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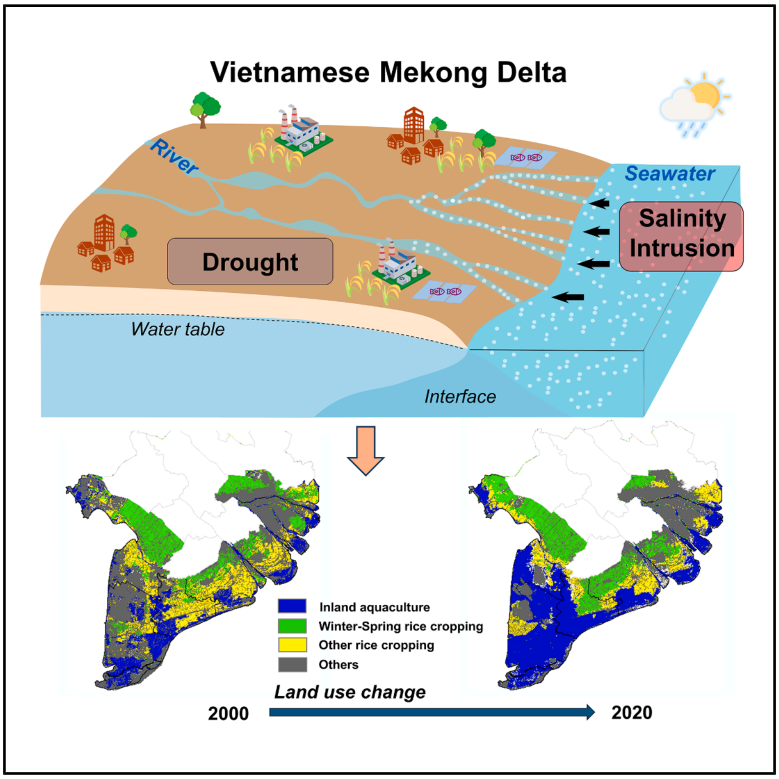
Land use change in the Vietnamese Mekong Delta: Long-term impacts of drought and salinity intrusion using satellite and monitoring data

Graphical abstract



Highlights

- Salinity intrusion and drought reduce rice yields in VMD's coastal provinces
- Satellite data reveal shifting land use patterns linked to extreme dry seasons
- Adaptive cropping and water strategies are vital for delta agricultural resilience

Authors

Doan Van Binh, Dung Duc Tran, Vũ Hoàng Thái Dương, Jonas Bauer, Edward Park, Ho Huu Loc

Correspondence

dungtranducvn@yahoo.com

In brief

Earth-surface processes; Remote sensing; Agricultural land

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Land use change in the Vietnamese Mekong Delta: Long-term impacts of drought and salinity intrusion using satellite and monitoring data

Doan Van Binh,[1] Dung Duc Tran,[2,3,6,*] Vũ Hoàng Thái Dương,[4] Jonas Bauer,[4] Edward Park,[3] and Ho Huu Loc[5]

[1]Master Program in Water Technology, Reuse and Management, Faculty of Engineering, Vietnamese German University, Binh Duong 75000, Vietnam

[2]Center of Water Management and Climate Change (WACC), Institute for Environment and Resources (IER), Vietnam National University Ho Chi Minh City (VNU−HCM), Ho Chi Minh City, Vietnam

[3]National Institute of Education, Earth Observatory of Singapore and Asian School of the Environment, Nanyang Technological University, Singapore

[4]Karlsruhe Institute of Technology, Karlsruhe, Germany

[5]Earth Systems and Global Change Group (ESC), Wageningen University and Research (WUR), Wageningen, the Netherlands

[6]Lead contact

*Correspondence: dungtranducvn@yahoo.com

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SUMMARY

Drought and salinity intrusion (DSI) increasingly threaten agriculture and aquaculture in coastal regions. Focusing on the Vietnamese Mekong Delta (VMD), we examined how DSI from 2000 to 2020 influences rice cropping, aquaculture area, and rice yield across seven coastal provinces. *In-situ* discharge and salinity monitoring, combined with satellite-derived land use data and yield validation, revealed the highest DSI impacts during the 2010–2011, 2015–2016, and 2019–2020 dry seasons. Local governments employed strategies such as drought-tolerant rice, improved irrigation, and revised cropping schedules to mitigate losses, yet further investments remain vital. Our findings provide evidence-based insights for managing DSI and strengthening agricultural resilience in the VMD and other vulnerable deltas worldwide.

INTRODUCTION

Drought and saline intrusion (DSI) have increasingly affected aquaculture and agricultural production in many river deltas worldwide, home to over half a billion people.[1,2] These phenomena and processes have adversely undermined the livelihoods and sustainability of millions of coastal inhabitants, especially those based on agriculture and aquaculture. A drought is defined as a period when an area or region experiences below-normal values of precipitation (meteorological drought), streamflow (hydrological drought), or soil water content (agricultural drought).[3] SI refers to the upstream movement of saline water from the sea into freshwater zones[4] and becomes more extreme in drought years.[5] Recent intensification of SI has degraded crucial ecosystem services worth trillions of dollars globally that provide fertile alluvial soils, sustaining biological diversity, and aquatic habitat for flora, fauna, and fisheries in many deltas worldwide.[1]

DSI has caused direct impacts on various economic sectors in different regions worldwide. Five of the direct consequences are: (1) crop yield reduction in Bangladesh's coastal agriculture,[6,7] (2) agricultural lands and aquaculture production in the Tagus Estuary of Portugal,[8] (3) significant loss of land, livestock, freshwater fish, agricultural yield reduction (∼30%), and migration of tens of thousands of inhabitants in the Indus and Ganges deltas,[9] (4) challenged livelihoods of thousands of farmers by blocking agriculture development in the Yellow River Delta,[10,11] and (5) mangrove habitat shift and significantly high tree mortality in some parts of the Orinori and Mississippi rivers.[2,12] Besides the direct consequences, SI has far-reaching socio-environmental impacts, as it can cause severe drinking water scarcity, threaten food security, and create health problems.[13] These examples highlight that socio-environmental consequences caused by SI are crucial at multiple scales. Intensifying SI at the global scale has recently become a crucial sustainability challenge of humankind designated by the United Nations' Sustainable Development Goals in terms of zero hunger, good health and well-being, and clean water and sanitation.[14] These studies also predicted that the increasing climate change–driven DSI may accelerate agricultural yield losses, thus threatening the livelihoods, food security, and income generation of many coastal inhabitants worldwide.

The Vietnamese Mekong Delta (VMD) is among the most affected regions in Southeast Asia by DSI.[14] Spatiotemporal agricultural production patterns and aquaculture have been severely affected by DSI across the delta, especially in the coastal provinces.[15] In recent dry seasons, the VMD has experienced two strong DSI events in 2015–2016 and 2019–2020,[5] and just recently in 2024, with the full extent of the impacts still unknown. During the 2015–2016 dry period, the DSI damaged a total agricultural area of 210,000 hectares (or ha) in almost all provinces in the VMD, whereas 250,000 households encountered freshwater shortages.[16] Subsequently, in the 2019–2020 dry season 10 out of 13 provinces experienced increased SI, resulting in a notable water shortage to 96,000 households (430,000 people) and harm to 58,000 ha of rice, 6,650 ha of fruit trees, 1,241 ha of vegetables, and 8,715 ha of aquaculture.[17] DSI is becoming more severe yearly, putting high pressure on local governments to seek adaptation strategies and alternative farming systems. At the grassroots level, many farmers have tried to adapt to the shocks and stressors entailed by DSI, i.e., land use transformation and learning new techniques, but their livelihoods remain insecure.[18] This insecurity is largely due to a lack of scientifically grounded guidance from authorities on adaptive measures. Instead, farmers have predominantly relied on their own experiences and observations to make land use decisions. As a result, in some regions, the newly transformed land may not be suitable due to the impacts of DSI.

