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Long-term hydrological alterations and the agricultural landscapes in the Mekong Delta: Insights from remote sensing and national statistics

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ABSTRACT

The Vietnamese Mekong Delta (VMD) is one of the most important food baskets in Southeast Asia, contributing to more than half of the country's food production capacity and the majority of its rice exports. Constantly threatened by a multitude of environmental pressures, including climate change-induced sea-level rise, delta-wide land subsidence, sedimentation reduction and, more recently, riverbed mining, steps towards the sustainable development of the VMD is becoming increasingly vulnerable. In this paper, we examine the effect of hydrological alterations of agricultural landscape in the VMD, more specifically, the temporal trends of triple rice crop in the Long Xuyen Quadrangle (LXQ). Landsat satellite data was used to map active rice paddy sites across the three major rice cropping seasons and identify the temporal distribution of triple rice crop areas over the last 24 years (1995–2019). Results were interpreted alongside official statistical data on agriculture from Vietnam and corroborated with ground truth data points from the study site. Our results reveal a notable fall in Landsat-detected triple rice crop area between 2016 and 2019, corroborating with both literature and agricultural data indicating an increase in aquaculture areas. Here, we take note for the first time the underlying links between riverbed mining and agricultural shifts in the VMD, which could highlight important policy and management implications for the local government in order to ensure environmental sustainability and food security. We argue that a tighter and more effective regulation of riverbed mining practices in the region is both integral and necessary for the agricultural sustainability of the VMD.

1. Introduction

As the world's third-largest delta, the Vietnamese Mekong Delta (VMD) is one of the most productive agricultural areas, contributing to more than half of the country's food production and over 90% of its rice exports (Dao et al., 2020). This is made possible with the occurrence of seasonal and sediment-replenishing floods, which are essential to sustaining the livelihoods of millions of delta residents, and ensuring both national and regional food security. However, the vulnerability of the VMD has become more prevalent in the last decade due to its ever-increasing susceptibility to climate change-induced sea-level rise (Wasserman et al., 2004; Park et al., 2020, 2021; Loc et al., 2021a, 2021b). Moreover, ongoing anthropogenic interventions, including hydropower development, dyke constructions and unsustainable groundwater extraction further compounds this issue, and have been noted to exacerbate sea-level rise in the region (Ericson et al., 2006). For instance, human activities such as upstream dam constructions and operations, and the development of dyke infrastructure have adversely affected transboundary downstream flow regimes and flood dynamics (Räsänen et al., 2017; Pokhrel et al., 2018), sediment loads (Van Binh et al., 2020), as well as introduced new flood risks (Tran et al., 2018). Another prominent issue that severely amplifies the threat of sea-level rise and delta loss is, a major cause of worsening land subsidence (Erban et al., 2014; Minderhoud et al., 2017; Loc et al., 2017, 2018).

More recently, the issue of riverbed mining and transport of river sand in the VMD has been gaining considerable attention among scientific literature. River sand aggregates are critical materials for the development of fast-growing economies in Southeast Asia. Large-scale river sand extraction operations are being conducted to fulfil ever-growing demands from construction industries and land reclamation projects both domestically and internationally. However, years of unregulated sand mining have led to the direct loss of bed material and

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bank erosions, adversely affecting the geomorphology and sediment loads across the entire VMD riverine systems (Brunier et al., 2014; Eslami et al., 2019; Jordan et al., 2019; Van Binh et al., 2020). Another important and often overlooked consequence is delta-wide hydrological alterations, for example, significant decreases in seasonal flood frequencies (Park et al., 2020). Despite growing discourse surrounding the environmental consequences of riverbed mining in the VMD, the scopes of these studies are largely limited to the morphological and fluvial impacts of these activities. Other critical issues concerning the diversification of framing practices (e.g., the rise of aquaculture), as well as the implications on riparian livelihoods resulting from environmental shifts in the VMD, however, have not been sufficiently studied. For instance, pivotal rice crops that depend on the annual flood pulse to bring beneficial sediments that support their cultivation are seeing their areas constantly decrease in recent years. These knowledge gaps are necessary to address as the VMD is considered an important regional food basket and its sustainability is of strategic importance.

