Dynamics of coastal aquaculture ponds in Vietnam from 1990 to 2015 using Landsat data

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Abstract: It is important to know coastal aquaculture distribution and dynamics for aquaculture sustainability and offshore ocean protection in coastal countries. Vietnam is one of the largest in Asia in aquaculture yield, and thus it is of great significance to map spatial-temporal changes of costal aquaculture for sustainable aquaculture and offshore environment protection in Vietnam. In this study, based on Landsat images from 1990 to 2015, we used object-oriented and decision trees to extract coastal aquaculture ponds, and then analyzed the spatial and temporal distribution and evolution of coastal aquaculture area in Vietnam. The results showed that: 1) the method proposed could effectively extract coastal aquaculture ponds with an overall accuracy of 86%; 2) Vietnam's coastal aquaculture ponds were unevenly distributed and greatly different, and mainly distributed in the Mekong River Delta and Red River Delta, accounting for about 87%; 3) the development of Vietnam's coastal aquaculture ponds can be divided into two main stages, including rapid growth stage before 2010 and slow growth after 2010. This study can provide support for making aquaculture policy and coastal environment protection in Vietnam.

Keywords: Coastal aquaculture ponds; Vietnam; Satellite remote sensing; Spatial-temporal variation

1. Introduction
Aquaculture is one of the fastest-growing food production sectors in the world, which is an important food supply industry in many countries and an important contributor to global food security and protein intake [1]. Now, it is becoming a viable alternative to traditional fisheries and agriculture [2].
Driven by huge demand and economic benefits, the aquaculture industry has been booming. According to the Food and Agriculture Organization of the United Nations (FAO), the annual growth rates of world aquaculture were 9.5% in the 1990s and 5.8% during the period from 2001 to 2016 [3]. With the rapid expansion of aquaculture ponds, the promotion of intensive farming methods, the abuse of chemicals such as antibiotics and the input of high nutrients, a series of water environmental problems such as eutrophication of water bodies have been triggered [4-6]. Surrounded by the sea, Vietnam has abundant water resources, which provides strong natural conditions for the development of the aquaculture industry in Vietnam. By 2014, Vietnam’s aquaculture production was the fourth in the world, accounting for 4.57% of the world’s total aquaculture production [7, 8]. Therefore, it is of great significance to know clearly the scale, distribution and spatiotemporal changes of aquaculture ponds in Vietnam for aquaculture and the protection of marine environment. However, there were few reports on the temporal and spatial evolution of aquaculture in Vietnam.

The traditional aquaculture area measurement method is mainly manual measurement with GPS, which is time-consuming and labor-consuming. Therefore, it is not suitable for large area measurements. More importantly, it couldn’t track the historical dynamics of aquaculture ponds. Satellite remote sensing can provide and track spatial distribution and historical dynamics of many properties, such as land cover and seagrass dynamics [9-11]. It is also an effective means to obtain spatial-temporal distribution of aquaculture. At present, high-resolution images have been widely used in aquaculture extraction [12-16]. Using WorldView-2 image as a data source, Fu et al. (2019) proposed a method based on multi-scale segmentation and object neighborhood features to divide existing coastal aquaculture areas in Sandu Island, Fujian [17]. Based on the SPOT-5 image, Zhang et al. (2013) used the region-based region-growth algorithm to separate the aquaculture pond shoreline from the ocean in the Bohai Sea and the Pearl River [18]. Virdis et al. (2014) used a SPOT-5 panchromatic image (5 m resolution) and WorldView-1 panchromatic image (0.5 m resolution) to extract coastal aquaculture in Tam Giang-Cau Hai Lagoon [2]. Hazarika et al. (2009) used QuickBird (4 m resolution), CBERS (China-Brazil Earth Resources Satellite data, 20 m resolution) and Landsat (30 m resolution) data to map seagrass from 1991 to 2006 in Xincun Bay, Hainan province [19]. In addition to high-resolution images, medium-resolution images were also used in aquaculture extraction [20-26]. For example, Stiller et al. (2019) combined Sentinel-1A data with Landsat images to extract aquaculture ponds in the Yellow River Delta and Pearl River Delta [27]. With the rapid expansion of aquaculture, it has triggered a series of ecological and environmental problems. For example, Veetti, Hauser and other studies suggested that the expansion of aquaculture ponds has become one of the main reasons for the degradation of mangroves in the coastal area [28, 29]; Cao et al. (2007) indicated that the intensification of aquaculture, the abuse of feed and antibiotics had an important impact on the eutrophication of coastal waters [30]. However, the above research mainly focused on mapping aquaculture ponds in some small regions. Over a large scale (e.g., provinces and countries), there are few reports on mapping aquaculture ponds and tracking its dynamics using medium-resolution images.