In the VMD, most previous studies have assessed the magnitude and impacts of either drought[19–22] or SI[23–25] on different fields. Some studies highlighted the intensification of SI under extreme drought events[5] and riverbed incision due to river damming and sand mining.[26] Tran et al. [2019] correlated soil salinity with drought intensity in Ben Tre Province, and they found that drought intensified salinity in rice-cultivated and natural cropland areas, but an opposite trend was detected in aquaculture areas.[27] However, a comprehensive assessment of the spatiotemporal correlation between DSI and land use change in the VMD's coastal area still needs further exploration. To date, Smajgl et al. [2015] was the most comprehensive research in assessing SI dynamics in the entire VMD under the combined impacts of climate change and human activities with an emphasis on the impact of the future projected SI on agriculture production, from which combined soft and hard measures were proposed.[25] However, SI dynamics were assessed merely using numerical modeling that was calibrated and validated using data before 2012, which is relatively outdated due to the region's fast-changing conditions. Moreover, their study did not consider SI in drought events which may exacerbate SI impacts.[15] Because of that, recent severe DSI events, e.g., in 2015–2016 and 2019–2020, should be investigated to understand their effects on land use changes and crop yields in the coastal provinces. A comprehensive study similar to Smajgl et al. [2015][25] for recent DSI for the entire VMD's coastal provinces using long-term monitored data is of an urgent need to understand the dynamics, the causes, and the consequences of the past DSI events, from which better solutions can be proposed for implementation in the future.

Several studies have examined the impacts of drought and SI individually on different aspects of agricultural land use change across the VMD[28–32]; however, none of these studies has explicitly examined the long-term relationship between DSI events and land use changes or their specific impacts on crop area and yields in the VMD. The coastal delta's land use management strategies have evolved in response to DSI, which has been exacerbated by climate change and environmental pressures.[24,31] Cultivated land is shrinking, while soil quality and crop yields have decreased over the years due to increased DSI in many coastal regions.[29,30] Pests also overgrow and increase their ability to cause disease, leading to a higher risk of disease transmission to animals, affecting crops and livestock.[17] While the river experiences lower water levels in the dry season,[23] coastal economic activities and fishing and aquaculture activities are seriously affected by the high-saline concentration water fluxes from the sea.[33] During the drought, people relied on fresh groundwater resources for domestic use, and this over-extraction has further worsened land subsidence and groundwater salinization.[34] Overall, the previous findings overlooked the impacts of the DSI on the long-term land use changes in coastal provinces. Evaluating the impacts of these changes, particularly on crop area and yields, remains essential for understanding this complex relationship.

The present study aims to address two knowledge gaps. First, we examine hydrological drought and salinity intrusion (DSI) patterns—using discharge, salinity, and satellite-based land use data—to understand long-term trends and their impact on Winter-Spring rice cropping in coastal provinces in terms of area and yield. Second, we evaluate how land use transformations mitigate the negative effects of DSI, particularly during extreme events (e.g., 2016 and 2020), and recommend sustainable strategies for different coastal regions. We aim to answer two key research questions: (1) How did DSI affect Winter-Spring rice crop area and yield from 2000 to 2020 in each study province? and (2) To what extent has DSI been extreme over the years in terms of intrusion boundary and intensity to agricultural activities? Our study contributes novel insights into hydrological DSI analysis and land use transformation strategies, offering evidence-based solutions that not only enhance agricultural and aquaculture resilience in the VMD but also serve as a blueprint for similarly vulnerable deltas and DSI-affected farming regions worldwide.

RESULTS

Drought and salinity intrusion in the last two decades

Drought years were identified using SSI-6 from 2000 to 2020 (Figure 1) and compared with the literature (Table 1). Six drought events were identified with two consecutive droughts occurring in 2003–2004 and 2004−2005. The most severe drought in magnitude was in 2019–2020 ($-1.5 <$ SSI-6 <-1.93), followed by the drought in 2015–2016 ($-1.67 <$ SSI-6 <-1.85). However, the 2015−2016 drought caused the strongest impacts on socioeconomics in the VMD.[15] During 2000−2020, the interval between two droughts ranged from one to five years, with an average of three years. This is alarming because the interval was up to eight years (1992 and 1998) before 2000.

Figure 2 shows that salinity concentrations at almost all analyzed stations have increasing trends, in which the trends in some stations are statistically significant of either 5% or 10% significance levels. At stations in the East Vietnam Sea, Binh Dai experienced the most increased maximum (0.15 g/L/yr) and minimum (0.4 g/L/yr with $p < 0.05$) salinity concentrations during 2000–2020. On the other hand, Tra Kha and Ganh Hao did not have a clear trend in both maximum and minimum salinity concentrations. At stations in the Gulf of Thailand, the highest increase in salinity is at Xeo Ro, with a rate of 0.35 and 0.19 g/L/yr in the maximum and minimum salinity concentrations (both have $p < 0.1$), respectively. In general, maximum salinity concentration increased in the Gulf of Thailand (i.e., at Xeo Ro) more than in the

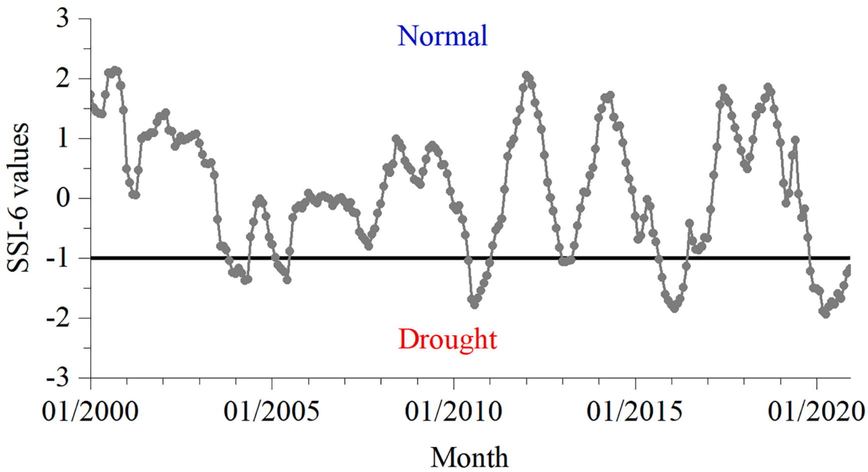

Figure 1. Monthly SSI-6 values at the Tan Chau station

East Vietnamese Sea; however, the reverse relation is true for minimum salinity concentration.