While changes to cropping patterns are also driven by factors such as regional or national development vision and changing prices of agricultural commodities, this paper suggests that more study is needed to understand the impacts of riverbed incision on hydrological regimes and agricultural land use in the VMD as well. Thus, this paper seeks to present a novel examination of recent shifts in agriculture – i.e., the annual staple rice crop, maize, sweet potatoes, cassava, and aquaculture – across the VMD as a consequence of lowered flooding frequencies and riverbed mining in the An Giang Province (AGP) between 1995 and 2019. Situated within the Long Xuyen Quadrangle (LXQ), which experiences one of the highest sand extraction rates in the country (Jordan et al., 2019; Bravard et al., 2013), the AGP depends heavily on freshwater and mineral-rich sediments supplied by the Bassac and Mekong Rivers during seasonal flooding for crop cultivation (mainly rice). With increasing alterations to annual flood regimes in the AGP as a result of riverbed mining (see Park et al. (2020) and Loc et al., (2021a, 2021b)), questions pertaining to the impacts on agriculture and the overall sustainability of integral agro-ecological systems like the VMD need to be addressed. Using agricultural data from the General Statistics Office of Vietnam (GSO) as well as remote sensing data with satellite imagery, we attempt to monitor changes in the area of rice paddy (triple rice crop) and other non-rice crops within AGP across a 24-year time frame.

This assessment of agricultural shifts in the VMD related to riverbed mining through the study of AGP seeks to expand scientific knowledge of the indirect environmental consequence of riverbed mining within existing literature covering the region. Moreover, as VMD is crucial to feeding millions of people both nationally and regionally, findings on agricultural dynamics in the area will benefit countries looking to safeguard food security, and the socio-economic conditions of their populations. Finally, the results of this research also pose important policy and management implications for local governments to better regulate regional riverbed mining practices to ensure environmental sustainability and food security for the locals.

2. Data and methods

2.1. Study area

The study site, An Giang Province (AGP), with a total area of 3406 square kilometers, forms part of the larger Long Xuyen Quadrangle (LXQ), along with the neighbouring provinces of Kien Giang and Can Tho (see Fig. 1). As one of the most productive regions for rice and aquaculture cultivation of the VMD, the area is heavily influenced by floods of the Mekong River that inundate large areas of the LXQ (Balica et al., 2014). While the seasonal floodwaters benefit the region by depositing sediments, supplying wild fish and shrimps as a source of food and clearing agrochemical pollutants, they are also responsible for the physical damages of irrigation infrastructures, agriculture harvests and threaten the safety of local communities (Loc et al., 2021b; Tuan et al., 2007; Tran et al., 2021).

Table 1
Major rice cropping season in An Giang, Vietnam (Phan et al., 2018).

Rice crop season	Sowing/ Transplanting	Harvest
Winter-Spring	November-December	March–April
Summer-Autumn	April-May	July–August
Autumn-Winter	July-September	October–December

Since the late 1990s, efforts to divert part of overland flood flow from Cambodia towards the Gulf of Thailand have manifested in the construction of flood control infrastructure such as dykes, sluice gates and pumps within the LXQ (Tran and Weger, 2018). In the case of VMD, these dyke systems include semi and full dykes. While the semi dykes are only high enough to keep floodwater out from the first flood peak until mid-August, the full dykes can protect the cropland entirely from inundation (Triet et al., 2020). The type of dykes also strongly corresponds to different rice cultivation practices. Accounting for 13% of LXQ within AGP, full-dyke zones enable triple rice cultivation, where floodwater is kept out entirely and water is supplied to rice crops only via irrigation; the remaining 38% of LXQ comprises semi-dyke zones for double rice cultivation, receiving pumped water only during initial cultivation of first two rice crops and becoming inundated during the subsequent wet season (Park et al., 2020). Crop cultivation is, therefore, highly dependent on floodplain processes in the VMD, and shaped by the complex hydrodynamic interaction of fluvial dynamics and operation of delta flood infrastructures (Triet et al., 2020). While the long-term economic costs and impacts of persistent high dyke construction on agriculture and aquaculture area have been studied (Tran et al., 2019), the impacts of changing fluvial dynamics, as a result of riverbed mining, have not been sufficiently underscored.

2.2. Satellite data processing

As shown in Fig. 2, Landsat observations were used to map active rice paddy areas and subsequently triple rice crop areas in the AGP study site over the investigated time frame (1995–2019). Acquired from the U.S. Geological Survey (USGS) ([dataset] U.S. Geological Survey, Earth Explorer, 2020), satellite images from Landsat 5 Thematic Mapper (TM), 7 Enhanced Thematic Mapper+ (ETM+) and 8 Operational Land Imager (Oli), as part of the Landsat Collection 1 Level-2 data products, were downloaded. The satellites, capturing optical images at 30 m resolution every 16 days, differ mainly in their operation periods and surface reflectance processing algorithms. A total of 54 satellite images, with a cloud cover of under 30%, were chosen from specific harvest periods of the three major rice cropping seasons, i.e., Spring, Autumn and Winter. Table 1 shows the dates of the major cropping seasons in AGP, while Table S.1 details the collection of satellite images downloaded for processing. Noting that cultivation practices and crop calendar are not entirely homogenous in the region (Phan et al., 2018) due to the number of smaller farms, the dates of the images may differ slightly from the original harvest periods, as shown in Table 1. However, in general, the choice of images was unbiased, considering how they were temporally distributed over different cropping seasons across the investigated time frame. Vegetated areas from rice cropping seasons of Spring, Autumn and Winter were extracted through the Normalized Difference Vegetation Index (NDVI) (Guan et al., 2016), calculated as a ratio between the red (R) and near-infrared (NIR) values (individually extracted spectral bands):