Therefore, in this study, based on Landsat data, we developed a method for mapping coastal aquaculture ponds and then analyzed its spatial-temporal dynamics from 1990 to 2015.
2. Material and Methods

2.1. Study area
The study area was defined as a buffer zone extending 40km inland from the coastline of Vietnam (8°10´~21°57´N,102°09´~109°30´E), which was located in the coastal area of east Vietnam (Figure 1). The study area has a tropical monsoon climate, with high temperature and humidity throughout the year, and an obvious dry and rainy season. The rainy season is from June to October every year, with abundant precipitation. From November to May of the following year, there is a dry season, with little rain. The research area has abundant water resources such as lagoons, estuaries, and deltas, which provide natural favorable conditions for developing aquaculture. Vietnam has hundreds of species of fish, shrimp, crab, and other economic aquatic products. It has developed a variety of aquaculture ponds mainly based on pond culture, supplemented by fish culture in rice fields, animal husbandry, and mangrove aquaculture. According to FAO, the total aquaculture volume of Vietnam ranked fourth in the world in 2014, making it a major aquaculture country in the world [8].

In order to analyze the changes of coastal aquaculture ponds, the study area was divided into 6 regions, namely Northeast Region, Red River Delta, Southeast Region, North Central Region, South Central Region and Mekong River Delta.
2.2. Satellites remote sensing data and pre-processing
A total of 80 scenes of cloud-free Landsat TM/OLI images were used for mapping aquaculture ponds in the study area for the periods including around 1990, 2000, 2010 and 2015 (downloaded from https://earthexplorer.usgs.gov/) (Figure 2). Landsat TM images have seven bands with a spatial resolution of 30m. Landsat OLI has 9 bands, of which band 1 - 7 are a multi-spectral band with a spatial resolution of 30 m, band 8 is a full-color band with a resolution of 10 m, and band 9 is a convoluted cloud band. Considering the obvious spectral features of aquaculture ponds, only four bands, including red, green, blue, and near-infrared bands, were used in this study. Due to the tropical monsoon climate in Vietnam, the whole year is warm and humid, and it is suitable for aquaculture throughout the year. Therefore, we selected cloudless images data covered by study area in different months in the interested year to map aquaculture ponds.

2.3. Methods
The object-oriented and decision tree technology was used to map aquaculture ponds in Vietnam. The detailed methods and steps for mapping aquaculture ponds were as shown in Figure 3.
First, Multiresolution segmentation was used in this study. Multiresolution segmentation is a pixel-based bottom-up segmentation method. It not only makes full use of the spectral features of images but also deeply considers the context features such as texture features and shapes. It is a comprehensive region segmentation algorithm. The segmentation result is the smallest heterogeneity in the region while ensuring the maximum homogeneity. Multiresolution segmentation involves multiple parameters, where segmentation scale, compactness and shape factor are the three most important parameters. The size of the segmentation scale has the greatest influence on the segmentation result. The optimal segmentation scale is the segmentation boundary just the same as the real boundary of the same kind of object. By repeatedly setting the segmentation parameters, in this study, the segmentation scale was 30, and the compactness and shape factor were 0.1. 0.5, respectively [31].

Second, we selected a large amount of typical aquaculture ponds and non-aquaculture ponds sample sets from images combined with Google Earth. Meanwhile, many potential feature sets such as NDVI, NDWI, were calculated. And then the feature sets of sample sets were input into Software See 5, and finally a decision tree of interested image was output from See 5. The decision tree was conducted in eCognition Developer 8.9 and the distribution of aquaculture ponds in responding image were obtained. Manual checking and modification by expert with experience knowledge was an important steps after automatically operation.