In drought years, e.g., 2004−2005, 2012−2013, 2015−2016, and 2019−2020, salinity concentrations were significantly higher than in normal years. Maximum salinity concentrations in 2016 were higher than the long-term (2000–2020) average by 3.9%, 31.1%, 17.0%, 16.6%, and 49.8% at Binh Dai, An Thuan, Tra Kha, Song Doc, and Xeo Ro, respectively. In 2020, maximum salinity concentrations were even higher, increasing by 11.7%, 31.2%, 87.5%, 26.4%, and 38.2% at Binh Dai, An Thuan, Tra Kha, Song Doc, and Xeo Ro, respectively, compared to the long-term average. The increasing rates in the minimum salinity concentrations were even greater than those in the maximum values, for instance, by 58.8%, 110.3%, 87.5%, 22.0%, and 138.6% in 2020 compared to the long-term average. At Ganh Hao, however, the maximum salinity concentrations in 2016 and 2020 were slightly lower than the long-term average by −4.0% and −1.5%, respectively. The dynamics of salinity in the area are complex, and additional research is necessary to grasp all contributing factors, both natural and anthropogenic.

Dynamics of the Winter-Spring rice area and yield

Figure 3 presents the high agreement between MODIS satellite products and statistical data on total rice planted and aquaculture areas in seven provinces. The figure shows that the MODIS satellite can accurately detect areas of rice and aquaculture in the studied province, although it slightly underestimated the aquaculture area in Kien Giang Province. In general, with correlations of determination R^2 of 0.97 and 0.95 for rice and aquaculture, respectively, applying satellite products in land use pattern detection is considered reliable.

The dynamics of the Winter-Spring rice cropping area were investigated from 2000 to 2020 in the coastal areas, as shown in Figure 4 for a temporal scale of five years, and Figure S1 in the Supplementary for the temporal scale of one year. Four classes of land use types were examined, including (1) inland aquaculture (blue), (2) Winter-Spring rice cropping (green), (3) other rice cropping (yellow), and (4) other land use pattern, i.e., forest, orchards, and built-up areas (gray). Land use patterns exhibit varying changes across provinces. Specifically, Winter-Spring rice cropping and other crops were practiced mainly in Kien Giang, Soc Trang, and Tra Vinh provinces, while the areas in Ca Mau and Bac Lieu were cultivated mainly with aquaculture. On the other hand, orchard gardens were located mainly in Tien Giang province.

Effects of drought and salinity on Winter-Spring rice area and yield

Analyzing long-term trends during 2000–2020, we found that the Winter-Spring rice area increased in Kien Giang ($p < 0.001$), Tra Vinh ($p = 0.0002$), Bac Lieu ($p = 0.0001$), and Soc Trang ($p < 0.001$), but decreased in Ben Tre ($p < 0.001$) and Tien Giang ($p < 0.001$) (Figure 5A). The increasing rate was highest in Kien Giang, at 3,382 ha/yr, followed by Soc Trang, at 1,451 ha/yr. Tien Giang experienced the greatest decreasing rate, at −1,330 ha/yr, while Ben Tre decreased by −595 ha/yr. On the other hand, the Winter-Spring rice yield has statistically increased in five out of seven coastal provinces. For Ben Tre ($p > 0.05$) and Ca Mau, limited data are available for trend testing, but a similar trend can be inferred (Figure 5B). Bac Lieu increased the most in regard to Winter-Spring rice yield (by 19 quintals/ha/yr, $p < 0.001$), followed by Kien Giang (by 12 quintals/ha/yr, $p < 0.001$) and Soc Trang (by 11 quintals/ha/yr, $p < 0.001$). Ben Tre insignificantly increased by 1 quintal/ha/yr ($p > 0.05$).

As seen in Figure 5A, the Winter-Spring rice cropping area between 2000 and 2020 only changed slightly in the seven coastal provinces of the VMD. Kien Giang (green color) had the largest area for rice cropping, increasing steadily from 230,000 ha in 2000 to 260,000 ha in 2003. Afterward, this area decreased to 250,000 ha in the drought years 2004 and 2005, then increased steadily to 300,000 ha in 2016 and slightly declined to 280,000 ha in 2020. The area of the Winter-Spring rice cropping in Soc Trang province (red color) was relatively stable from 2000 to 2014 with approximately 140,000 ha, but then increased significantly in 2015, remaining unchanged until 2020 at 200,000 ha. The rice cropping area in Tien Giang shows a reduction from 100,000 ha in 2000 to 50,000 ha in 2020. The areas of rice practiced in Tra Vinh, Ben Tre, Ca Mau, and Bac Lieu were limited, varying from only 20 ha to 50,000 ha

The Winter-Spring rice cropping area in Ben Tre decreased substantially during the 2016 and 2020 drought years. Although the rice cropping area in Ben Tre is generally smaller compared to other provinces, it experienced a sharp decline in 2016, reducing to just 1/74 of the average area recorded between 2000 and 2015. In 2020, this area further declined, shrinking to only 1/440 of that average. In the other coastal provinces of the VMD, the Winter-Spring rice cropping area did not decrease significantly during the historically severe drought years of 2016 and 2020.

Table 1. Drought years in the VMD using SSI-6

Year	This study SSI-6	This study Severity	Apel et al.[29]	Loc et al.[5]	Nguyen et al.[23]
2000–2001	Normal				
2001–2002	Normal				
2002–2003	Normal				
2003–2004	**Drought**	Moderate	Drought		
2004–2005	**Drought**	Moderate	Drought	Drought	Drought
2005–2006	Normal				
2006–2007	Normal				
2007–2008	Normal				
2008–2009	Normal				
2009–2010	Normal				
2010–2011	**Drought**	Severe	Drought	Drought	Drought
2011–2012	Normal				
2012–2013	**Drought**	Moderate	Drought		
2013–2014	Normal				
2014–2015	Normal				
2015–2016	**Drought**	Severe	Drought	Drought	Drought
2016–2017	Normal				
2017–2018	Normal				
2018–2019	Normal				
2019–2020	**Drought**	Severe		Drought	Drought

The influence of droughts on rice yield is presented in Figure 5B. Rice yield in the seven provinces varies from 40–55 to 60–65 quintals/ha from 2000 to 2020. Within six drought events over the last two decades (Table 1), the droughts in 2015–2016 and 2019–2020 were considered extreme.[5,18] As a result, rice yield was affected in 2016 and 2020, as illustrated in Figure 5B. Particularly, rice yield in Ben Tre and Tra Vinh provinces was impacted seriously in 2016, with a reduction of 23.6 quintals/ha (reduced by 45%) and 14 quintals/ha (reduced by 26%), respectively, in comparison with the mean values in previous years (2000−2015). Similarly, rice yield in 2020 dropped by 14 quintals/ha (reduced by 27%) in Ben Tre and 19 quintals/ha (reduced by 35%) in Tra Vinh compared with the 2000–2015 average.

Figure 6 shows pairwise relationships between maximum salinity concentration and the Winter-Spring rice area and yield in six coastal provinces (Ca Mau was excluded because of a lack of data on rice cultivation in some years). In Ben Tre, an increase in salinity caused a significant reduction in the rice cropping area ($p = 0.04$, Figure 6A) and rice yield ($p = 0.04$, Figure 6G). If salinity concentration increased by 1.0 g/L, the rice area and yield in Ben Tre would decrease by 864 ha and 0.9 quintal/ha, respectively. The Winter-Spring rice crop in Ben Tre was significantly affected by DSI, likely due to the province's long-standing poor soil quality and groundwater conditions. In Tien Giang, salinity was negatively correlated with the rice area (Figure 6E), but positively correlated with rice yield (Figure 6K) indicating that yield increased even as salinity rose ($p = 0.06$) (Figure 6K). This can be explained by the fact that local farmers in Tien Giang, following warnings and guidance from local authorities, have not cultivated the Winter-Spring rice crop during years of high salinity, particularly in drought years. As a result, the areas not affected by salinity have been able to maintain productive rice yields even during the DSI years.