$$NDVI = \frac{R_{NIR} - R_{Red}}{R_{Red} + R_{NIR}} \quad (1)$$

where R_{NIR} and R_{Red} indicate the reflectance of the Near Infrared (NIR) and Red bands, represented by Landsat (4–7)'s bands 4 and 3 and Landsat 8's bands 5 and 4, respectively.

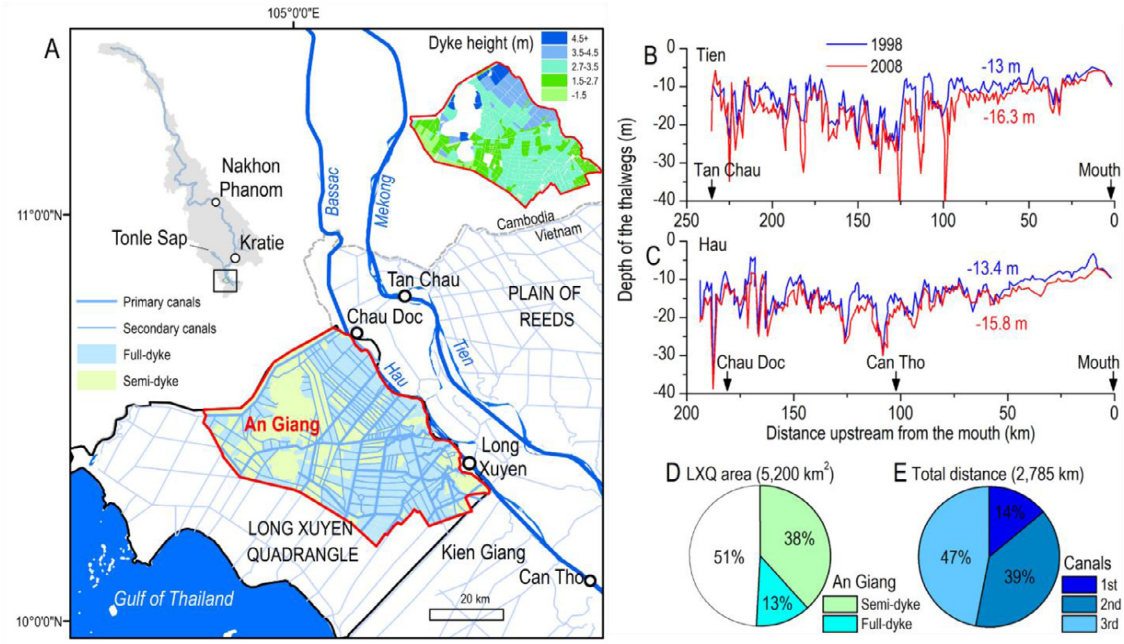

Fig. 1. A: Map of study site in An Giang Province (AGP in red outline) situated within the larger Long Xuyen Quadrangle (LXQ) floodplain, along the Lower Mekong River in Vietnam. The distribution of dykes and irrigation networks are depicted. B and C: Thalweg along the Tien (B) and Hau (C) Rivers between 1998 and 2008 (Brunier et al., 2014). D: Area distribution of full and semi dyke systems in LXQ. E: Distribution of irrigation canals (1st: Primary, 2nd: Secondary, 3rd: Tertiary) within AGP, expressed in the distance (Park et al., 2020).

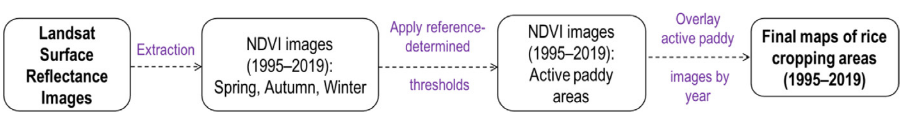

Fig. 2. Flowchart depicting the sequence of steps to acquire the final distribution of rice cropping areas from Landsat satellite data.