Finally, the accuracy of mapping results were assessed and validated using two methods: (a) assessing area interpretation accuracy using a visual interpretation result derived from a high resolution image (e. g., Sentinel-2); (b) assessing spatial interpretation accuracy based on samples including aquiculture ponds and non-aquiculture ponds samples derived from Google Earth. Based on the reference samples and the interpretation result, the error matrix was obtained, and the producer accuracy (PA), user precision (UA), overall precision (OA) and Kappa coefficient were calculated [32].

We defined the classification map derived from the Landsat OLI as Map A and visual interpretation map as Map B. By overlay analysis, we could get correct aquaculture area (the area classified or
interpreted as aquaculture both in Maps A and B), omission and commission area to conduct a spatial accuracy assessment. Further, based on statistical data of aquaculture ponds information, overall accuracy, errors of commission and omission were calculated to assess extracting accuracy of pen aquaculture in Map A using the following formulas [14]:

$$P_O = \frac{S_O}{S_A} \times 100\%$$  \hfill (1)  

$$P_E = \frac{S_E}{S_B} \times 100\%$$  \hfill (2)  

$$P_C = \frac{S_C}{S_B} \times 100\%$$  \hfill (3)  

where, $P_O$, $P_E$, and $P_C$ are the errors of omission, commission, and correction respectively; $S_O$ and $S_E$ are the areas of omission region and commission region, respectively; $S_A$ and $S_B$ are the area of aquaculture extracted by Landsat and visual interpretation, respectively; $S_C$ is the area classified as aquaculture ponds in both Maps A and B.

3. Results

3.1. Mapping aquaculture ponds datasets and accuracy assessment

Figure 4 shows the distribution maps of coastal aquaculture ponds in Vietnam in 1990, 2000, 2010 and 2015. Aquaculture ponds were mainly distributed in the eastern coastal areas. The results of the four periods indicated that the distribution of the coastal aquaculture ponds in Vietnam was uneven with more in the north and south and less in the middle part. It was obvious that the area of aquaculture ponds continuously expanded from 1990 to 2015, especially in the Mekong River Delta. Meanwhile, the RGB composition images overlapped with interpreting results in some typical locations with dramatic change also were displayed in the Figure 4.
Figure 4. Spatial distribution maps of coastal aquaculture ponds in Vietnam in 1990, 2000, 2000 and 2015

Based on the reference data interpreted by sentinel-2A, the spatial distribution of the omission areas, misclassified areas, and the correct areas are shown in Figure 5. Spatially, most of the omission and misclassified areas were located along with the interval and edge between the aquaculture ponds. Table 1 presents that overall accuracy of the extracted result was 93.09% with a commission error of 13.61% and an omission error of 6.47%. The confusion matrix is also shown in Table 1.
Figure 5.

Accuracy assessment map of remote sensing monitoring aquaculture area (a: Interpretation results of aquaculture in Mekong Delta. b: Interpretation results of aquaculture based on Landsat. c: The results of aquaculture based on Sentinel-2A. d: Error distribution map)

Table 1: Accuracy assessment summary in the four periods. Note: PA, UA and OA are Producer’s accuracy, user’s accuracy and overall accuracy, respectively.

| Pattern consistency | $S_B$ | $S_A$ | $S_C$ | $S_O$ | $S_E$ |
|---------------------|-------|-------|-------|-------|-------|
|                      | 14.77 km² | 15.76 km² | 13.75 km² | 1.02 km² | 2.01 km² |

$P_C = 93.09\%$; $P_D = 6.47\%$; $P_E = 13.61\%$

| Time | PA | OA (%) | Kappa |
|------|----|--------|-------|
|      | Aquaculture | Non-aquaculture | Aquaculture | Non-aquaculture |
| 1990 | 0.76 | 0.86 | 0.85 | 0.78 | 81 | 0.63 |
| 2000 | 0.77 | 0.93 | 0.91 | 0.81 | 86 | 0.71 |
| 2010 | 0.87 | 0.89 | 0.88 | 0.87 | 88 | 0.75 |
| 2015 | 0.83 | 0.90 | 0.89 | 0.84 | 87 | 0.73 |

3.2. Dynamic changes of coastal aquaculture ponds in Vietnam

Figure 6 depicts the spatial-temporal dynamics of coastal aquaculture ponds in Vietnam in four periods. We divided the study area into 456 hexagons (each hexagon area corresponds to approximately 350 km²) to display the changes in the four periods. The trends are roughly fallen into three classes: increase, decrease and no change. Coastal aquaculture ponds have been increasing in most zones,
especially in the Mekong River Delta.

