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Rapid expansion of coastal aquaculture ponds in China from Landsat observations during 1984–2016

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ABSTRACT

Aquaculture is one of the fastest growing animal food production sectors mainly developed in fertile coastal areas. Monitoring and mapping of aquaculture ponds are of utmost importance for the sustainable management of coastal ecosystems. In this study, an integrated updating and object-based classification approach was developed to generate maps of coastal aquaculture ponds in China from 1984 to 2016 at 30-m spatial resolution. The current extent and change of coastal aquaculture ponds in China were analyzed over the course of 32 years. In addition, spatial-temporal dynamics of coastal aquaculture ponds were examined by buffer and overlay analyses. The results showed that the total area of coastal aquaculture ponds in China expanded by 10,463 km^2, with the largest gain occurring from 1990 to 2000 (4,207 km^2). The coastal provinces of Guangdong, Shandong, Jiangsu, Liaoning, and Hebei had significant increases of aquaculture ponds areas, accounting for 83% of totally expanded ponds in the coastal zone of China. Rapid expansion of coastal aquaculture ponds was observed in the 0–10 km inshore buffer and the loss of wetlands and arable land contributed more than 50% to the expansion. Socio-economic factors helped drive the continual increase of coastal aquaculture ponds in China. Scientific environmental regulations and planning and management strategies at the national and international policy levels should be enhanced to consider the ecological impacts of aquaculture expansion.

1. Introduction

Aquaculture (e.g., fishes, shrimps), one of the fastest growing food production sectors worldwide, is an important source of protein for people and is likely to play an essential and increasing role for future global food security (FAO, 2011; UN, 2011). Low-lying coastal areas are the most favorable areas for aquaculture (Primavera, 2006), due to the presence of highly productive arable land and rich marine and freshwater resources (Kuenzer and Renaud, 2012; Renaud et al., 2013). The rapid global expansion of the aquaculture industry has caused transformation of large areas of valuable coastal lands with strong adverse effects on natural ecosystems, including destruction of coastal wetlands, decrease of biodiversity, pollution of water and soil (Virdis, 2014). China was the world's top aquaculture producer, contributing 61.5% to the world production in 2016 (FAO, 2016), and has undergone tremendous expansion of aquaculture. Aquaculture has rapidly expanded at different coastal regions of China and was responsible for large scale loss and fragmentation of wetland habitats through land reclamation and conversion along the coast of the South China Sea (Peng et al., 2013; Spalding et al., 2014). However, a holistic view of the coastal aquaculture of China using consistent data sources and methodology was not available. Such information is critically important for analyzing the increasing pressure on coastal ecosystems, related environmental impacts, and sustainable development planning of the coastal region.

In addition to being accurate, rapid, and cost effective, remote sensing has been a useful tool for the spatial assessment of aquaculture

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areas at different scales (Ottinger et al., 2017). However, aquaculture is not the central objective in previous studies and is most often indirectly investigated with coastal land reclamation (Meng et al., 2017; Mao et al., 2018), mangrove deforestation (Lu et al., 2018), and loss of coastal wetlands (Long et al., 2016). Great effort has been directed towards using remote sensing data to map aquaculture and estimate its extent around the globe, especially in Asia and China (Gusmawati et al., 2018; Loberternos et al., 2016). Although data sources varied from moderate to high spatial resolution imagery, from multispectral to hyperspectral data (Abd-Elrahman et al., 2011), from optical to microwave data (Marini et al., 2013), most previous studies focused on the mono-temporal precise mapping of aquaculture. Time series data analyses have great potential to reveal long term dynamics of aquaculture structures, extents, and ecological parameters (Kuenzer et al., 2015), and could provide the baseline data and valuable information for efficiently planning and managing aquaculture practices. However, time series analyses of aquaculture using remote sensing data has rarely been conducted.

In this study, we aim to explore the spatial and temporal dynamics of coastal aquaculture ponds in China from 1984 to 2016 using time series Landsat images. The specific objectives of this study were to: (1) generate accurate maps of coastal aquaculture ponds in China using an integrated updating and object-based method, and (2) quantify spatial and temporal changes of coastal aquaculture ponds during 1984–2016, and (3) identify the major factors that have driven the observed changes in coastal aquaculture ponds and related ecological impacts on coastal environments.

2. Materials and methods

2.1. Study area

China's coastal zone stretches from the mouth of the Yalu River in the north to the estuary of Beilun River in the south (18.2 °N to 40.5 °N) (Wang et al., 2018) (Fig. 1). Our study focused on the coastal aquaculture ponds and the distance between the farthest aquaculture ponds and the coastline is about 50-km. Thus, the study area was defined as a 50-km wide buffer within the coastal zone (i.e., from the coastline to the land side), while maintaining the integrity of administrative boundaries within the prefecture level. The right boundary was relaxed and the coastal aquaculture ponds were entirely included. The coastal zone encompasses approximately $44.6 \times 10^4\,\text{km}^2$, including the provinces/cities of Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, Tianjin and Shanghai. This region covers the tropical, sub-tropical, and temperate climate zones from south to north. The elevation of the China's coastal zone ranges from sea level to over 3700-m above sea level (Wang et al., 2018).

2.2. Landsat imagery and preprocessing

In this study, the coastal zone of China could be covered by 37 scenes of Landsat images (spatial resolution 30 m) for each time period. As an example, a complete list of the images used in 2016 is listed in Table 1, most of which were acquired from around May to October in 2016. In total, 185 cloud-free Landsat images, including Landsat Thematic Mapper (TM), Enhanced Thematic (ETM+), and Operational Land Imager (OLI) images, were used for mapping and monitoring aquaculture ponds of the coastal zone of China for the years around 1984, 1990, 2000, 2010 and 2016 (downloaded from http://glovis.usgs.gov). All of the images were atmospherically corrected through the Fast Line-of-sight Atmospheric Analysis of Spectral hypercubers (FLAASH) model. Geometric correction was performed to improve the geolocation with the registration error being less than half a pixel (< 15 m). The atmospheric and geometric corrections were completed in the ENVI 5.0 software (ITT, 2010). All corrected images were projected into an Albers projection with a WGS-84 ellipsoid.

2.3. Integrated updating and object-based classification method

The updating approach has been increasingly used in visual interpretation and automatic classifications (Zhou et al., 2011; Jin et al., 2013), which synthesize the post-classification comparison and pre-classification change detection (Xian and Homer, 2010). This approach typically started with the reference map, based on which the classification and change analysis are conducted (Yu et al., 2016). We integrated the updating approach with an object-based method to map coastal aquaculture ponds from 1984 to 2016 using the workflow illustrated in Fig. 2.