To establish and apply standard thresholds for the extraction of active rice paddy areas for each season, the 2016 NDVI image was picked to be a reference to be compared with the corresponding 2016 high-resolution annual land-use and landcover map (LULC) of Vietnam by Japan Aerospace Exploration Agency (JAXA). Produced using multi-temporal Phased-Array L-band Synthetic Aperture Radar-2 (PALSAR-2/ScanSAR), multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS) / Normalized Difference Vegetation Index (NDVI) and Shuttle Radar Topography Mission (SRTM) images, assessments of JAXA's annual LULC maps from 2015–2018 reveal an overall accuracy of 80% ([dataset] Advanced Land Observing Satellite, 2020). JAXA's 2016 LULC map of Vietnam, An Giang, was resampled from its original 250 m resolution to 30 m resolution to match that of the processed NDVI images for each season. Based on the LULC classification: water, built-up (areas), forest, rice paddy, orchards, barren (areas), and other crops; classes of rice paddy areas and other crops were distinguished and isolated from other forms of vegetation like forests (not relevant to the study). The attribute tables of the resulting raster layers were exported into Microsoft Excel, where the distribution of NDVI values of all individual pixels was graphed (Fig. 3). Within the graph, multiple peaks at varying NDVI values were identified as other crop groups (i.e., orchards, other crops) while the most prominent peaks (with the highest frequency) were identified as the average NDVI value of the rice paddy crop. Suitable thresholds for each season were determined manually via trial and error, noting that crop growth during varying seasons may have a different extent of surface reflectance (and hence, different NDVI range). For both Spring and Autumn rice paddy, the optimum threshold range was calculated using mean ± SD, unlike for Winter rice paddy, using mean ± *2*(SD). These thresholds were then applied to all NDVI images per season across all study years, producing a set of 18 images differentiating the active rice paddy areas in each cropping season per year. To determine double and triple rice crop areas, these seasonal maps were overlaid by adding the individual raster layers together. All data processing was done via the software ArcMap.

In addition to satellite data processing methods, relevant agricultural statistics were compiled from the GSO to assess agricultural land use changes involving other non-rice annual crops such as maize and sweet potatoes, as well as aquaculture.

3. Results and discussion

3.1. Recent decrease in triple rice crop area and winter crops

Having overlaid the raster layers of active rice paddy areas from across the three cropping seasons annually, the resultant map (Fig. 5A) exhibits various spatial intersections between single, double and triple rice crop areas within the AGP study site. In general, the results point to a visible decrease in triple rice crop area between 2016 and 2019. Since 2000, the double-crop area has also reduced. While there has not been much conclusive trend in terms of the triple rice area change from the period between 1995 and 2005, the maps indicate the presence of triple-cropping, as indicated by the dark green area, since 1995. During this period, the majority of the land was double-cropped. With the region-wide intensification of rice agriculture following Vietnam's Doi Moi (Restoration) national policy reforms in the late 1990s, the state has improved dyke systems to protect the rice production areas from seasonal floods, thus facilitating more rice crops in a one year cycle. Also, people's lives and properties within AGP have been under the protection of these dyke systems against the annual floods throughout the years. Yet, despite the expansion of dyke systems to facilitate triple cropping, the observed triple rice crop area in AGP during the early 2000s is rather sparse.

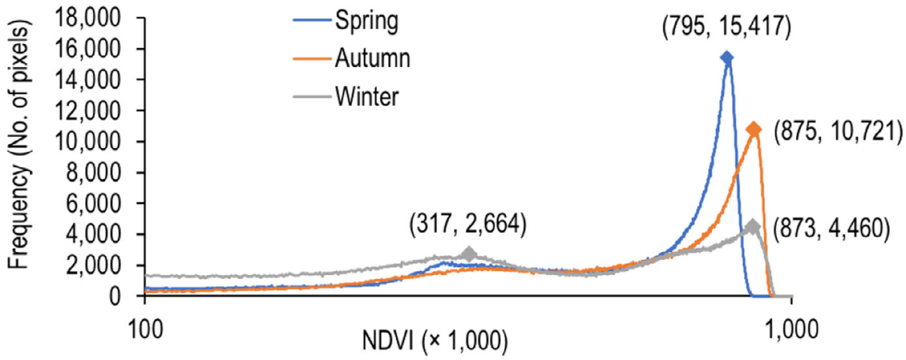

Fig. 3. Graph of pixels' NDVI value distribution in 2016 NDVI maps for determining an appropriate NDVI threshold to facilitate the extraction of active rice paddy areas.