Differently, an increase in salinity tended to increase the rice area ($p = 0.08$, Figure 6B) and yield in Kien Giang ($p = 0.13$, Figure 6H). Farmers in this province may cultivate rice-shrimp farming and salinity-tolerant rice varieties[35] which, therefore, were not affected by salinity intrusion (SI). Additionally, farmers may have gained more valuable experience after the 2015–2016 event, enhancing the resilience of their farming activities to DSI. In Tra Vinh, the rice yield would significantly decrease if salinity increased ($p = 0.04$, Figure 6L), although the rice area did not show a statistical relation with salinity increase ($p > 0.05$, Figure 6F). Similar to Ben Tre, farmers in Tra Vinh would need support from local authorities to mitigate the impacts of salinity on rice cultivation. Regarding the remaining provinces, increases in salinity potentially reduced the rice area but it is not statistically significant.

DISCUSSION

Reflections on the impacts of droughts and salinity intrusion (DSI) on land use change

We identified six drought events which are consistent with the findings of Apel et al. [2020], Loc et al., [2021b], and Nguyen et al. [2023].[5,22,28] However, the 2015−2016 drought caused the strongest impacts on socioeconomics in the VMD[15] because of good early warning in 2020, lessons learned from the 2015−2016 event, and well-prepared strategies.[5,15,28] During 2000−2020, the interval between two droughts ranged from

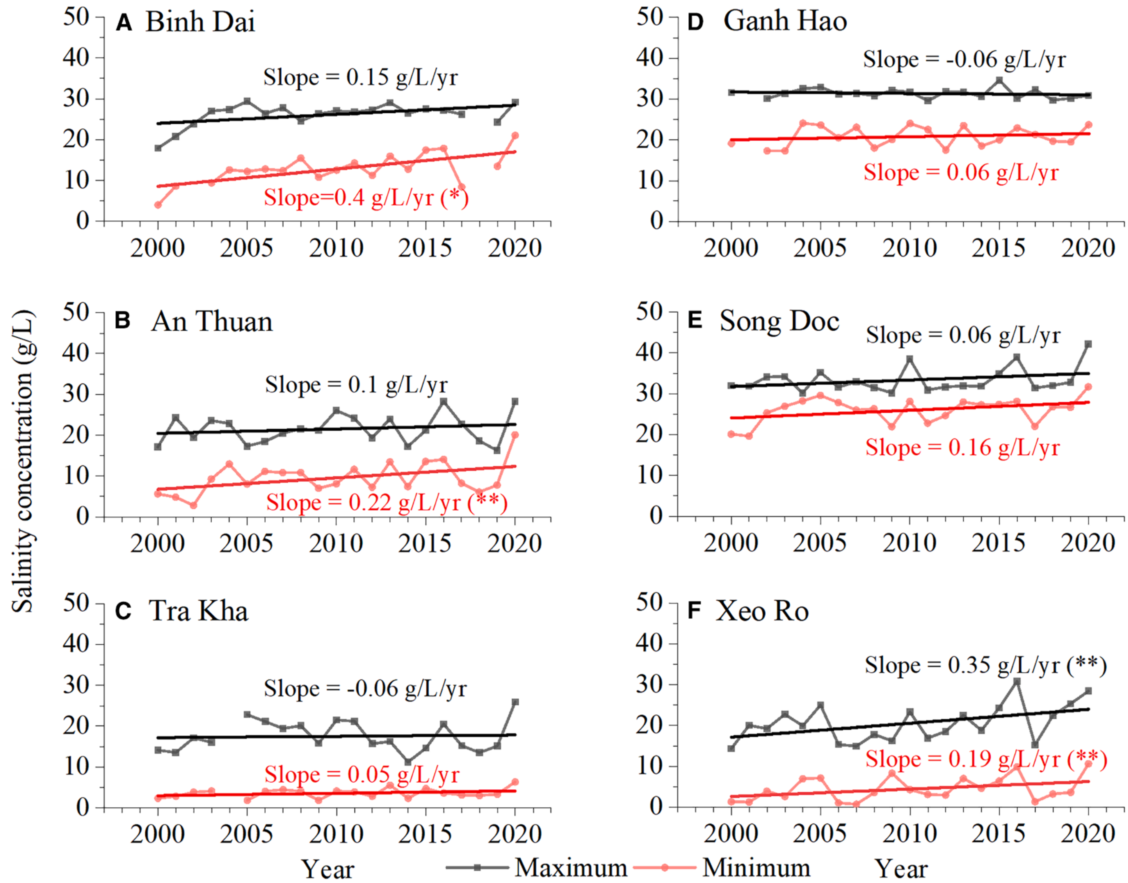

Figure 2. Max–min salinity (Feb–Apr) at six stations, with Sen's slope trends and significance at 95% (*) and 90% (**) confidence levels by Mann–Kendall test

Trends of maximum and minimum salinity concentrations (from February to April) at Binh Dai (A), An Thuan (B), Tra Kha (C), Ganh Hao (D), Song Doc (E), and Xeo Ro (F) Stations from 2000 to 2020. Slope values are from Sen's slope method, while the symbols (*) and (**) mean values are statistically significant at 95% and 90% confidence levels, respectively, by Mann-Kendall tests.

one to five years, with an average of three years. This is alarming because the interval was up to eight years (1992 and 1998) before 2000, as Loc et al. [2021b][5] indicated that there would be more frequent drought events in the upcoming decades. This phenomenon may also be controlled by stronger El-Niño events in recent years. El-Niño Southern Oscillation (ENSO) prediction is highly complex and contains significant uncertainties.[36,37] However, there are hints that anthropogenic forcing might be responsible for changes in ENSO patterns, potentially promoting ENSO variability and extremes.[38] Furthermore, recent studies assume that the influence of ENSO has increased significantly in the post-dam era since 2010 in the VMD,[39] which might contribute to the severity of the most recent drought events. In addition, according to a 40-year analysis from 1977 to 2010, average temperatures in Vietnam, particularly in the southern part, are rising at a rate more than twice the global average. Therefore, evaporation could become a growing concern for freshwater resources, particularly for open systems like rice farming or aquaculture, and especially during the dry season, further contributing to drought scenarios.[40]

Salinity concentrations at almost all analyzed stations show increasing trends, except at Tra Kha and Ganh Hao where no clear trend was observed in either maximum or minimum salinity levels. This may be due to large sluice gates protecting the land behind Ganh Hao, allowing seawater to remain surrounding this station area during the dry season, which may explain why an increasing trend in SI was not observable. This means that sluice gate management complicates spatiotemporal SI patterns. Despite these trends, land use patterns in the coastal area remained relatively stable over the past two decades. This result fits previous studies by Nguyen et al. [2021b][33] and Tran et al. [2017][41] regarding agricultural transformation and aquaculture bonds in the coastal provinces.