We first generated the reference aquaculture ponds map for 1984 using 1984 Landsat TM images and an object-based classification method by the software eCognition Developer 8.64 (Definiens, 2011). The workflow of classification involved image segmentation, rule-building, and manual editing. Segmentation is the first step in the object-based classification process, and homogeneous objects were obtained based on three parameters: scale, shape and compactness (Jia et al., 2018). From purely visual inspections for the segmentation parameters tests, a satisfactory match between image objects and pond features was achieved when the scale, shape, and compactness parameter was set to 30, 0.1, and 0.5, respectively. The rule sets were created based on the statistical analysis of the training areas resulting from the field surveys and images. Aquaculture ponds have a spectral signature characteristic of water bodies, so we calculated the mean Normalized Difference Water Index (NDWI) for all the pixels in a pond object to separate pure water and non-water objects. The NDWI is defined by the following equation (McFeeters, 1996):

$$\text{NDWI} = (\text{Green} - \text{NIR})/(\text{Green} + \text{NIR}) \tag{1}$$

Where Green and NIR represent Green band and NIR band of Landsat TM/ETM+/OLI imagery. Visual interpretation and manual editing were conducted by remote sensing experts to correct some misclassifications based on previous knowledge and field survey data, especially for patches near the boundaries of natural and artificial water surfaces.

The maps of aquaculture ponds for 1990, 2000, 2010, and 2016 were derived separately using an object-based updating approach at 30-m spatial resolution. The reference map, Map1984, was used as the thematic layer when segmenting the imagery, which will not allow the generated objects across any of the borders separating thematic classes of Map1990. Object-based change detection were applied to obtain the objects with changes and no changes, and the detailed introduction about the approach can be found in previous studies (Xian and Homer, 2010; Yu et al., 2016). Objects with no changes from 1984 to 1990 were assigned as the attributes of Map1984. Objects with changes were then classified into 2 classes: aquaculture ponds and others. We produced the final aquaculture ponds map of 1990 by assigning the attribute of no change objects and merging the change objects. Subsequent aquaculture ponds map (T_2) was produced from the previous map (T_1).

Field surveys were conducted between July and September from 2015 to 2017 along the coastal zone of China to collect ground reference data. A total of 2,171 sampling points were obtained to evaluate the accuracy of classification results in 2016, including 966 samples of aquaculture ponds and 1205 samples of others. Owing to the lack of field survey data in 1984, 1990, 2000, and 2010, we collected 3,890 reference samples via visual inspection of very high resolution images such as QuickBird and IKONOS available within Google Earth. Finally, the reference data obtained in 1984, 1990, 2000, 2010, and 2016 consisted of 830, 850, 960, 1,250, and 2,171 samples, respectively.

2.4. Spatial-temporal analysis of aquaculture ponds maps

We analyzed the spatio-temporal dynamics of the coastal aquaculture ponds at provincial and national levels. The total area, change

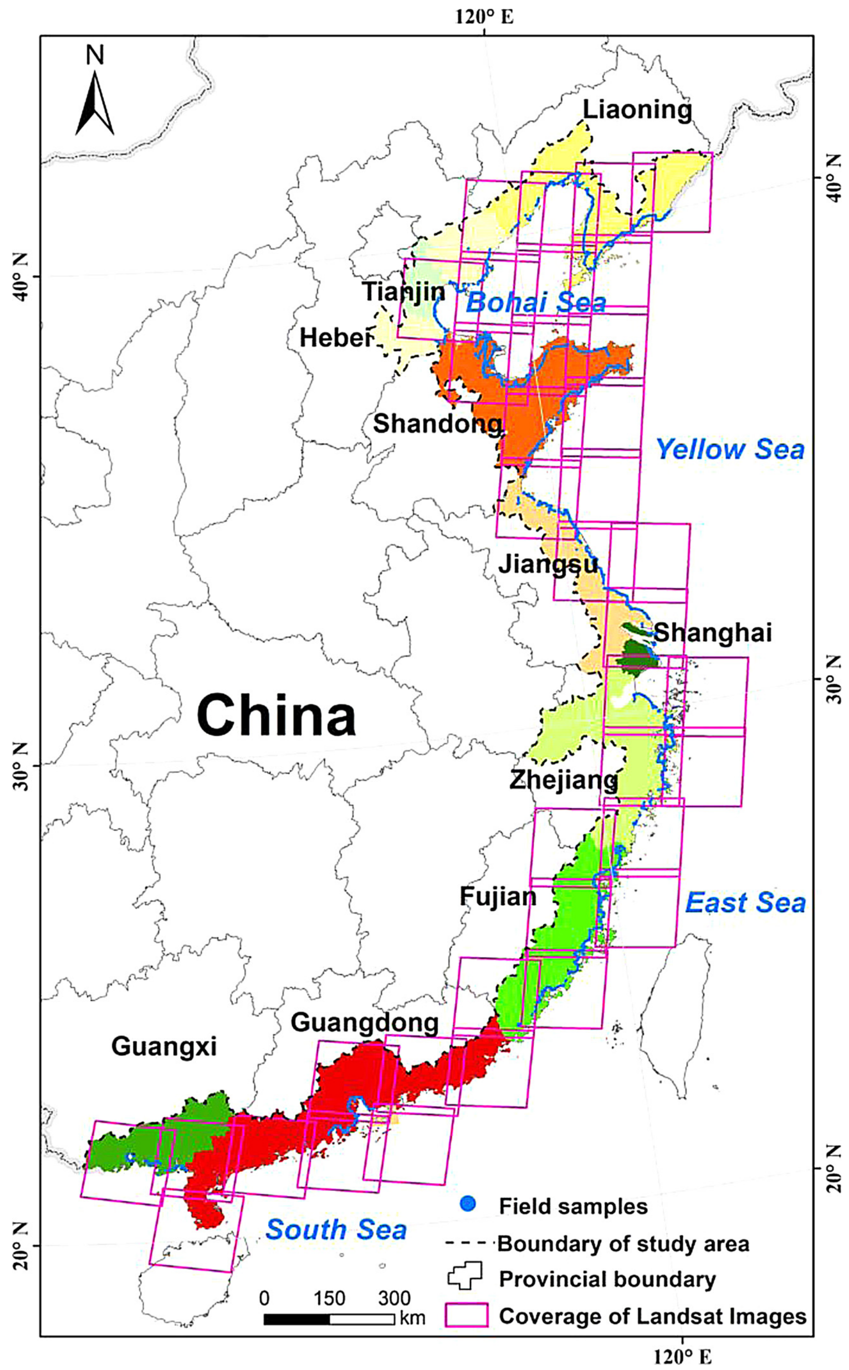

Fig. 1. Location of study area and field sampling sites.

area, and annual change rate (km^2/year) of the coastal aquaculture ponds were calculated at each spatial scale. The annual change rate (ACR) of aquaculture ponds is defined as follows:

$$ACR = (S_{end} - S_{\mathrm{start}})/n \tag{2}$$

Where S_{end} (km^2) and S_{end} (km^2) represents the area of aquaculture ponds at the end and start of the period, respectively, and n is the duration between the start and end time. We further examined the aquaculture ponds dynamics using buffer analysis with 10 km interval and the changes among offshore and inshore buffers were also compared.

