bạc Liêu provinces, there was a clear trend of early sowing/transplanting in 2020. As demonstrated in the two provinces severely affected by salinity intrusion, the affected area (>4 g/L) accounts for more than 45% of the rice area. Thus, agricultural managers recommended farmers to grow rice earlier to avoid being affected subsequently by salinity intrusion. In addition, the results showed that because areas often affected by salinity intrusion have reduced rice yield, farmers will not crop in the following year. Bến Tre, the province most affected by salinity intrusion, recorded a continuous decrease in the rice area of Winter–Spring crop over the years. This leads to some changes in the livelihoods of affected households. The results confirm that salinity intrusion has a direct or indirect effect on changing the rice crop calendar in coastal provinces. This allows us to conclude that the rice cultivation pattern in the coastal provinces of the Mekong Delta is affected by the high salinity intrusion during the dry season. The study also shows the potential of multi-temporal Sentinel-1 data to extract information on rice growth stage to support the decisions and planning of agricultural managers.

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References

1. IRRI; AfricaRice; CIAT. Global Rice Science Partnership (GRiSP) Full Proposal. Available online: http://ricecrp.org/wp-content/uploads/2017/03/RICE-phase-I-2011-2015.pdf (accessed on 4 March 2020).
2. Bandumula, N. Rice production in asia: Key to global food security. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2018**, *88*, 1323–1328. [CrossRef]
3. FAO. *Bridging the Rice Yield Gap in the Asia-Pacific Region*; Papademetriou, M.K., Dent, F.J., Edward, M.H., Eds.; RAP Publication: Bangkok, Thailand, 2000.
4. GSO. General Statistics Office of Vietnam. Available online: https://www.gso.gov.vn/default_en.aspx?tabid=778 (accessed on 4 March 2020).
5. Wassmann, R.; Phong, N.D.; Tho, T.Q.; Hoanh, C.T.; Khoi, N.H.; Hien, N.X.; Vo, T.B.T.; Tuong, T.P. High-resolution mapping of flood and salinity risks for rice production in the vietnamese mekong delta. *Field Crops Res.* **2019**, *236*, 111–120. [CrossRef]
6. Ngo, D.; Chu, T.; Tran, Q.; Nguyen, V.; Tran, D.; To, P.; Nguyen, H.; Nguyen, X.; Nguyen, T. Water management for agricultural production in a coastal province of the mekong river delta under sea-level rise. In *Climate Change and Agricultural Water Management in Developing Countries*; CABI: Wallingford, UK, 2015; pp. 120–134; ISBN 9781780643663.
7. CGIAR. Assessment Report: The Drought and Salinity Intrusion in the Mekong River Delta of Vietnam. CGIAR Research Program on Climate Change, Agriculture and Food Security-Southeast Asia (CCAFS SEA): Hanoi, Vietnam, 2016. Available online: https://cgspace.cgiar.org/handle/10568/75633 (accessed on 4 March 2020).
8. Paik, S.; Le, D.T.P.; Nhu, L.T.; Mills, B.F. Salt-tolerant rice variety adoption in the mekong river delta: Farmer adaptation to sea-level rise. *PLoS ONE* **2020**, *15*, e0229464. [CrossRef] [PubMed]
9. Dam, T.H.T.; Amjath-Babu, T.S.; Zander, P.; Müller, K. Paddy in saline water: Analysing variety-specific effects of saline water intrusion on the technical efficiency of rice production in Vietnam. *Outlook Agric.* **2019**, *48*, 237–245. [CrossRef]
10. Sherif, M.M.; Singh, V.P. Effect of climate change on sea water intrusion in coastal aquifers. *Hydrol. Process.* **1999**, *13*, 1277–1287. [CrossRef]
11. Wassmann, R.; Hien, N.X.; Hoanh, C.T.; Tuong, T.P. Sea level rise affecting the vietnamese mekong delta: Water elevation in the flood season and implications for rice production. *Clim. Chang.* **2004**, *66*, 89–107. [CrossRef]
12. Singh, A.; Sengar, R. Salinity stress in rice: An overview. *Plant Arch.* **2014**, *14*, 643–648.
13. Ghosh, B.; Ali Md, N. Response of rice under salinity stress: A review update. *Rice Res. Open Access* **2016**, *4*, 1441–1447. [CrossRef]
14. MARD. Ministry of Agriculture and Rural Development. Decision No 1915/QĐ-BNN-KH. Available online: http://vukehoach.mard.gov.vn/DataStore/News/20186423-De (accessed on 4 March 2020).