Provincial policies on rice and aquaculture developments

This study has uncovered different magnitudes of effects of DSI on rice yields and areas across coastal provinces over the past two decades, with notable peaks observed during the dry seasons of 2005, 2016, and 2020. In practice, provincial governments have implemented various strategies to mitigate the impacts on

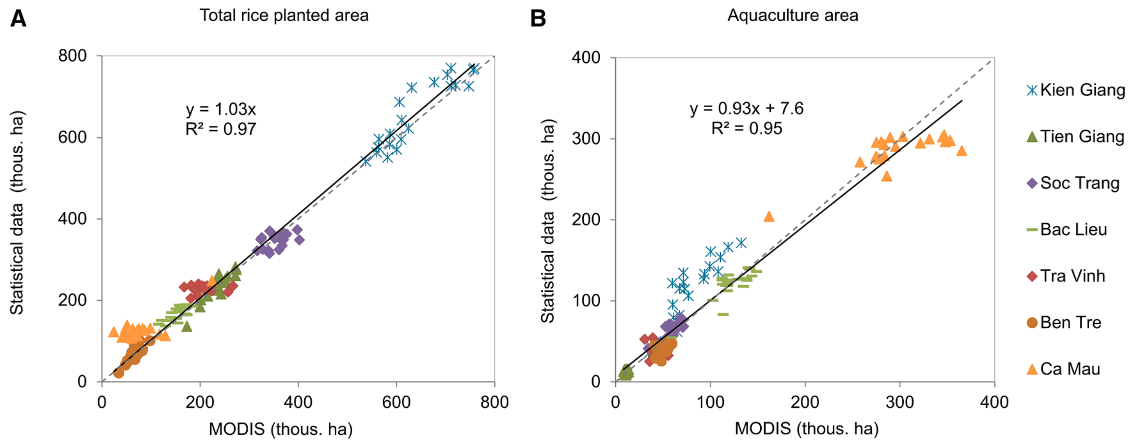

Figure 3. Accuracy of satellite land use data compared with statistical data at the provincial level

rice-based crops and aquaculture developments.[35,42] One key measure involves the advancement of drought and salt-tolerant rice varieties and crop rescheduling following forecasting,[35] as well as the adoption of water-saving irrigation techniques and water management strategies,[43,44] particularly after the severe damage in 2016. By encouraging the cultivation of resilient rice-based varieties that can withstand saline conditions and require less water, these provinces aim to safeguard rice yield and integrated crops against the adverse effects of the DSI. We emphasize the importance of continuous innovation in crop selection and water management, the introduction of stricter regulations managed by local authorities for specific locations with scalable solutions over time, and enhanced stakeholder collaboration through annual evaluation programs—all essential for ensuring the sustainability and resilience of agricultural practices in the face of climate-related challenges.

Additionally, investment in infrastructure for water management, such as the construction of sluice gates and embankments, helps regulate freshwater flow and minimize salinity levels in rice-growing areas, thereby preserving crop yields but only for the locations protected for freshwater cultivation.[32] These infrastructures are, however, costly, especially for developing countries such as Vietnam in terms of investment, operation, and maintenance[45]; hence, nature-based solutions, such as actively promoting freshwater storage reservoirs and rainwater harvesting systems, would be seriously considered to upscale for the long-term sustainability of the delta.[46,47] Diversifying agricultural activities is a key strategy for enhancing resilience against rising DSI, alongside efforts to reduce freshwater demands.[30] The government could introduce pilot projects in salinity-affected areas to demonstrate the success of these diversified models and build farmer confidence. By broadening income sources and reducing dependence on freshwater, such measures help sustain agriculture and aquaculture amid fluctuating salinity levels. Given agriculture and aquaculture's vital role in most coastal communities in the VMD, developing saline-tolerant species and integrating rice farming with aquaculture should be considered as top priorities for adapting to environmental changes projected to worsen due to climate change and human activities in the future.[32,48]

To address freshwater scarcity sustainably, stricter regulation and monitoring of deep groundwater extraction are essential. While large-scale rice farming and aquaculture are prohibited from using groundwater, unregulated private wells persist due to limited farmer awareness, underscoring the need for comprehensive oversight and education programs.[49] The overexploitation might in the long term exacerbate land subsidence and, thus, further promote SI. Overall, strategies, despite directly relying on the effort of farmers, could not be successful without the orientation and leadership of multiple-scale governments, enterprises, and scientists to enhance investment in research and technology transfer initiatives which enable farmers to access knowledge and resources for sustainable aquaculture practices tailored to the challenges posed by the DSI across the coastal provinces and beyond the VMD.

Limitations of the study

It is essential to express certain limitations in this research. First, an indirect relationship between SI and agricultural yield in the VMD was detected as our research primarily focuses on the relationship between rice yield and DSI, which may not fully capture the broader spectrum of agricultural activities affected by these drivers. Second, the complexity of the delta's ecosystem suggests that other variables, such as soil types and water management techniques, could influence the observed outcomes.[50] Third, although satellite sensors are able to provide daily images for processing land use products, the publishing of statistical data is typically delayed until a year later.[51,52] This impedes the examination of the relationship between the effect of salinity and drought on rice yield in real time, e.g., the current drought year observed in 2024 cannot be assessed; hence, future studies could develop predictive models for the DSI index. Fourth, we analyzed long-term SI by examining salinity during the peak months from February to April, which is in the later phases of the Winter-Spring rice crop. This ensures the consistent availability of salinity data at all analyzed stations. However, if comprehensive data become available, analyzing the full spectrum of salinity concentration throughout the Winter-Spring rice season (December to April), along with mapping the spatiotemporal extent of DSI for the entire region, may provide more insightful results.