An overlay analysis was applied to create a conversion matrix between aquaculture ponds and other land cover types from 1984 to 2016. Land cover data in 1984 was provided by National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://www.geodata.cn). The overall accuracy of this dataset is 92.9% based on evaluation by field survey patches (Liu et al., 2005). The classification system of land cover data used in this study were modified into seven classes: arable land, forest, grassland, settlement, wetland, other land, and sea water. The description of each land cover class is given in Table 2. The newly developed aquaculture ponds during 1984–2016 were extracted and then overlaid with land cover data of 1984. The original land use types of those new ponds were identified for the conversion analysis.

In addition, the statistical data including aquaculture area, aquaculture production, total population, gross domestic product (GDP), gross product of fisheries, and per capita fisheries income were collected from the Chinese Fishery Statistical Yearbook (1979–2016), and

Table 1
List of Landsat OLI images used in 2016.

Path/Row	Date	Path/Row	Date
117/39	Jul, 29	120/33	Jun, 16
117/40	Aug, 30	120/34	Jun, 16
118/32	May, 17	120/35	Jun, 16
118/37	May, 17	120/36	Apr, 29
118/38	Aug, 3	120/43	May, 13
118/39	May, 1	120/44	May, 28
118/40	Jul, 20	121/32	Aug, 26
118/41	Jul, 20	121/33	Aug, 26
118/42	Jul, 20	121/34	Aug, 26
119/32	Sep, 29	121/44	Sep, 27
119/33	Aug, 28	121/45	Sep, 27
119/34	Jun, 25	122/33	Oct, 2
119/35	Jun, 25	122/44	Oct, 18
119/36	Jun, 25	122/45	Oct, 18
119/37	Oct, 13	123/45	Jul, 23
119/41	Sep, 29	124/45	Sep, 16
119/42	Jul, 27	124/46	Jun, 12
119/43	Jul, 27	125/45	Oct, 9
120/32	Jun, 16		

Thematic Database for Human-earth System (http://data.ac.cn/index.asp).

3. Results

3.1. Areas and spatial distribution of coastal aquaculture ponds in 2016

The confusion matrix of the classification was calculated and the results showed that the map of aquaculture ponds in 2016 across the coastal zone of China had high overall accuracy (94%) with a kappa coefficient of 0.91 (Table 3). Classification errors were mainly observed between aquaculture ponds and salt pans. The similar regular shapes and water reflection characteristics of them contributed to this confusion. The accuracy assessments demonstrated that the mapping results could meet the requirements for the spatial analysis in this study.

The total area of coastal aquaculture ponds in China in 2016 was 13,075 km^2, and was distributed unevenly. The average aquaculture ponds area per unit land (ha/km^2) in 2016 in Guangdong and the provinces located in the north of Yangtze River were relatively higher (Fig. 3A). Guangdong Province had the largest extent of coastal aquaculture ponds (3,485 km^2, 26.7%), followed by Shandong Province (2,291 km^2, 17.6%), Jiangsu Province (1,663 km^2, 12.7%), Liaoning Province (1,449 km^2, 11.1%) and Hebei Province (1,327 km^2, 10.2%) (Fig. 3B and C). Aquaculture ponds in those provinces accounted for approximately 80% of total coastal aquaculture ponds in China. Shanghai had the least area of aquaculture ponds (104.8 km^2).

3.2. Spatial and temporal dynamics of coastal aquaculture ponds

The coastal aquaculture ponds in China have increased continuously during the 32-year period, from 2,612 km^2 in 1984 to 13,075 km^2 in 2016. The net increase of coastal aquaculture ponds was about 10,463 km^2 with an overall rate of 327 km^2/year during 1984–2016. The largest gain occurred from 1990 to 2000 (4,207 km^2), followed by the period of 1984–1990 (2,705 km^2). The expansion rate of aquaculture ponds decreased after 2000 and the net increase area was approximately 2,143 km^2 and 1,408 km^2 for the period 2000–2010 and 2010–2016, respectively. The ACR (10^2 ha/year) from 1984 to 2016 in each province are shown in Fig. 4A and had a similar pattern with the spatial distribution of area within per unit land (Fig. 3A). Guangdong, Shandong, and Jiangsu had relatively higher ACR and could be identified as the hotspots for the expansion of aquaculture ponds considering the quantity and changing rate.

Among the coastal provinces, Guangdong, Shandong, Jiangsu, Liaoning, and Hebei accounted more than 83% of the coastal aquaculture ponds expansion that occurred between 1984 and 2016. The

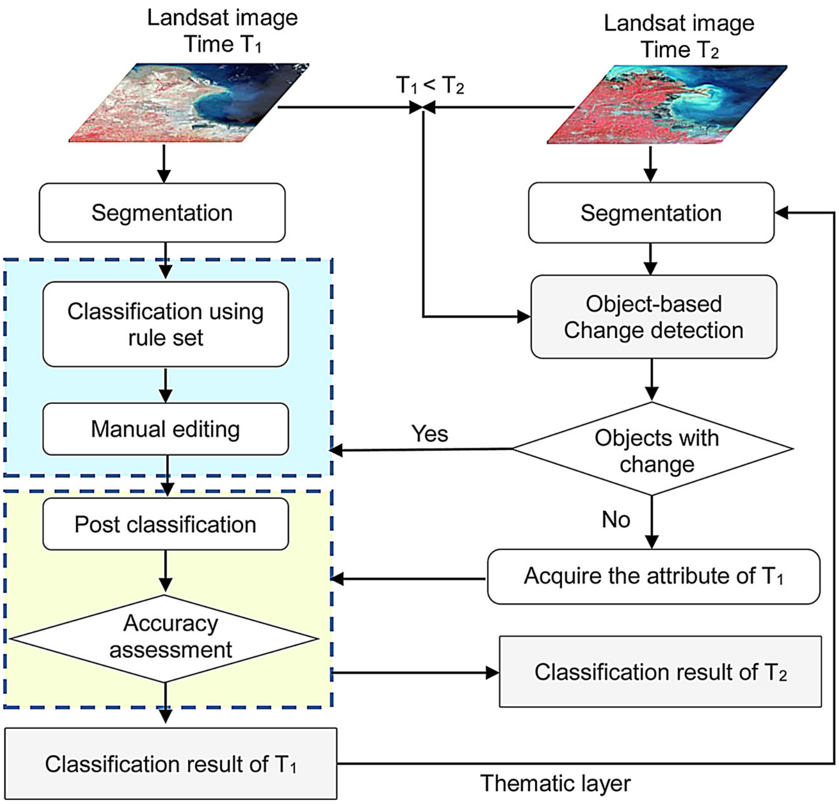

Fig. 2. Flowchart of integrated updating and object-based classification method for aquaculture ponds.

Table 2
The land cover classification system.

Class name	Descriptions
Arable land	Lands cultivated for crops, including paddy land and dry land.
Forest	Lands growing trees including arbor, shrub, and for forestry use.
Grassland	Lands covered by herbaceous plants with coverage greater than 5%.
Wetland	Lands covered by water bodies, or lands with a permanent mixture of water and herbaceous or woody vegetation, including swampland, rivers, lakes, reservoirs, mangrove, mudflat, etc.
Settlement	Lands used for urban and rural settlements, factories and transportation facilities, oil field, stope, and salt pans, etc.
Other land	Lands that are not put into practical use or are difficult to use, including sandy land, salina, bare soil, bare rock and others.
Sea water	The open ocean overlying the continental shelf

Table 3
The overall accuracies and Kappa coefficients for classification.