Factors that could have led to poor triple-crop detection from the Landsat observations are multifold, including both structural and circumstantial reasons. First, the uptake of the new high dykes to facilitate triple cropping began in 1996 and dyke construction was only completed in 2014, when a total of 404 high dike compartments covered 1700 km^2 across An Giang Province, approximately 60% of agricultural land (An Giang Department of Agriculture and Rural Development, 2016). Dyke construction in AGP during the 2000s was reported to be lacking in coordination and poorly maintained (Tran and Weger, 2018), resulting in a performance deficit compared to their expectations. Furthermore, most of the dykes were only utilized at a small local scale, while their operations were originally designed to be synchronized at the provincial scale. This poses limitations to their operations, impeding the overall effectiveness of its functions (Southern Institute of Water Resources Research (SIWRR), 2012). Since the high dykes facilitate triple rice cropping, the functionality of the dykes and the flood control extent might have had certain implications on rice agriculture and even possibly affecting the extent of the triple rice crop area detected by Landsat. Second, as noted by Phan et al. (2018), cultivation practices and crop calendars across smaller-scale farms tend to differ and are not entirely homogeneous, even within the same province. Although the selection of image scenes was chosen based on the dates of past rice cropping seasons (between sowing/transplanting and harvest dates), such variability can lead to some crop areas being left out inevitably. Finally, pre-harvest losses attributed to pest outbreaks, such as the brown planthopper, in this case, can jeopardize rice production and account for triple rice loss. Not only do brown planthoppers cause extensive damage to rice plants by feeding on them, they are also vectors of rice viruses that stunt rice growth (Cabauatan et al., 2009). An exponential increase in these pests typically results in tremendous losses of rice crops. This is common across rice-producing regions in Vietnam and Southeast Asia. Farmers are sometimes forced to forgo certain harvests intentionally due to outbreaks of pest infestations. In fact, Du et al. (2007) note that between 2005 and 2006, approximately 485 km^2 of rice production area in southern Vietnam were forgone due to the viral diseases that had been spread by brown planthopper.

For the subsequent years of the analysis, from 2009 to 2019, triple-crop area is shown more visibly, likely due to the complete construction of the dyke network in AGP. In order to verify the accuracy of remote sensing analysis results of the rice paddy area, we conducted field observations at 40 locations with the help of students from An Giang University. Out of the 40 rice points surveyed in 2020, more than 90% (37 points) of them were located at double and triple-crop areas as mapped in the most recent image from 2019 (in Fig. 5A), suggesting that classification results mostly cohere to the observed ground truth. Our results show that the area of the triple-crop has shown signs of reduction in recent years between the 2016 and 2019 period, where triple-crop area was reduced from 601 to 384 km^2. With reference to the data on planted rice areas in the AGP, the ratio of planted area of winter to autumn rice crop has seen a drastic plunge (Fig. 4A), with a sizable fall in winter crop area of 240 km^2 between 1995 and 2019. Given that dyke infrastructure has been improving and, more specifically, with the recent completion of a high dyke network to facilitate more triple cropping, the observed decline in the triple-crop is worth interrogating.

3.2. Lowered flooding frequencies in relation to riverbed mining

Intensive rice cultivation, involving double and triple cropping of high-yielding rice varieties (HYVs), necessitates not only a substantial use of agrochemicals but also a considerable amount of freshwater for irrigation (Berg, 2002). Analyses by Park et al. (2020) reveal both a dramatic lowering of flood frequencies and river water levels around Long Xuyen Quadrangle (LXQ) as well as its hydrological connectivity between 2005 and 2015 – a result of the intensified riverbed-mining activities in the early 2000s. Not only did the annual flood frequency of the AGP decrease by 7.8% between investigated time periods of 1995-2005 to 2005-2015, but the annual peak water level of 5 m at the Chau Doc station in AGP in 2000 has also decreased to about 3.5 m in 2010, with the 1.5 m drop in water level being corroborated by a decrease of 1.3 m in riverbed between 1998 and 2008 (Brunier et al., 2014). With an alarming riverbed sand extraction rate that has increased by almost ten times in the past 20 years (Jordan et al., 2019), there is undoubtedly growing pressure on the water resources available for irrigation, as well as the costs of supplying freshwater for agricultural purposes (Park et al., 2020).