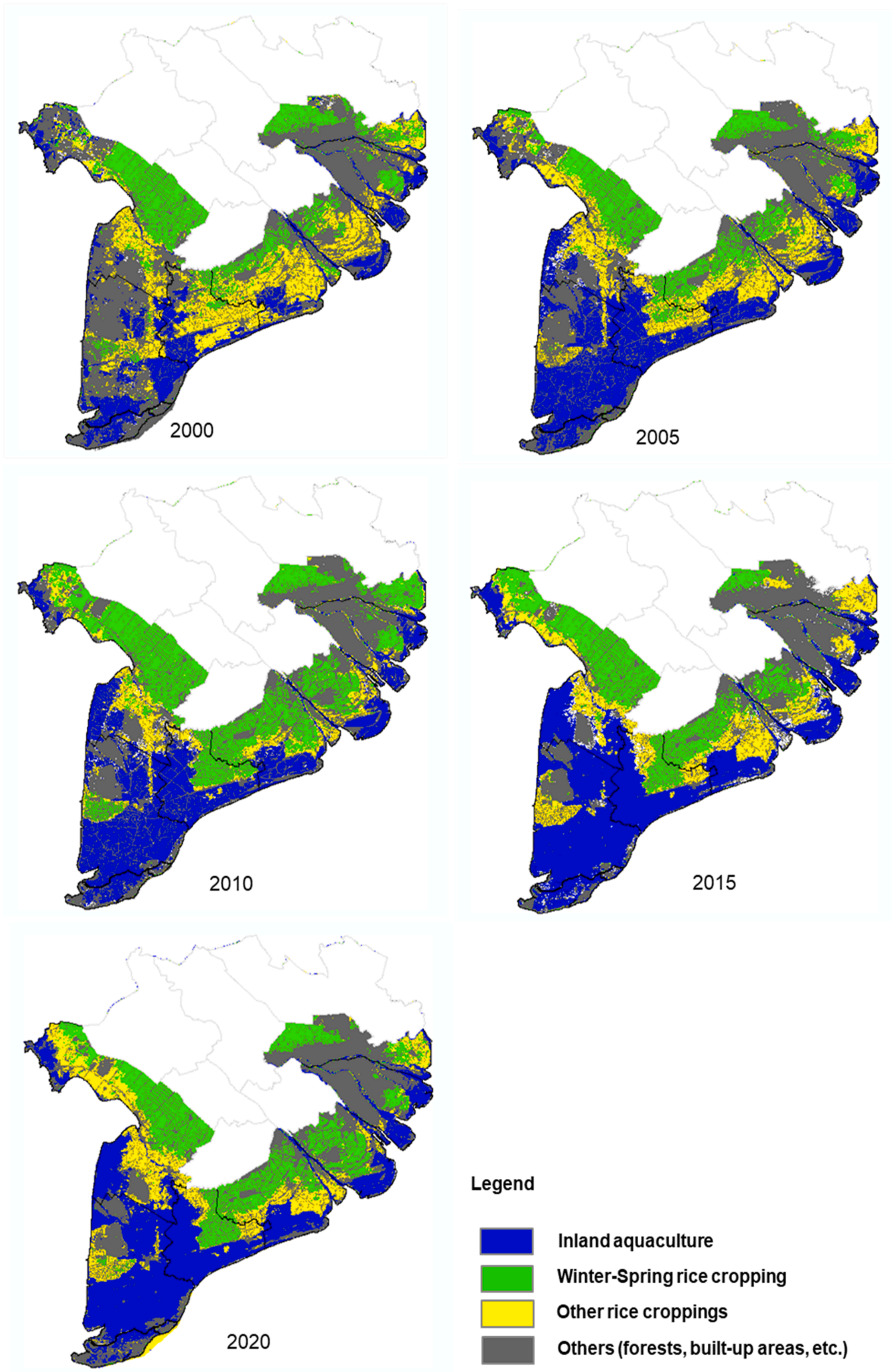

Figure 4. Dynamics of Winter-Spring rice cropping area in the coastal provinces

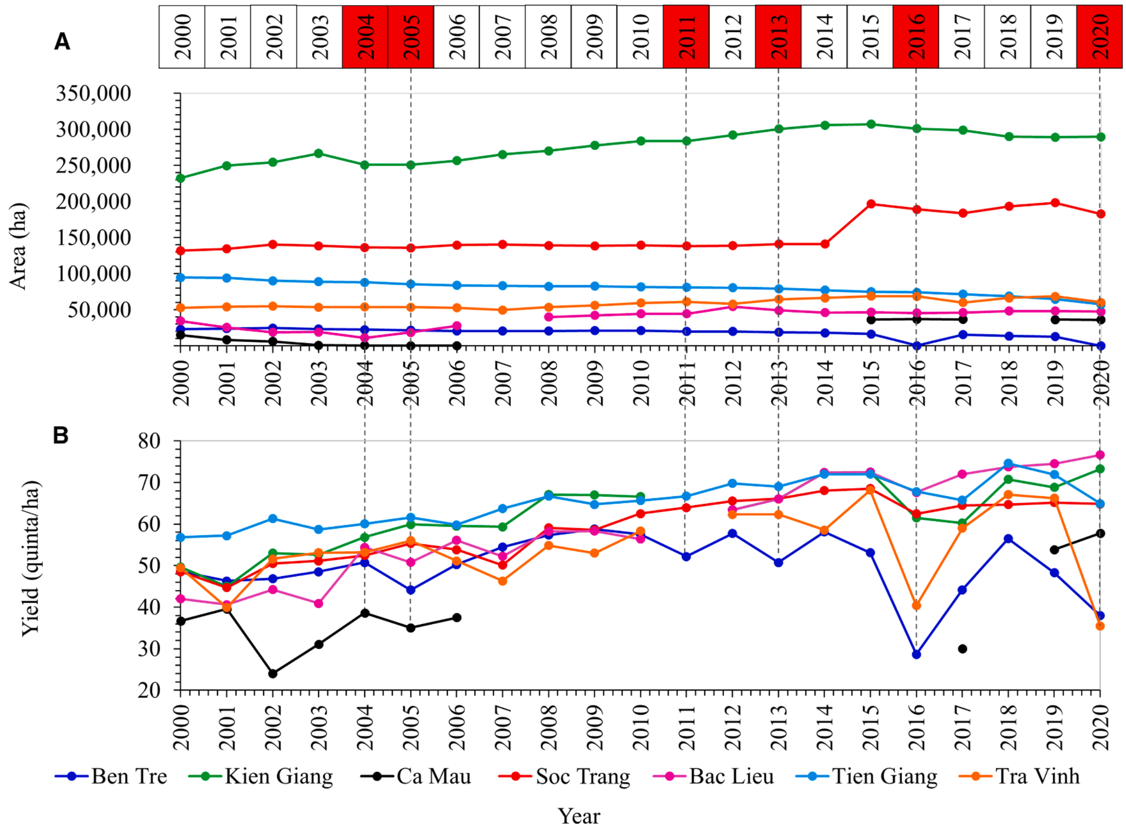

Figure 5. Trends in Winter–Spring rice area and yield from 2000–2020

Dynamics of Winter-Spring rice cropping area (A) and yield (B) from 2000 to 2020 in relation to droughts. The year (*x* axis) represents the later year to reflect the growing season of the Winter-Spring crop; for instance, "2020" stands for 2019–2020.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and information should be directed to Dung Duc Tran, dungtranducvn@yahoo.com.

Materials availability

No new unique materials, data or reagents were generated in this study.

Data and code availability

- Data: the data reported in this paper are available within the main text or supplemental information and will be shared by the lead contact upon reasonable request.
- Code: this paper does not report original code.
- Other items: Any additional information required to reanalyze the data reported in this paper will be shared by the lead contact upon reasonable request.

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AUTHOR CONTRIBUTIONS

D.V.B., D.D.T.: Conceptualization, methodology, data curation, formal analysis, software, visualization, writing – original draft, and writing – review and editing. V.H.T.D., J.B., E.P., H.H.L.: Writing – review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests. Dr. Park is a Guest Editor on the Special Issue titled "Salinization of soils in agriculture: Threats, monitoring, and mitigation" and he was not involved in the peer-review process of this paper.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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  - Drought classification analysis
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  - Land use detection of Winter-Spring cropping area