From the Figure 6, the most hexagons showed increase. During the period from 1990 to 2000, only 8.1% of the hexagons show a decrease trend in aquaculture ponds and about 51.75% reveal increase. The growth zones were mainly distributed in the Mekong River Delta and the Red River Delta. However, aquaculture ponds also had the most obvious decrease in the Mekong River Delta, accounting for about 51% of the total reduction. Compared with the period 1990-2000, the scope and area of aquaculture expansion during 2000-2010 was more obvious. About 10.9% of hexagons show decrease, which presented an aggregate trend. Around 59.87% hexagons revealed increase, among which about 8.05% increased by more than 100km$^2$. After the 2000-2010 period, aquaculture expansion entered a period of moderation. As shown in Figure 6, aquaculture ponds had been expanding in most of regions, but, the increase intensity significantly reduced. Only two hexagons had increased over 100km$^2$. For about 46.93% of the hexagons, area was < 6.03km$^2$. Besides, the change trend of aquaculture ponds from 1990 to 2015 can also be shown as figure 6. Only aquaculture area in five hexagons showed decrease and about 73.68% of all hexagons presented increase. There were very few areas where there was no change, which distributed dispersely. During the period from 1990 to 2015, increased area was greater than 100km$^2$ in only about 23 hexagons, and increase area were smaller than 6.03km$^2$ in most hexagons.
Figure 6. Change patterns and hotspots of aquaculture in Vietnam from 1990 to 2015 (a: Changes in aquaculture areas from 1990 to 2000; b: Changes in aquaculture areas from 2000 to 2010; c: Changes in aquaculture areas from 2010 to 2015; d: Changes in aquaculture areas from 1990 to 2015)

In 2015, the area and density of aquaculture ponds in the Mekong River Delta were the largest, with an area of about 7599.24km$^2$ and density of 24%, respectively. The area of aquaculture ponds in
the Northeast Region was about 88.52km$^2$. Except for the aquaculture area in the North Central Region of 500km, the area of the aquaculture area in other regions was about 200km. The area of aquaculture ponds in 2010 significantly decreased compared with 2015, but the area and density in the Mekong River Delta were still the Largest. The trend of area and density of aquaculture in different regions in 1990 and 2000 was roughly same as that in 2015. In addition, as shown in Figure 7, a greater aquaculture area didn’t mean a high aquaculture density, for example, the area of aquaculture ponds in Red River Delta and Southeast Region was smaller but density was higher.

Figure 7. Area and density of coastal aquaculture ponds in different districts in four periods

The annual rate of change in Vietnam's aquaculture ponds varied from times in the different districts. In most of districts and periods, the change rates were positive and tended to decrease first and then increase over time. From 1990 to 2000, the greatest change rate in the Mekong region was about 14.70%, and the smallest change rate was approximately 2.59% in the Northeast region. The rate of change from 2000 to 2010 decreased in different degrees compared with 1990-2000. From 2000 to 2010, change rate in the Mekong River Delta was highest. Aquaculture ponds in the North Central Region decreased at a rate of 3.12% at the period.

During the period from 2010 to 2015, the change rate increased significantly in the North Central Region and decreased in other districts. At the same time, the change rate in the Southeast Region was negative. The area of aquaculture ponds in Southeast Region decreased at that period. In addition, Figure 8 also shows the change rate of aquaculture ponds in each region from 1990 to 2015. Over the past 25 years, the change rate was positive and varied greatly from regions. The maximum change rate was up to 18.15% in the Mekong River Delta, which was approximately the sum of the rates of change in other regions, followed by Red River Delta with a change rate of 10.40%. The lowest rates of change was 2.08% in the Northeast Region.
4. Discussion

4.1. Uncertainties in mapping aquaculture ponds
Aquaculture ponds area and scales varied from the distances from land. Based on our the mapped results, we established several buffers with an interval of 1km towards land along with the coastline and calculated aquaculture area in the corresponding buffers in every region in Vietnam to reveal the distribution pattern of aquaculture ponds (Figure 9). The result showed that the aquaculture ponds in each region were mainly distributed within 30km from the coastline, accounting for 87% of the total aquaculture area in 2015. At a distance of 40km from the coastline, the aquaculture area in most regions was very small. Therefore, it was appropriate to select a buffer zone 40km inland from the coastline as focus study area of costal aquaculture ponds.
Spatial resolution of image was one of the important factors influenced the accuracy of mapping aquaculture ponds.\(^{[5, 7]}\). At a country scale, Landsat data is an effective and proper data resource to map aquaculture ponds. Although the accuracy was limited, it can meet the demand for aquaculture decision. At the same time, the setting of the segmentation scale has also a great influence on the accuracy of mapping aquaculture ponds. When the segmentation scale is too large, the aquaculture ponds with small area are missed or the smaller non-aquaculture areas are merged into the adjacent parts of the aquaculture areas with a large area.