In light of the changes in seasonal flooding patterns in AGP over the last 20 years, where severe reduction of flood levels during the wet season (June–November) was reported by Park et al. (2020), it is inferable that the decreased flooding, as a result of riverbed mining, may have led to a reduced triple rice area due to insubstantial flood levels to sustain the Winter crop (harvested during the end of wet season). The seasonal flood regimes altered by excessive riverbed mining activities have led to a reduction in water and sediment volumes, both vital to the crops of the AGP and the larger VMD alike. Not only do floodwaters wash out residual pesticides and fertilizers applied during intensive agriculture processes, but they also replenish the cropland for the subsequent cropping season by depositing nutrient-rich silt and fertile sediments from the upstream. Hung et al. (2014) note that such sediment and associated nutrient input from the annual floods have multiple critical impacts on agricultural productivity. More specifically, sediment deposition in the VMD contributes potassium, a predominant fertilizer used in rice agriculture (Nguyen et al., 2006). In fact, deposited nutrients like nitrogen, phosphorus and potassium (N, P, K) supply more than half of the mineral fertilizers needed for a season of rice agriculture (Manh et al., 2014). Given that flooding frequencies are on a decline, soil quality and fertility will decrease accordingly, reducing "*the frequency and duration at which farmlands benefit from these natural soil quality enhancement processes*" (Park et al., 2020, Hung et al., 2014). Beyond the challenge of decreased sedimentation, the reduced water levels also make it difficult for farmers to maintain the third rice crop, given that rice is inherently among some of the most water-intensive crops. As most farmers depend on the river water as an irrigation source, the lowered flood frequencies

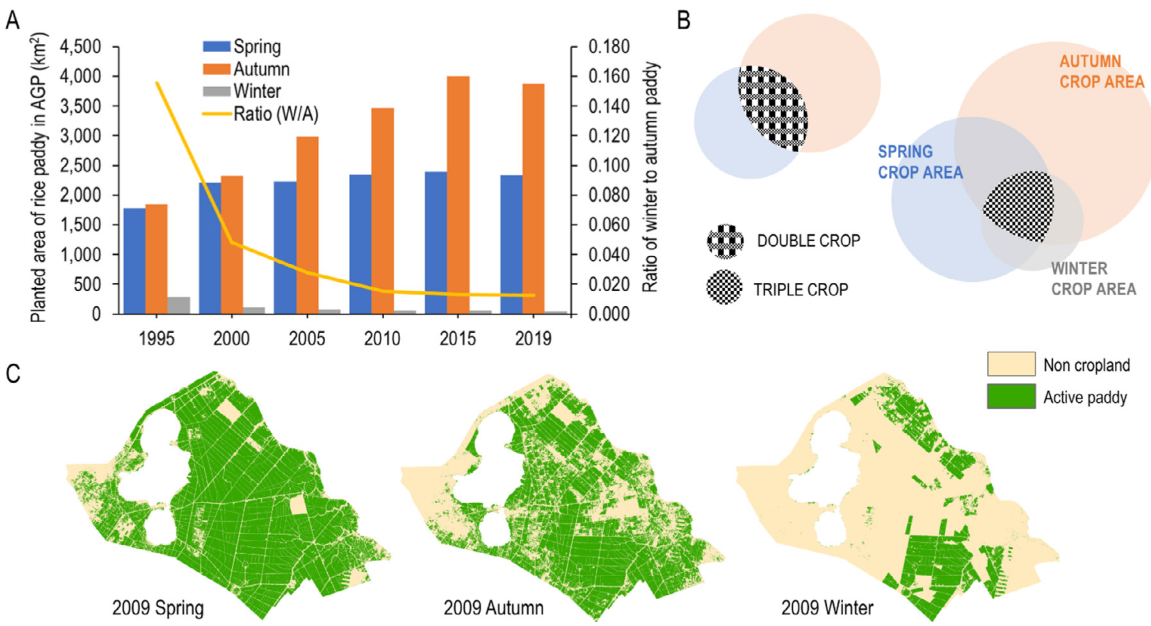

Fig. 4. A: Graph of planted area of a seasonal rice paddy in AGP between 1995 and 2019. All data was acquired from the General Statistics Office of Vietnam (GSO) ([dataset] GSO, 1995 2019). B: A conceptual figure depicting how the double and triple rice crop areas are identified and estimated from the intersections between planted areas of seasonal rice crops. C: Active rice paddy areas identified in AGP after applying appropriate thresholds to filter out NDVI images.