Year	Aquaculture ponds		Accuracy	
	Ground truth	Classification results	Overall accuracy	Kappa coefficients
1984	420	365	87%	0.80
1990	561	500	89%	0.83
2000	742	668	90%	0.84
2010	823	765	93%	0.87
2016	966	908	94%	0.91

aquaculture ponds in Guangdong sharply expanded by 3,253 km^2 from 1984 to 2016, which was the largest increase among all provinces (Fig. 4B). The ACR (km^2/year) of aquaculture ponds in coastal provinces during different periods are shown in Fig. 4C. The most dramatic expansion of aquaculture ponds, with a rate of 208 km^2/year, occurred in Guangdong (1990–2000), followed by Shandong (1984–1990) with a rate of 164 km^2/year. Although decreases were observed in Tianjin and Shanghai since 2000, the reduced area was small and the net area of aquaculture ponds in 2016 was nearly double that of 1984 in Tianjin and Shanghai. In addition, the provinces located south of China's coastal zone, such as Zhejiang, Fujian, and Guangxi, had a relatively lower ACR (green color) compared with the provinces located north of China's coastal zone (yellow and red colors).

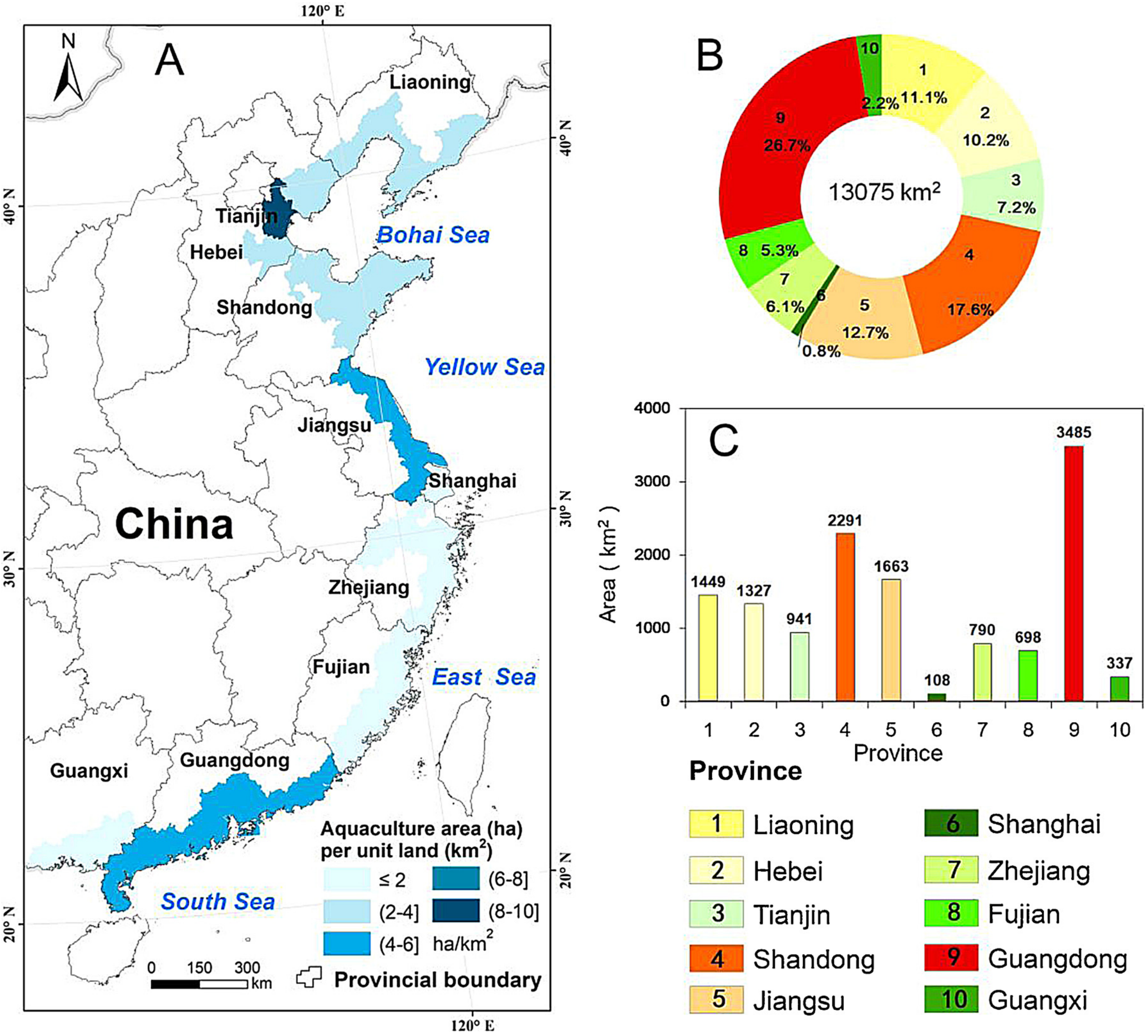

Fig. 3. Area within per unit land (ha/km^2) (A), areal proportion (B) and total area (C) of aquaculture ponds in the coastal provinces of China in 2016.