4.2. Impact of Vietnamese policies on changes in aquaculture ponds

Vietnam has a long coastline of 3260 km, so it has abundant coastal resources, such as aquaculture. As a part of the Marine strategy, the aquaculture industry was paid much attention by the Vietnamese governments. Therefore, there has been a series of policies about aquaculture and fishery made in Vietnam. Consequently, the policies bound to produce some significant impacts on aquaculture changes. For example, between 1975 and 1985, Vietnam was in the period of public ownership of the means of production, prohibiting private production materials. During this period, labor productivity and the development of fishery were greatly restricted\(^{[33]}\). During the economic reforms in 1986, The Vietnamese government lifted the ban on the means of production and supported the private ownership, which greatly improved the productivity of the fishery and the enthusiasm of fishermen. At the same time, the Vietnamese government had carried out some reforms, such as the revision of the land law, the fishery law, and the investment law, which had liberated the productive forces and attracted the foreign capital, providing the foundation for the explosive growth of the aquaculture area\(^{[33, 34]}\). In the 1990s, Vietnam adjusted its economic structure and advocated the development of fisheries. So far, the aquaculture ponds in Vietnam had entered a stage of rapid growth\(^{[34]}\). So, during the period from 1990 to 2000, the area of aquaculture ponds rapidly increased from 1372.28km\(^2\) to 3389.12km\(^2\). In 2007, the communist party of Vietnam promulgated the Marine strategy to 2020, which attached great importance to the fishery economy and encouraged the development of aquaculture. A set of development goals for fisheries were made, for example, the aquaculture yield would increase from 200,000 to 260,000 tons by 2020\(^{[35]}\). In 2013, The Master Plan of Vietnam Fisheries and Aquaculture Development through 2020 and vision to 2030 was promulgated. The two plans pointed the way for Vietnam's aquaculture industry to become industrialized, sustainable and highly productive\(^{[36]}\).

In addition to guiding and encouraging the development of fishery in policy means, the Vietnamese government also encouraged aquaculture development by economic and technological means. In 1997, Vietnam cooperated with Switzerland in aquaculture research, which laid a foundation for exporting aquatic products to the EU and other countries\(^{[37]}\). Meanwhile, this method was promoted and stimulated the development of aquaculture industry in the ocean strategy. The Vietnamese government developed advanced management systems, strengthened port construction and surveyed Marine resources to provide technical information support for the development of aquaculture\(^{[35]}\). When there were some problems in the development of intertidal fishery, the Vietnamese government adjusted the land allocation policy, eased the contradictions and laid a foundation for the stable development of fishery\(^{[38]}\). When the continuous expansion of aquaculture has caused a series of environmental problems, Vietnam paid attention to environmental protection, such as mangrove protection and reform of the management system, which
provided a guarantee for the sustainable development of aquaculture in Vietnam\cite{39-42}.

5. Conclusion

It is of great significance to know about the spatial distribution and evolution of coastal aquaculture ponds in Vietnam for coastal managers, environmentalists, and stakeholders. Satellite remote sensing was an effective tool to monitor distribution and dynamics of aquaculture ponds. In this study, we mapped coastal aquaculture ponds in Vietnam in 1990, 2000, 2010 and 2015 based on Landsat data, and then analyzed the spatial and temporal dynamics and change patterns in four periods. The main conclusions included: 1) the spatial distribution of coastal aquaculture areas in Vietnam was uneven and varies greatly, mainly in the Mekong River Delta and the Red River Delta, accounting for 87% of the total aquaculture area in Vietnam; 2) change patterns of coastal aquaculture ponds could be divided two stages including the stage of high-speed growth before 2010 and the stage of slow growth after 2010.

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