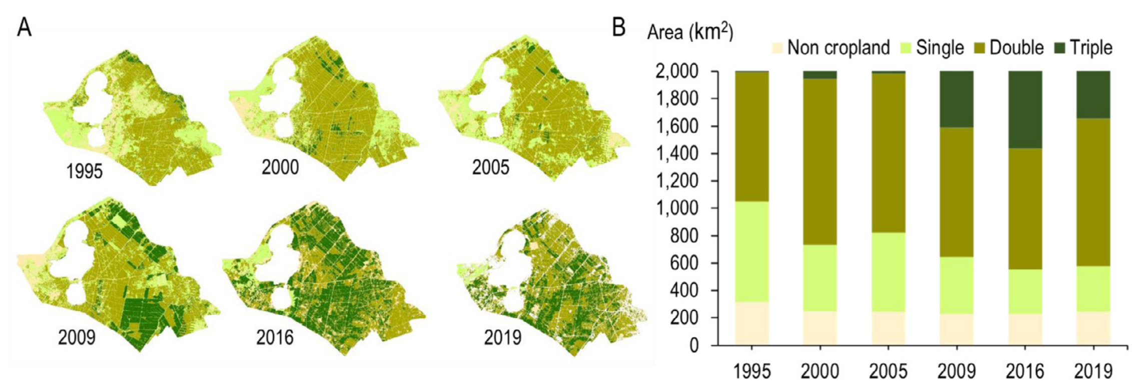

Fig. 5. A: Map showing the distribution of Landsat-observed rice cropping types within AGP between 1995 and 2019, with the classifications 'single', 'double' and 'triple' (crop) dependent on the number of times rice paddy areas overlapped across Spring, Autumn, Winter rice cropping seasons (see Fig. 4B). B: Stacked bar graph showing the relative distribution for single, double and triple rice areas.

reduce the amount of water needed for rice cultivation. This may therefore encourage farmers to convert rice cropping areas for other uses such as growing less water-intensive crops. Evidently, beyond geophysical factors, there are considerable economic and socio-political influences such as fluctuating rice market prices, visionary planning of national agricultural policies that affect the farmers' choices of crops to cultivate (Nguyen et al., 2012). However, we also argue that changing hydrological regimes and concerns of water availability for agriculture irrigation, that factor into farmer's decision-making on crop cultivation, is possibly much more immediate and responsive. Fig. 6 shows the change in the planted area of other main annual crops (maize, sweet potatoes, cassava) and the area of aquaculture in AGP over the same investigated time frame. In general, there is no distinct increasing trend observed in the planted area of the annual crops, except for aquaculture, which has more than doubled, from 10 km^2 in 1995 to 35 km^2 in 2019, a result of increased production of freshwater fish in ponds, particularly local catfish, which has developed into a major export industry in AGP and other regions in the upper delta. In part, this phenomenon may be attributed to the construction of the dykes systems to help with the intensification of rice production via triple cropping, in turn compromising the local natural river food catch and prompting a gradual shift to aquaculture to supply fish instead (Nguyen et al., 2019). However, as Mekong River fish species' migratory patterns are driven by the hydrological pulses during their lifespan (Neiland and Béné, 2008), recent changes to inundation regimes (i.e. lowered flooding) and the dynamics of seasonal flood pulse are also likely to have worsened the hydrological and, consequently, habitat connectivity, reducing dispersal ability of fishes (Ngor, 2018). Seng (2017) notes that fisheries in Cambodia are largely reliant on the seasonal flooding of the Tonle Sap lake, indicating that irregular flood regimes of a low frequency present unfavorable conditions for the wild fish catch, further exacerbating the issue of diminishing wild fish catch. This, in turn, changes agricultural dynamics by fuelling more demand for aquaculture and its cultivation area.

3.3. *Compounded effects of dyke construction on croplands*

In addition to water level variability, another factor that needs to be accounted for in flood frequency changes is the effect of flood control structures like dykes (both semi and high dykes). Multiple regression analyses by Park et al. (2020) revealed that water level variability had contributed to the flood frequency dynamics (~52%), followed by dyke construction (~23%). Evidently, the decrease in flood frequencies can-

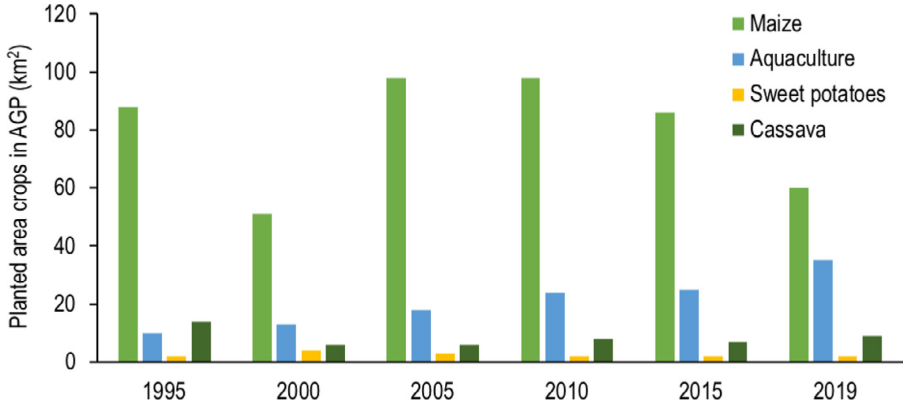

Fig. 6. Planted area of annual crops and aquaculture in AGP (beyond rice paddy) between 1995 and 2019. All data was acquired from the General Statistics Office of Vietnam ([dataset] GSO, 1995 2019).

not be isolated from the effect of dyke construction, and all the more so when changes in agriculture and crop cultivation are considered. Triet et al. (2020) note that crop cultivation is especially dependent on floodplain processes in the VMD, shaped by both the complex hydrodynamic interaction of fluvial dynamics as well as operation of delta flood infrastructures. Under the triple cropping system where cropland is already protected by high dykes from inundation (mostly to sustain the third rice crop) and receiving very minimal inundation and deposition between crops (Manh et al., 2014), the lowering of flood frequencies, as a result of sand mining, is expected to be detrimental to the overall health and fertility of cropland, and therefore highly unsustainable for agriculture.