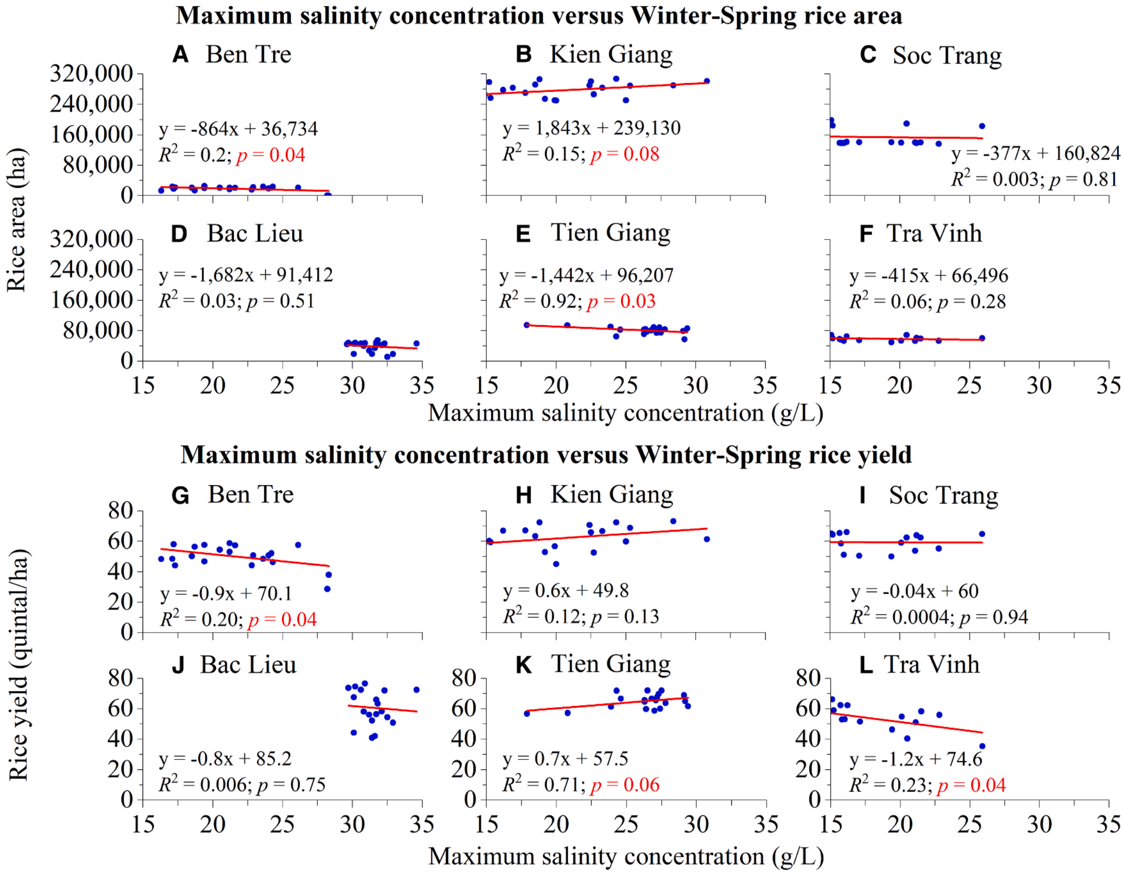

Figure 6. Relationship between station-based maximum salinity concentration and the Winter-Spring rice area and yield in the coastal provinces. The null hypothesis (no trend) is rejected when −1.96 < Z < 1.96 (p < 0.05 at the 5% significance level) and −2.576 < Z < 2.576 (p < 0.01 at the 1% significance level).

- ○ Linking salinity impacts to rice farming alternative and management solutions

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2025.112723.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
ArcGIS Desktop	ESRI	https://desktop.arcgis.com https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources
Python	OSI-approved open source	https://github.com/python

METHOD DETAILS

Study area

The VMD is located at the end of the Mekong River Basin, where the Tien and Hau Rivers flow across the delta plain (Figure S4). The study area (green colour) includes seven coastal provinces of the VMD, i.e., Kien Giang, Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, and Tien Giang. In this region, land use types are mainly rice (accounting for 40%–60%), fish/shrimp farming (10–20 %), and other land use systems (32–42%), see Figures S1–S3. While the upper areas of the VMD are facing challenges due to flooding,[53,54] riverbank erosion,[55,56] and sand mining,[57] the coastal areas are severely impacted by coastal erosion,[58,59] land subsidence due to over-exploitation of groundwater,[60] and especially by salinity intrusion and droughts.[5,61]

Salinity intrusion is an annual event in the coastal provinces of the VMD, lasting about six months from January to June, peaking in February-April, affecting 1.7 million ha.[42] However, it can appear earlier with higher magnitude and longer intrusion length in severe drought years.[15,23] The two extreme droughts in 2016 and 2020 are marked by extensive saltwater intrusion (contour lines in Figure S4) into the inland of the VMD. Although the former was recorded as the most severe drought and SI over the past 90 years, four years later, the latter surpassed the former, with a deeper SI length of approximately 10 km.[15]

Data collection

Discharge and salinity concentration data

Tan Chau (on the Tien River) and Chau Doc (on the Hau River) (Figure S4) are the two gauges that monitor the river discharge at the entrance of the VMD close to the Vietnam-Cambodia border. The flow regimes of these two stations largely reflect hydrological processes in the VMD. The Tien River transports approximately 80% of the total water entering the VMD from the Mekong River.[38] Therefore, while drought events cover larger areas, the drought conditions at the Tan Chau station provide a reliable representation of the overall drought status in the VMD. The daily discharge dataset at Tan Chau was collected from 1980 to 2020 from the Vietnamese National Hydro-meteorological Data Centre (VNHDC) to determine the drought status. Daily discharge values stretch continuously from 1996 to 2020 with some missing values from 1980 to 1995. The missing discharges were reconstructed using distinct discharge-water level rating curves for the rising (April to September) and falling (October to March) phases fitted by polynomial regression with the least squares optimization scheme. Details of data treatment and processing were available in Binh et al. [2020, 2021].[23,26]

Daily maximum salinity concentrations at six monitoring stations, namely Binh Dai, An Thuan, Tra Kha, Ganh Hao, Song Doc, and Xeo Ro, from February to April (the peaking DSI period) during 2000–2020 in both the Gulf of Thailand and the East Vietnam Sea (Figure S4) are incorporated in the analysis. Salinity concentrations were measured every two hours per day, from which the daily maximum and minimum values were obtained. We pre-processed the collected raw data for which outliers were checked and removed using the *Statsmodels* library in Python. Salinity concentration data were provided by the VNHDC, the Southern Regional Hydrometeorological Center, and the Japan-ASEAN Science, Technology and Innovation Platform (JASTIP) project. These three months of salinity concentrations are assessed because they are the main factor affecting the productivity of the Winter-Spring rice crop in the VMD's coastal provinces (from December to April) - the most important crop in a year. Moreover, the February-April salinity data are consistently available during 2000–2020. The stations were selected because they met the following three criteria. First, they are evenly distributed in the study area. Second, the distance from the selected stations to the river mouths is relatively similar, ranging from four to seven km, to facilitate the comparison. Third, they have long-term data from 2000 to 2020, meeting the requirement for statistical tests and being consistent with other datasets used. Therefore, the chosen monitoring locations can be considered representative of the seven coastal provinces of the VMD.

Satellite land use maps

Land use/land cover maps in the VMD from satellite products were collected from 2000 to 2020.[51,62] The MODIS land use maps were processed for land use detection by applying three important indices, i.e., Enhanced Vegetation Index (EVI), Land Surface Water

Index (LSWI), and Difference Value between EVI and LSWI (DVEL). Within the scope of this study, we only presented the EVI index to show the characteristics of rice and aquacultures based on MODIS time-series images, the EVI index is expressed as:

$$EVI = 2.5\frac{NIR - RED}{NIR+6RED - 7.5BLUE+1} \quad \text{(Equation 1)}$$

where RED is the red band (sur_refl_b01), NIR is the near-infrared band (sur_refl_b02), SIWR is the short-wave infrared band (sur_refl_b06), and BLUE is the blue band (sur_refl_b03) of the MODIS surface reflectance.[52,63]

Land use maps are used to examine the spatiotemporal dynamics of cropping patterns and areas in the coastal provinces within the last two decades (Figures S1 and S2 in the Supplementary). Afterward, we focused on the Winter-Spring rice crop, normally cultivated from the beginning of December to the end of April.