15. Sakamoto, T.; Van Nguyen, N.; Ohno, H.; Ishitsuka, N.; Yokozawa, M. Spatio-temporal distribution of rice phenology and cropping systems in the mekong delta with special reference to the seasonal water flow of the mekong and bassac rivers. *Remote Sens. Environ.* **2006**, *100*, 1–16. [CrossRef]
16. Gumma, M.K.; Thenkabail, P.S.; Maunahan, A.; Islam, S.; Nelson, A. Mapping seasonal rice cropland extent and area in the high cropping intensity environment of Bangladesh using MODIS 500m data for the year 2010. *ISPRS J. Photogramm. Remote Sens.* **2014**, *91*, 98–113. [CrossRef]
17. Nguyen, T.T.H.; De Bie, C.A.J.M.; Ali, A.; Smaling, E.M.A.; Chu, T.H. Mapping the irrigated rice cropping patterns of the mekong delta, vietnam, through hyper-temporal SPOT NDVI image analysis. *Int. J. Remote Sens.* **2012**, *33*, 415–434. [CrossRef]
18. Boschetti, M.; Busetto, L.; Manfron, G.; Laborte, A.; Asilo, S.; Pazhanivelan, S.; Nelson, A. PhenoRice: A method for automatic extraction of spatio-temporal information on rice crops using satellite data time series. *Remote Sens. Environ.* **2017**, *194*, 347–365. [CrossRef]

19. Onojeghuo, A.O.; Blackburn, G.A.; Wang, Q.; Atkinson, P.M.; Kindred, D.; Miao, Y. Rice crop phenology mapping at high spatial and temporal resolution using downscaled MODIS time-series. *GIScience Remote Sens.* **2018**, *55*, 659–677. [CrossRef]
20. Son, N.T.; Chen, C.F.; Chang, L.Y.; Chen, C.R.; Sobue, S.I.; Minh, V.Q.; Chiang, S.H.; Nguyen, L.D.; Lin, Y.W. A logistic-based method for rice monitoring from multi-temporal MODIS-landsat fusion data. *Eur. J. Remote Sens.* **2016**, *49*, 39–56. [CrossRef]
21. Xinghua, L.; Huanfeng, S.; Liangpei, Z.; Hongyan, Z.; Qiangqiang, Y.; Gang, Y. Recovering quantitative remote sensing products contaminated by thick clouds and shadows using multitemporal dictionary learning. *IEEE Trans. Geosci. Remote Sens.* **2014**, *52*, 7086–7098. [CrossRef]
22. Li, X.; Wang, L.; Cheng, Q.; Wu, P.; Gan, W.; Fang, L. Cloud removal in remote sensing images using nonnegative matrix factorization and error correction. *ISPRS J. Photogramm. Remote Sens.* **2019**, *148*, 103–113. [CrossRef]
23. Lee, K.Y.; Sim, J.Y. Cloud removal of satellite images using convolutional neural network with reliable cloudy image synthesis model. In Proceedings of the International Conference on Image Processing, ICIP, Taipei, Taiwan, 22–25 September 2019; pp. 3581–3585.
24. Minh, H.V.T.; Avtar, R.; Mohan, G.; Misra, P.; Kurasaki, M. Monitoring and mapping of rice cropping pattern in flooding area in the vietnamese mekong delta using sentinel-1A data: A case of an giang province. *ISPRS Int. J. Geo Inf.* **2019**, *8*, 211. [CrossRef]
25. Phung, H.P.; Nguyen, L.D. Rice crop monitoring in the mekong delta, vietnam using multi-temporal sentinel-1 data with c-band. In *ICSCEA 2019, Lecture Notes in Civil Engineering 80*; Reddy, J.N., Wang, C.M., Luong, V.H., Le, A.T., Eds.; Springer Nature Singapore Pte Ltd.: Berlin/Heidelberg, Germany, 2020; pp. 979–986. ISBN 9789811551437.