3.4. Sustainable development of the Vietnamese Mekong Delta

Local sand extraction, if unregulated, will continue to contribute to the incision of riverbeds and loss of sediments that are of great importance to the agro-ecological productivity of the delta while intensifying several existing threats, including riverbank erosion (Hackney et al., 2020), salt-water intrusion and more recently, changes to seasonal inundation regimes (Park et al., 2020). Despite various attempts at multiple government levels, including the enforcement of legal regulations, e.g. restrictions on the extraction rates or even permanent bans on sand exports, the rate at which sand is being harvested from major rivers in Southeast Asia remains critically high due to the ever-growing demands (from both domestic and foreign markets) for sand for construction and reclamation purposes. Consequently, illegal sand mining activities have grown rampant and often overlooked as they usually take place in more remote areas. Till today, the discussion of sand extraction in the Mekong River, as a regional issue, has been treated with much caution due to the potential political implications and cross-border complexities. However, as the sand continues to be harvested and exploited at unsustainable levels, altering natural hydrological regimes, negative impacts on rural communities that depend on sediment-rich floods for agriculture are very likely to be inevitable (i.e., livelihood vulnerability) thus requiring *in-situ* adaptations given that the VMD supports agricultural and food production on a domestic and regional level, the rapid decline of riverbed material poses huge implications on the wider food security issues in the long-term. Our results from remote sensing data analysis and official government statistics on agriculture have revealed the emergence of increasingly diversified farming systems in AGP, characterized by a shift towards non-rice crops – in particular, aquaculture. Such cropping patterns are likely to also be a response to recent flooding patterns, given the strong interrelations between land-use dynamics and changes in hydrological regimes in the VMD (Tran et al., 2021; Le et al., 2018). Current literature on the VMD agriculture and land cover changes (Nguyen et al., 2020; Tran and James, 2017) have reported similar changes in rice-based agriculture in the region over the past decades: an increased conversion of rice paddy land for non-rice field crops, orchards, freshwater and brackish water aquaculture, with more small-scale farmers practising integrated farming models and farming diversification during the flooding season. However, it is crucial to note that land-use changes at the farm level are also often driven by many factors other than alterations in hydrological regimes and operation of flood infrastructures, such as the direction of national agricultural policies and market forces affecting crop valuation. More importantly, while adaptation measures, though the changes in land use, prove to be necessary for ensuring survival and sustaining livelihoods, the trajectory of the unsustainable development of the delta cannot be neglected, and necessary interventions at the provincial and national level must be implemented to ensure the longevity of the VMD (Loc et al., 2018; Trang and Loc, 2021; Loc et al., 2020).

4. Conclusion

In this paper, for the first time, we have presented the potential interplays between unsustainable riverbed mining activities and dynamic land use, and more specifically, key agricultural shifts in the VMD, by examining the changing area distribution of rice crops, aquaculture and other annual crops in AGP. Through a remote sensing analysis of rice cropping areas and corroboration with relevant agricultural statistics, our findings indicate that the triple rice crop area over the last 20 years has shown signs of reduction. Moreover, agricultural statistics reveal, simultaneously, an upward trend in aquaculture among other annual crops examined in AGP. These observations of changing agricultural patterns and land use demonstrate potential indirect implications of riverbed incision on agricultural productivity (among other factors like dyke construction, development vision and prices of agricultural commodities) as a result of alterations to flow regimes that inundate at lower frequencies previously reported (Park et al., 2020; Van Binh et al., 2021). As the VMD supports agriculture that is critical to both national and regional food security and sustaining the livelihoods of delta residents, it is imperative for future research to inform policymakers about the (indirect) detrimental agro-ecological impacts of riverbed mining. Moving forward, ensuring the sustainable development of the VMD will not only require more careful management of riverbed incision issues through regulatory frameworks to control rampant sand extraction activities but also a more comprehensive understanding of fragile delta ecologies in the Mekong river basin.

Conflict of interest

The authors whose names are listed above certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2022.100454.

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