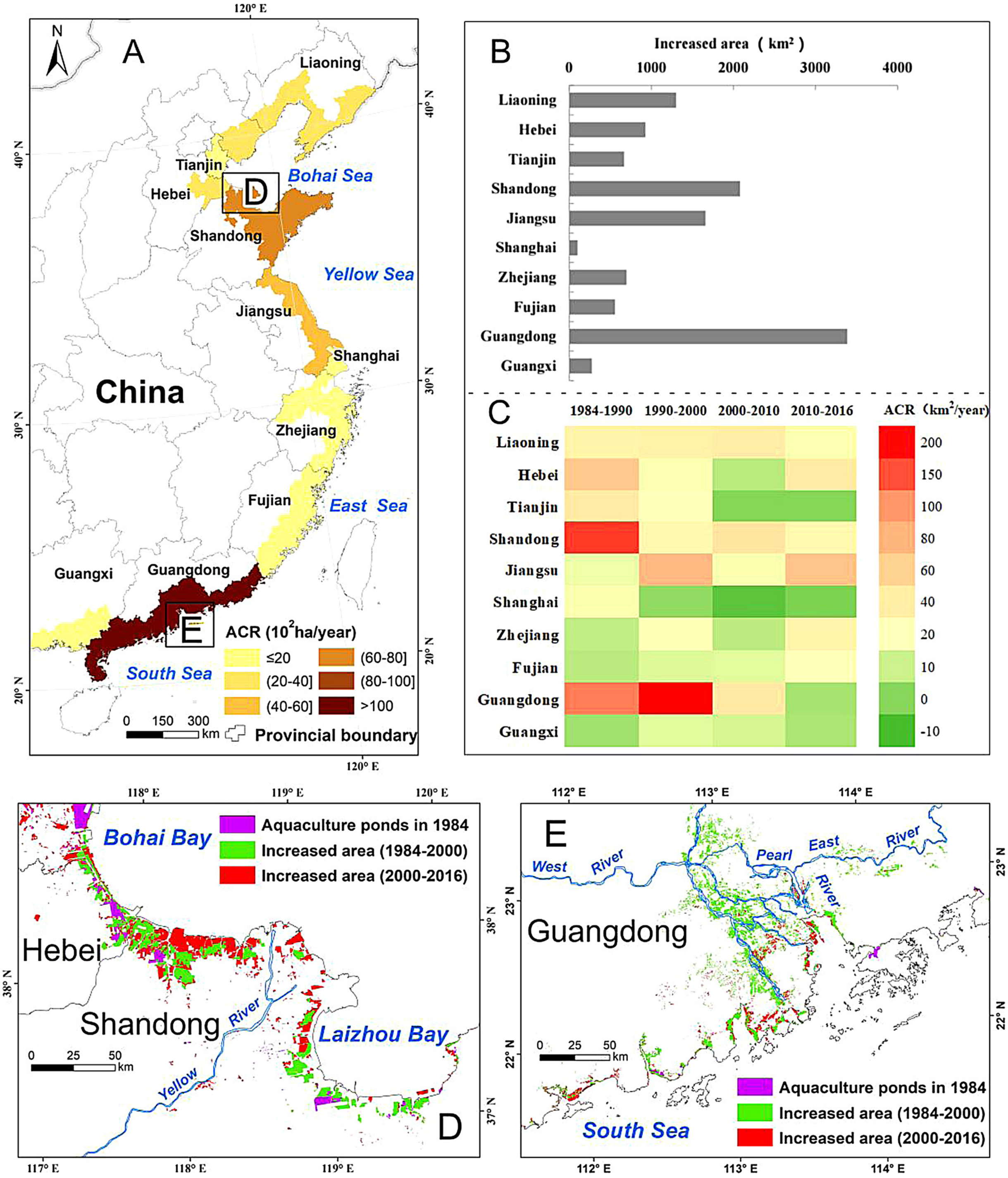

Fig. 4. Areal changes of coastal aquaculture ponds in the coastal zone of China and change hotspots during 1984–2016 (A: ACR of aquaculture ponds in coastal provinces during 1984–2016; B: Increased area of aquaculture ponds in coastal provinces from 1984 to 2016; C: ACR of aquaculture ponds in coastal provinces during four periods; Spatial dynamics of aquaculture ponds in the Yellow River Delta (D) and the Pearl River Delta (E)).

We selected the Yellow River Delta (YRD) (Fig. 4D) and Pearl River Delta (PRD) (Fig. 4E) to illustrate the spatial distribution and dynamics of coastal aquaculture ponds from 1984 to 2016. The newly converted aquaculture ponds in the YRD were mainly distributed near the shoreline and expanded seaward. In the PRD, most of newly converted aquaculture ponds were in the riversides where water is abundant and occurred before 2000.

The area changes of aquaculture ponds in different buffer zones of inshore versus offshore were listed in Table 4. The aquaculture ponds were mostly concentrated within the 0–10 km inshore buffer, occupying 81% of total aquaculture ponds area in 1984. The aquaculture ponds in all buffers increased over the 32 years and the largest net increase was observed in the 0–10 km inshore buffer (6,610 km^2), accounting for 63% of total increased area in the study area. The aquaculture ponds in the 10–20 km inshore buffer and 0–10 km offshore buffer increased almost five-fold and fifty times over that of 1984, respectively. The area increased sharply during 1984–2000 in all buffers, and then pond area increased at a slower rate after 2000.

Table 4
Area of aquaculture ponds in different buffers in China from 1984 to 2016.

	Inshore buffers					Offshore buffers	
	0–10km	10–20km	20–30km	30–40km	40–50km	0–10km	10–20km
1984	2120	263	92	37	36	26	16
1990	4034	596	207	140	139	151	23
2000	6914	1213	408	332	316	282	33
2010	8060	1457	582	388	487	623	42
2016	8730	1514	623	409	495	1206	43

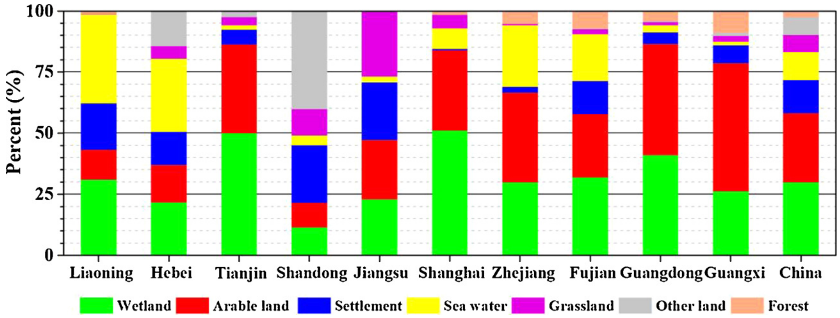

Fig. 5. Percentage of land cover types converted into aquaculture pond in China's coastal provinces during 1984–2016.

3.3. *Land conversions contributing to the expansion of aquaculture ponds*

The percentage of different land cover types converted into the coastal aquaculture ponds in China and coastal provinces were shown in Fig. 5. Results indicated that the expansion of coastal aquaculture ponds in China were mainly induced by the loss of wetland (30%), arable land (28%), settlement (14%) and reclamation from sea water (11%). Wetland contributed more than 25% to the increase of aquaculture ponds in all coastal provinces except for Hebei, Shandong and Jiangsu, and was especially high in Shanghai (51%) and Tianjin (50%). A remarkable amount of wetlands were transformed into aquaculture ponds in Guangdong (1,393 km^2), Liaoning (403 km^2), and Jiangsu (381 km^2). Arable lands converted to aquaculture ponds in Guangxi, Guangdong, Zhejiang and Tianjin occupied 52%, 45%, 37%, and 36% of provincial increased area, respectively. The noticeable conversion from arable land to aquaculture ponds was observed in Guangdong (1,539 km^2), followed by Jiangsu (406 km^2) and Zhejiang (256 km^2). The proportion of settlement converted into aquaculture ponds in Shandong, Jiangsu, and Liaoning were relatively higher than that in other provinces, which may be attributed to the transformation from salt pans. In the land cover map of 1984, salt pans were classified into the settlement land cover type. Land reclamation from sea water to aquaculture ponds was concentrated in Liaoning, Hebei, Zhejiang, and Fujian. Images in Fig. 6 showed typical conversions from wetland (mudflat), sea water, and arable land.