26. Phan, H.; Le Toan, T.; Bouvet, A.; Nguyen, L.D.; Duy, T.P.; Zribi, M. Mapping of rice varieties and sowing date using X-band SAR data. *Sensors* **2018**, *18*, 316. [CrossRef]
27. Phung, H.-P.; Nguyen, L.-D.; Thong, N.-H.; Thuy, L.-T.; Apan, A.A. Monitoring rice growth status in the mekong delta, vietnam using multitemporal sentinel-1 data. *J. Appl. Remote Sens.* **2020**, *14*, 1. [CrossRef]
28. White, I. *Water Management in the Mekong Delta: Changes, Conflicts and Opportunities*; Paris, France, 2002. Available online: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=30A7A75283420ED220E60A5693E87C62?doi=10.1.1.562.8908&rep=rep1&type=pdf (accessed on 25 September 2020).
29. Park, E.; Ho, H.L.; Tran, D.D.; Yang, X.; Alcantara, E.; Merino, E.; Son, V.H. Dramatic decrease of flood frequency in the mekong delta due to river-bed mining and dyke construction. *Sci. Total Environ.* **2020**, *723*, 138066. [CrossRef]
30. Dang, H.D. Sustainability of the rice-shrimp farming system in mekong delta, vietnam: A climate adaptive model. *J. Econ. Dev.* **2020**, *22*, 21–45. [CrossRef]
31. Tran, T.B. Sustainability of Rice-Shrimp Farming System in a Brackish Water Area in the Mekong Delta of Vietnam. Master's Thesis, University of Western Sydney, Hawkesbury, Australia, 1994.
32. Räsänen, T.A.; Someth, P.; Lauri, H.; Koponen, J.; Sarkkula, J.; Kummu, M. Observed river discharge changes due to hydropower operations in the upper mekong basin. *J. Hydrol.* **2017**, *545*, 28–41. [CrossRef]
33. Lu, X.X.; Li, S.; Kummu, M.; Padawangi, R.; Wang, J.J. Observed changes in the water flow at chiang saen in the lower mekong: Impacts of Chinese dams? *Quat. Int.* **2014**, *336*, 145–157. [CrossRef]
34. MRC. Discharge time series-mekong river commission portal. Available online: https://portal.mrcmekong.org/time-series/discharge (accessed on 25 September 2020).
35. Nguyen, L.D. Rice Crop Monitoring Using New Generation Synthetic Aperture Radar (SAR) Imagery. Ph.D. Thesis, University of Southern Queensland, Toowoomba, Australia, 2009.
36. Small, D.; Schubert, A. *Guide to ASAR Geocoding*; RSL, University of Zürich, 2008. Available online: https://www.geo.uzh.ch/microsite/rsl-documents/research/publications/other-sci-communications/2008_RSL-ASAR-GC-AD-v101-0335607552/2008_RSL-ASAR-GC-AD-v101.pdf (accessed on 29 September 2020).
37. Quegan, S.; Le Toan, T.; Yu, J.J.; Ribbes, F.; Floury, N. Multitemporal ERS SAR analysis applied to forest mapping. *IEEE Trans. Geosci. Remote Sens.* **2000**, *38*, 741–753. [CrossRef]
38. Quegan, S.; Jiong Jiong, Y.U. Filtering of multichannel SAR images. *IEEE Trans. Geosci. Remote Sens.* **2001**, *39*, 2373–2379. [CrossRef]
39. Matsushima, S. *Crop Science in Rice*; Fuji Publ. Co., Ltd.: Tokyo, Janpan, 1970.
40. Yoshida, S. *Fundamentals of Rice Crop Science*; The International Rice Research Institute: Manila, Philippines, 1981.

41. Stehman, S.V. Selecting and interpreting measures of thematic classification accuracy. *Remote Sens. Environ.* **1997**, *62*, 77–89. [CrossRef]
42. Cohen, J. A Coefficient of agreement for nominal scales. *Educ. Psychol. Meas.* **1960**, *20*, 37–46. [CrossRef]
43. MARD. Ministry of Agriculture and Rural Development. Available online: https://mard.gov.vn/Pages/nam-bo-dbscl-trien-khai-ke-hoach-san-xuat-vu-dong-xuan-2019-2020.aspx (accessed on 9 July 2020).