Statistical data

Statistical data on rice crop and aquaculture areas were collected online from the General Statistical Office for the period of 2000−2020 to evaluate the accuracy of land use data from remote sensing products. Besides, the data on rice yield of the Winter-Spring rice crop were additionally collected from statistical yearbooks in seven coastal provinces, i.e., Kien Giang, Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, and Tien Giang to evaluate the rice yields and rice area within the dry seasons.

QUANTIFICATION AND STATISTICAL ANALYSIS

Figure S5 shows the flowchart of the research methodology. First, we collected, processed, and treated the data for the daily discharge, daily salinity concentrations, monthly land use maps from the MODIS satellite, and the Winter-Spring rice crop area and yield. Second, we identified and classified hydrological drought using the monthly-averaged discharge at the Tan Chau station. Third, we analyzed long-term trends of the maximum salinity concentration at six salinity stations in the studied coastal provinces. Fourth, we analyzed long-term spatiotemporal changes in the annual land use during the Winter-Spring crop in the dry season extracted from MODIS satellite imagery. Fifth, we linked extreme salinity intrusion events with hydrological droughts. Sixth, we assessed the effect of DSI, especially in extreme years, on land use changes in terms of the extent and yield of rice. Finally, our results were discussed in the context of DSI mitigation measures, in particular after the 2016 extreme event, and recommend suitable land uses along with corresponding management solutions.

Drought classification analysis

There are typically four categories of drought, including meteorological, hydrological, agricultural, and socioeconomic droughts.[3] Land use management in the VMD is directly linked with hydrological drought because agriculture in the delta is irrigated using water directly from the Mekong River system. The standardized streamflow index (SSI) was used to determine whether a year can be classified as a drought year. SSI was calculated using monthly discharge data at Tan Chau, which was averaged from the daily discharge. Although drought was assessed from 2000 to 2020, we calculated SSI from 1980 to 2020 so that there is long-term data for statistical analysis. Past drought events identified by SSI were cross-validated with the literature and recorded information from the statistical yearbook.

SSI was calculated from the monthly discharge data using Log-logistic distribution.[64] SSI, first introduced by Modarres [2007],[65] is principally similar to the standardized precipitation index (SPI). SSI calculation was performed using the following equation:

$$SSI = \Phi - 1(F(T(Q_i))) \quad \text{(Equation 2)}$$

where: Q_i is the observed monthly discharge; $T(Q_i)$ is the transformed discharge data (using a logarithmic transformation to normalize the distribution); and $F(T(Q_i))$ is the cumulative distribution function (CDF) of the transformed streamflow data. $\Phi-1$ is the inverse standard normal distribution function, which converts the CDF value into a standardized SSI.

The drought status was evaluated using SSI-6 (6-month average) following the finding from Nguyen et al. [2023].[22] We first categorized the monthly SSI-6 into normal (SSI-6 > −1.0) or drought (SSI-6 ≤ −1.0), and then classified the severity of the drought into moderate (−1.49 < SSI-6 < −1.0), severe (−1.99 < SSI-6 < −1.5), and extreme (SSI-6 < −2.0) by adopting the drought classification of Modarres [2007].[65] The drought years detected by the SSI-6 were cross-checked with the literature[5,22,28]

Salinity intrusion analysis

Daily maximum salinity concentrations from February to April were processed to derive annual maximum, mean, and minimum salinity concentrations. Then, the trend and rate of change were estimated using the Mann-Kendall test[66,67] and the slope method of Sen,[68] respectively. These methods were previously used to assess long-term changes in flow regimes in the Mekong River.[23]

In the Mann-Kendall test, statistic S for a given time series $\{x_t: t= 1, 2, \ldots, n\}$ is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad \text{(Equation 3)}$$

$$sgn(x_j - x_i) = \begin{cases} +1 & \text{if } x_j > x_i \\ 0 & \text{if } x_j = x_i \\ -1 & \text{if } x_j < x_i \end{cases} \quad \text{(Equation 4)}$$

The variance of S is computed as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i+5)}{18} \quad \text{(Equation 5)}$$

When the sample size $n > 10$, the standard normal test statistic Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \quad \text{(Equation 6)}$$

where x_i and x_j are the data values in time series i and j ($j > i$), respectively; n is the number of data (observations); $sgn(x_j - x_i)$ is the sign function; $Var(S)$ is the variance of statistic S; m is the number of tie groups; t_i is the number of ties of extent i. Positive Z indicates an increasing trend, while negative Z indicates a decreasing trend. The null hypothesis (no trend) is rejected when $-1.96 < Z < 1.96$ ($p < 0.05$ at the 5% significance level) and $-2.576 < Z < 2.576$ ($p < 0.01$ at the 1% significance level).

The rate of change is estimated using the slope method of Sen using a non-parametric procedure. The estimates of the slope of N pairs of data are calculated as:

$$Q_i = \left(\frac{x_j - x_k}{j - k}\right) \text{ for } i = 1, ..., N \quad \text{(Equation 7)}$$

where x_j and x_k are date values at times j and k ($j > k$). The N values of Q_i are ranked from the smallest to the largest and the median of the slope, that is the Sen's slope estimator, is estimated as:

$$Q_{med} = \begin{cases} Q_{[(N+1)/2]} & \text{if } N \text{ is odd} \\ \frac{Q_{[N/2]} + Q_{[(N+2)/2]}}{2} & \text{if } N \text{ is even} \end{cases} \quad \text{(Equation 8)}$$

The sign of Q_{med} reflects the time series trend, and its values reveal the slope of the trend.

Land use detection of Winter-Spring cropping area

In this research, we analyzed the land use patterns for the coastal areas in the dry season from December to the end of April to detect the Winter-Spring rice cropping areas to investigate the effect of drought and salinity on rice yield during the dry season. The land use maps were derived from MODIS satellite products based on the algorithms by Sakamoto et al. [2009].[52] Figure S6 illustrates an example of the time series of *EVI* variations for typical land use types in three years of 2018–2020, i.e., the rice cropping area in Kien Giang Province (a), the shrimp farming in Ca Mau Province (b), and other types of land use patterns in Tien Giang Province (c). It can be seen that the *EVI* time series in Figure S6A varies significantly around 0.4 (from −0.15 to 0.8) with clear peaks. Here, the Winter-Spring cropping was selected as the first peak in a year (red boxes). The *EVI* time series in Figure S6B shows a minor change from 0 to 0.2 for the shrimp farming area, while Figure S6C displays a variation of the *EVI* time series from 0.4 to 0.7 without any trend at the other land use pattern.

Linking salinity impacts to rice farming alternative and management solutions

The Winter-Spring rice area and yield were pairwise correlated with maximum salinity concentration to understand how salinity influences rice farming. Using simple linear regression, we identified the rate of impact through the slope of the regression line. By comparing spatial similarities and differences among the analyzed provinces, we evaluated the suitability of existing land use patterns and current rice-farming policies in each region. We then proposed adaptive farming alternatives and policy implications on management solutions to ensure the sustainability of rice-based agriculture.