4. Discussion

4.1. *Expansion of coastal aquaculture ponds in China*

China's coastal provinces cover 13% of the nation's territory (Duan et al., 2016; Wang et al., 2014), hosts nearly half of aquaculture area, and contributes more than 60% of the aquaculture production of China based on statistical data (Fig. 7). The aquaculture area and production of the coastal provinces in 2016 increased by 2.7 times and ˜36 fold than that of 1980, which were much higher than the average annual growth rate of world aquaculture production during 1980–2016 (FAO, 2016).

Our estimates based on Landsat observations showed a sharp fourfold increase of aquaculture ponds in the coastal zone of China over the past 32 years. The statistical data for China and coastal provinces involved the entire administrative domain of provinces, while our study area only include the coastal zone defined by 50-km buffer from shoreline. Therefore, the amount of aquaculture area are not suitable to be directly compared. We listed the periodical increase area and ACR for China, coastal provinces and coastal zone defined in this study in Table 5. Our result confirms that the largest expansion of aquaculture ponds in the coastal zone occurred during 1990–2000, in accordance with the trends of that in China and coastal provinces. The ACR of aquaculture from 1990 to 2000 was the highest in China and coastal provinces but slowed down since 2000. However, the ACR of coastal zone during 1990–2000 was slightly lower than that in 1984–1990. The higher ACR was mainly attributed to short term expansion occurred in 1984–1990 in Shandong, Hebei, Tianjin, and Shanghai (Fig. 4C).

Previous studies found that aquaculture ponds in the Pearl River Estuary (Guangdong) increased by 2.75 times from 1985 to 2000 (Gao et al., 2010), and the largest expansion was observed during 1990–2000 (Sun et al., 2010). The aquaculture ponds in Shandong Province experienced rapid expansion from 1980s to 2000 and the net increase in area from 1980s to 2010 was 4.35 times than that of 1980s (Xu et al., 2014). Our results showed that the coastal aquaculture ponds of Guangdong increased by 12-fold from 1984 to 2000, and the net increase in area in Shandong from 1984 to 2010 was 5.8 times than in 1984. Our results had higher area estimates of coastal aquaculture ponds compared to other studies, which are mostly attributed to the different definitions of coastal zone. Although the study areas were different, previous studies and our study have found the similar trends in the increase of coastal aquaculture ponds area and also validated that the period of rapid expansion at hotspots was consistent with national scale statistics.

Additionally, our study explored the characteristics of the spatial distribution and expansion of aquaculture ponds in the coastal zone of China during 1984–2016. First, we found that Guangdong Province had the largest extent of aquaculture ponds in the 0–10 km buffer area in 2016, followed by Shandong Province and Liaoning Province. The length of shoreline, complexity of estuaries, and river shapes were main factors influencing the distribution of aquaculture ponds in Guangdong and Shandong provinces (Fig. 4D and E). Second, our results revealed that most expanded ponds were observed in the 0–10 km inshore buffer area, followed by the 10–20 km inshore buffer area and 0–10 km

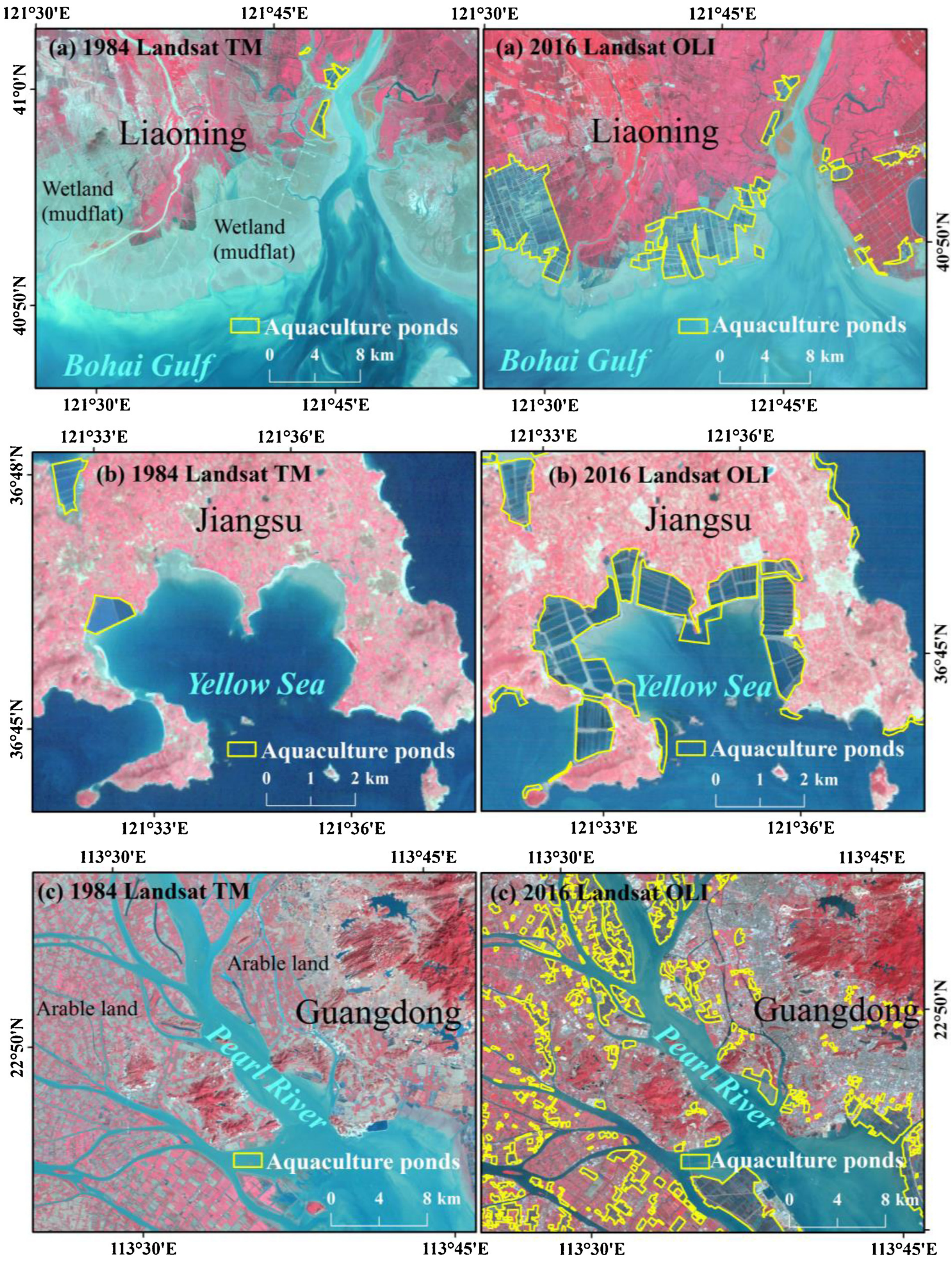

Fig. 6. Landsat image examples (false color composite) for the aquaculture ponds converted from wetland (a), sea water (b), and arable land (c).