44. Chen, J.; Lin, H.; Pei, Z. Application of envisat asar data in mapping rice crop growth in southern China. *IEEE Geosci. Remote Sens. Lett.* **2007**, *4*, 431–435. [CrossRef]
45. Ferrant, S.; Selles, A.; Le Page, M.; Herrault, P.-A.; Pelletier, C.; Al-Bitar, A.; Mermoz, S.; Gascoin, S.; Bouvet, A.; Saqalli, M.; et al. Detection of irrigated crops from sentinel-1 and sentinel-2 data to estimate seasonal groundwater use in south India. *Remote Sens.* **2017**, *9*, 1119. [CrossRef]
46. Hussain, M.; Chen, D.; Cheng, A.; Wei, H.; Stanley, D. Change detection from remotely sensed images: From pixel-based to object-based approaches. *ISPRS J. Photogramm. Remote Sens.* **2013**, *80*, 91–106. [CrossRef]
47. Asilo, S.; de Bie, K.; Skidmore, A.; Nelson, A.; Barbieri, M.; Maunahan, A. Complementarity of two rice mapping approaches: Characterizing strata mapped by hypertemporal MODIS and rice paddy identification using multitemporal SAR. *Remote Sens.* **2014**, *6*, 12789–12814. [CrossRef]
48. He, Z.; Li, S.; Wang, Y.; Dai, L.; Lin, S. Monitoring rice phenology based on backscattering characteristics of multi-temporal RADARSAT-2 datasets. *Remote Sens.* **2018**, *10*, 340. [CrossRef]
49. Ha, D.T.T.; Kim, S.-H.; Bae, D.-H. Impacts of upstream structures on downstream discharge in the transboundary imjin river Basin, Korean Peninsula. *Appl. Sci.* **2020**, *10*, 3333. [CrossRef]
50. Biemans, H.; Haddeland, I.; Kabat, P.; Ludwig, F.; Hutjes, R.W.A.; Heinke, J.; Von Bloh, W.; Gerten, D. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. *Water Resour. Res.* **2011**, *47*, 1–15. [CrossRef]
51. Thirumalai, K.; DInezio, P.N.; Okumura, Y.; Deser, C. Extreme temperatures in southeast Asia caused by El Ninõ and worsened by global warming. *Nat. Commun.* **2017**, *8*, 1–8. [CrossRef] [PubMed]
52. Grattan, S.R.; Zeng, L.; Shannon, M.C.; Roberts, S.R. Rice is more sensitive to salinity than previously thought. *Calif. Agric.* **2002**, *56*, 189–198. [CrossRef]
53. Maas, E.V.; Hoffman, G.J. Crop salt tolerance-current assessment. *Irrig. Drain. Div.* **1977**, *103*, 115–134.
54. Tấn, H.M.; Sáng, V.Q.; Thanh, N.K. *Giáo trình sinh lý thực vật—Curriculum of Plant Physiology (Vietnamese)*; Nhà Xuất Bản Đại Học Sư Phạm: Hanoi, Vietnam, 2006; p. 392. Available online: http://www2.hcmuaf.edu.vn/data/pvhien/Gi%C3%A1o%20Tr%C3%ACnh%20Sinh%20L%C3%AD%20Th%E1%BB%B1c%20V%E1%BA%ADt%20(NXB%20%C4%90%E1%BA%A1i%20H%E1%BB%8Dc%20S%C6%B0%20Ph%E1%BA%A1m%202006)%20-%20Ho%C3%A0ng%20Minh%20T%E1%BA%A5n,%20392%20Trang(1).pdf (accessed on 25 September 2020).
55. Larranaga, A.; Alvarez-Mozos, J.; Albizua, L.; Peters, J. Backscattering Behavior of rain-fed crops along the growing season. *IEEE Geosci. Remote Sens. Lett.* **2013**, *10*, 386–390. [CrossRef]