offshore buffer area. The inland expansion rate and area were both significantly higher than those of seaward expansion at the coast of China over the past 32 years. In the PRD, the centroid of aquaculture patches showed obvious movement to the northwest of inshore areas (Gao et al., 2010). The inshore change degree of aquaculture ponds in the coast of Shandong Province from the 1980s to 2010 was higher than that of offshore areas (Xu et al., 2014). These studies proved that the spatial expansion of aquaculture ponds mainly occurred in inshore areas at local scales, which is consistent with our results. Scientific spatial planning of coastal development should consider the carrying

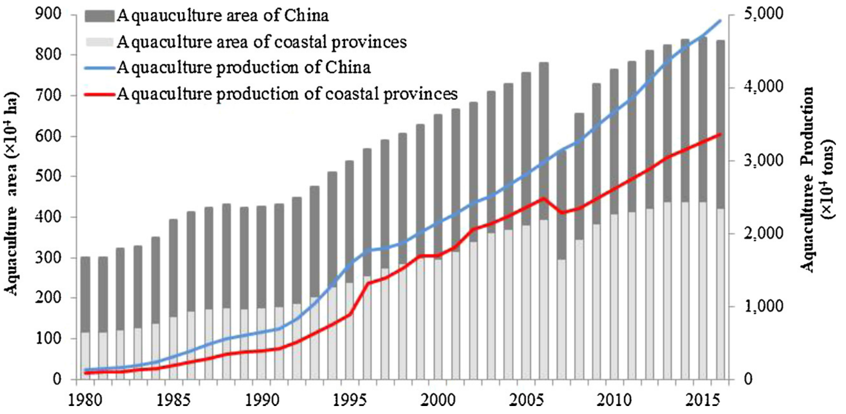

Fig. 7. Temporal variation of aquaculture area and production in China and coastal provinces based on statistical data during 1980–2016.

capacity of specific inshore or offshore areas at provincial and national scales.

4.2. Driving factors for the expansion of coastal aquaculture ponds

Coastal socio-economic development and associated land reclamation are the major driving factors of the expansion of aquaculture ponds in China. All coastal provinces and metropolises in China have experienced severe coastal reclamation related to land scarcity caused by rapid economic growth and urbanization (Tian et al., 2016). During the third stage of coastal land reclamation in China, from the 1980s to late 1990s (Fig. 8a), vast patches of mudflat and sandy beach were reclaimed for mariculture (Liu and Liu, 2008; Wang et al., 2014). It is estimated that the aquaculture ponds contributed the most to land reclamation during 1990–2000 (Gao et al., 2014). Ma et al. (2015) also confirmed that the aquaculture ponds occupied the largest proportion of land reclaimed from wetland, arable land or sea water in the major river deltas of China from 1990 to 2008. Local government policies promoted the development of the aquaculture industry in the coastal provinces of China. For example, in 1985 Fujian Province issued "Outline of Eight Bases Construction" and decided to focus attention on the development of mudflat aquaculture in the shallow sea, and by 1996 aquaculture was declared the pillar industry for Fujian Province. In 2000, "Control Regulations of Mudflat Aquaculture in the Shallow Sea of Fujian Province" encouraged the development and consolidation abandoned mudflats for the aquaculture industry. Consequently, the area of aquaculture ponds in Xiamen City of Fujian Province sharply increased by 6654.97 hm^2 during 1986–2001 (Lin et al., 2007). The central government of China put constraints on coastal reclamation by passing "Sea-Use Law" in 2002 (Song and Liu, 2013), and related policies were further implemented to regulate coastal land reclamation in China. Due to these changes in the aquaculture industry, urbanization, and the rapid development of the coastal economy, reclaimed land was mostly repurposed for urban development, ports, and manufacturing after 2000. Thus, the expansion rate of aquaculture ponds has slowed down since 2000 (Table 5), but the area of coastal aquaculture ponds continues to increase due to the rapid development of China's coastal economy.

Economic conditions have also played a significant role in the expansion of coastal aquaculture ponds due to high profitability and increased demand for seafood. The implementation of the so-called "Reform and Open-up" policy in China led to an increase in demand for seafood for both domestic consumption and export to world market, which prompted a rapid expansion of mariculture (Wang et al., 2014). Furthermore, consumers' demand for mariculture products is not only for high quality, but has also shifted from seasonal demand to perennial demand (Ren et al., 2018), which is a potential factor driving the continuous growth of aquaculture area. On the other hand, compared with traditional industries and agriculture, reclamation for aquaculture is characterized by a low cost, simple process that has a high economic benefit (MacKinnon et al., 2012). People would rather reclaim or convert land from mudflat, enclosed sea, or arable land to aquaculture ponds, especially in the coastal region which is rich in water resources. In addition, based upon statistical data, we can see that population, gross domestic product, gross product of fishery and per capita income of fishery were strongly correlated with aquaculture areas in the coastal provinces of China (Fig. 8(b) and (c)). Aquaculture provides high nutrition supply potential and has high economic benefit. That's the causes for the high correlation between aquaculture areas and population, gross product of fishery and per capita income of fishery.

4.3. Major ecological impacts of coastal aquaculture ponds expansion

The fast development of the coastal aquaculture sector required the conversion of coastal wetlands to ponds. Globally, more than a third of mangrove forests have disappeared over the last decades of the twentieth century (Valiela et al., 2001), and aquaculture is the major human activity accounting for 50% of the decline (Kuenzer et al., 2011). Reclamation for the purposes of aquaculture was listed as one of the major factors causing the decline of mangroves in southern China (Peng et al., 2008, 2013). Aquaculture has rapidly increased in the major river deltas and the initial expansion was followed by a coastward expansion which caused considerable loss of natural wetlands, especially mudflats (Zhu et al., 2016; Chen et al., 2017). Our results also demonstrated that

Table 5
Periodical changes of aquaculture area at different scales from 1984 to 2016.

	1984–1990		1990–2000		2000–2010		2010–2016	
	Increase area (10^4ha)	ACR (10^4ha·yr^{-1})	Increase area (10^4ha)	ACR (10^4ha·yr^{-1})	Increase area (10^4ha)	ACR (10^4ha·yr^{-1})	Increase area (10^4ha)	ACR (10^4ha·yr^{-1})
China	76.15	12.69	**225.78**	**22.58**	112.48	11.25	70.01	11.67
Coastal provinces	37.86	6.31	**121.65**	**12.17**	110.27	11.03	13.64	2.27
Coastal zone	27.05	**4.51**	**42.07**	4.21	21.43	2.14	14.08	2.35

The bold number in Table 5 was the largest increase area and annual change rate among three periods for China, coastal provinces, and coastal zone, respectively.

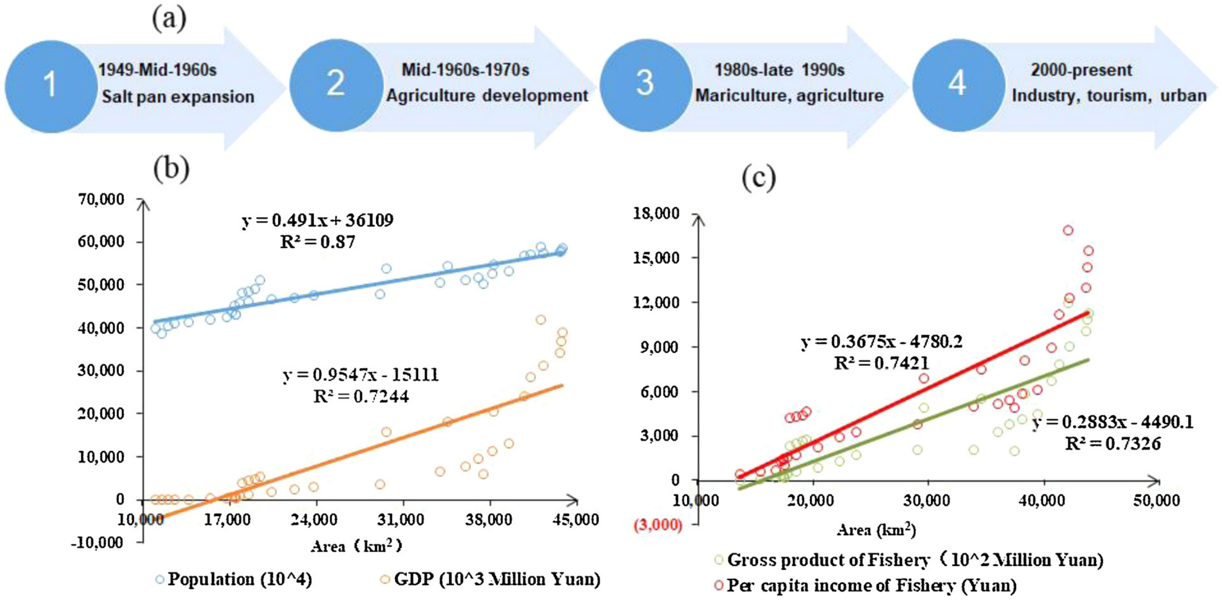

Fig. 8. Socio-economic factors of the aquaculture expansion. (a) Stages of coastal land reclamation in China; (b) Correlations between aquaculture area and total population, GDP of coastal provinces; (c) Correlations between aquaculture area and gross product of fishery, per capita income of fishery of coastal provinces.

the contribution of wetland to aquaculture ponds was approximately 30% in the coastal zone of China and loss of mudflat is the main consequence attributed to those conversions. This pattern was highly identical with the trends observed in other countries of America and Asia, particularly Bangladesh, Vietnam, Thailand, Ecuador and Honduras, where wetlands destruction has been documented in correlation with the expansion of shrimp aquaculture (Berlanga-Robles et al., 2011). Natural coastal wetlands such as mangroves, reeds and mudflats are precious natural landscapes and ecological resources, and play an important role in maintaining biodiversity, controlling pollution, protecting coastlines from disaster (Jiang et al., 2015). The large amount loss of coastal wetlands will lead to further environmental issues such as landscape fragmentation, destruction of coastal biodiversity, decline of ecosystem service value, salinization of coastal soils, increased erosion, and decline in coastal disaster prevention capacity (Kuenzer et al., 2011).

To boost increase in production of aquaculture farms, huge amount of artificial feed, pesticides, chemical additives and antibiotics are continuously added to the ponds (Pattanaik and Prasad, 2011). High amounts of mariculture wastewater enriched with nutrients are released into coastal seawater without treatment, which affects the water quality of the coastal ecosystem (Li et al., 2017). It was reported that excessive nitrogen and phosphorous on the surface of wetlands after a land reclamation project in Isahaya Bay of Japan led to growth of algae, a sharp increase in chlorophyll α, and a red tide algae bloom (Sato and Kanazawa, 2004). Excessive and unrestricted use of antibiotics and chemicals is a general problem in the aquaculture sector, particularly in developing countries (Ottinger et al., 2016). Rico and Van den Brink (2014) calculated that on average 25% of the applied veterinary medicines to aquaculture ponds is released into the environment. In China, large-scale and intensive aquaculture is listed as one of the major sources of coastal seawater pollution (Peng et al., 2013; Ottinger et al., 2016). It was estimated that 63 red tides occurred in a wide range along the coast of China from 2001 to 2014 (SOA, 2002-2015SOA, -, 2015SOA, 2002-2015), which were caused by eutrophic conditions partly due to aquaculture activities. Effluent pollution from shrimp farming contributed to strong local eutrophication processes and has been reported in several individual bays, such as the Bohai Bay, Rushan Bay, and the coast of Weihai in China (Li et al., 2017). Yang et al. (2017) estimated that approximately 47.7×10^3 tons of total nitrogen and 3.75×10^3 tons of total phosphorus are being discharged annually from mariculture ponds into the adjacent coastal zones across China, which represents about 5% of the total nutrient loadings from the main rivers of China into the sea (State Oceanic Administration, People's Republic of China, 2015). Negative effects of waste from aquaculture to aquatic environment are increasingly recognized, though they are just a small proportion compared to land-based pollutants (Cao et al., 2007). However, increasing demand for the services of aquatic ecosystems has resulted in a huge increase in the development of aquaculture in China's coastal areas and estuaries, eutrophic conditions and environmental degradation in the adjacent coastal waters will continue to occur or be exacerbated in the future. Effective treatment of aquaculture pond effluents before discharge will become an important challenge in the future to alleviate the pressures of eutrophication in coastal zones (Yang et al., 2017). Moreover, scientific planning and utilization of coastal areas for aquaculture production in China should be highlighted for sustainable development of economics and environmental protection.

5. Conclusions

We present the first comprehensive and consistent national coastal aquaculture ponds database, CAS_Coastal Aquaculture, at 30-m spatial resolution ever created. We developed and used an integrated updating and object-based classification approach and mapped aquaculture ponds with coherent data sources, wall-to-wall coverage and ancillary data (field samples and Google Earth). Our high-spatial-resolution database delivers national maps of coastal aquaculture ponds, which substantially advances our understanding of the distribution, trajectory and status of these poorly known coastal ecosystems.

Coastal aquaculture ponds in China significantly expanded during 1984–2016 by 10,463 km^2, with an overall rate of 327 km^2/year. Sharp expansion of aquaculture ponds were observed during 1990–2000 and mostly occurred 0–10 km inshore. Most of the expanding aquaculture ponds were converted from natural wetlands and arable land. The coastal provinces of Guangdong, Shandong, and Jiangsu were identified as hotspots of aquaculture ponds expansion and had inconsistent rates of change at different periods. However, the general trend of expansion in the whole coastal zone accelerated from 1984 to 2000 and slowed down after 2000. Rapid expansion of coastal aquaculture ponds in China was mainly driven by socio-economic factors, such as governmental policies related to land reclamation and ocean development, economic development, and population growth. Large losses in natural wetlands and water pollution have been the major ecological consequences of the expansion of coastal aquaculture ponds. Scientific, knowledge-based, and sustainable coastal zone development is needed. Our conclusions provide useful information and scientific guidance to governments and conservationists to make policies that effectively protect coastal ecosystems.

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