Chin. Geogra. Sci. 2018 Vol. 28 No. 3 pp. 430–442
https://doi.org/10.1007/s11769-017-0926-2

Springer Science Press
www.springerlink.com/content/1002-0063

Remote Monitoring of Expansion of Aquaculture Ponds Along Coastal Region of the Yellow River Delta from 1983 to 2015

REN Chunying[1], WANG Zongming[1], ZHANG Bai[1], LI Lin[2], CHEN Lin[1, 3], SONG Kaishan[1], JIA Mingming[1]

(1. *Key Laboratory of Wetland Ecology and Environment*, *Northeast Institute of Geography and Agroecology*, *Chinese Academy of Sciences*, *Changchun* 130102, *China*; 2. *Department of Earth Sciences*, *Indiana University-Purdue University*, *Indianapolis* 46202, *USA*; 3. *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*)

Abstract: Aquaculture ponds are one of the fastest-growing land use types in valuable and fertile coastal areas and have caused serious environmental problems. Quantitative assessment of the extent, spatial distribution, and dynamics of aquaculture ponds is of utmost importance for sustainable economic development and scientific management of land and water resources in the coastal area. An object-oriented classification approach was applied to Landsat images acquired over three decades to investigate the long-term change of aquaculture ponds in the coastal region of the Yellow River Delta. The results indicated that the aquaculture ponds in the study area undergone a sharp expansion from 40.38 km^2 in 1983 to 1406.89 km^2 in 2015, and the fast expansion occurred during the period of 2010–2015 and 1990–2000. Natural wetlands, especially mudflat, and cropland were main land use types contributing to the increase of aquaculture ponds. The patches of aquaculture ponds were consequently prevalence in the north of the Yellow River Estuary and landscape metrics indicated an increase of the aquaculture ponds of the study area in the quantity and complexity. The expansion of aquaculture ponds inevitably had negative effects on the coastal environment, including loss of natural wetlands, water pollution and land subsidence, *etc*. The results from this study provide baseline data and valuable information for efficiently planning and managing aquaculture practices and for effectively implementing adequate regulations and protection measures.

Keywords: aquaculture ponds; remote sensing; coastal region; Yellow River Delta

Citation: REN Chunying, WANG Zongming, ZHANG Bai, LI Lin, CHEN Lin, SONG Kaishan, JIA Mingming, 2018. Remote Monitoring of Expansion of Aquaculture Ponds Along Coastal Region of the Yellow River Delta from 1983 to 2015. *Chinese Geographical Science*, 28(3): 430–442. https://doi.org/10.1007/s11769-017-0926-2

1 Introduction

Intensive land reclamation from the sea occurs in many coastal countries (Kennish, 2001; Alonso-Pérez et al., 2003; Suzuki, 2003; Hoeksema, 2007; Ma et al., 2014). It is an effective way to acquire land resources and accommodate the increasing need for the development of agriculture and aquaculture, industrialization and urbanization (Zhu et al., 2016). Aquaculture is a main way of land reclamation in coastal regions. Aquaculture ponds have rapidly expanded with the fast development of aquaculture and created enormous economic benefits; however, it often results in serious environmental problems: immediate and severe damages to coastal wetlands ecosystems, the deterioration of marine environmental quality and other consequences, such as water pollution, biodiversity loss, landscape fragmentation (Duan et al., 2016; Tian et al., 2016). A scientific knowledge based space design for sea reclamation can improve coastal environment and minimize destruction and disturbance to marine environment (Daily, 1997). Hence, there is an urgent need to identify and assess the

Received date: 2017-05-08; accepted date: 2017-08-01
Foundation item: Under the auspices of National Program on Key Basic Research Project (No. 2013CB430401)
Corresponding author: ZHANG Bai. E-mail: zhangbai@iga.ac.cn

spatial distribution of aquaculture at local, regional and global scales. Such information is valuable to analyze the increasing pressure on ecosystems and related environmental impacts (Ottinger et al., 2016).

Remote sensing provides many advantages over field surveys in monitoring inaccessible coastal ecosystems in addition to being accurate, rapid, and cost effective (Spalding et al., 1997; Jia et al., 2016). Previous studies have used remote sensing to investigate and monitor aquaculture ponds. Fuchs et al. (1998) used Landsat Thermatic Mapper (TM), Satellite Pour l'Observation de la Terre (SPOT) and airborne hyper-spectral data to perform a supervised classification of land cover including aquaculture ponds. Virdis (2014) used a SPOT-5 image and WorldView-1 image to classify coastal aquaculture in Tam Giang-Cau Hai Lagoon. Zhang et al. (2010) assessed an automatic object-based approach for aquaculture mapping with TM imagery in the coastal zone of East China Sea. Hazarika et al. (2000) estimated the growth of shrimp farms in a coastal district of Chanthaburi province in Thailand using the Landsat TM and ADEOS-AVNIR (Advanced Visible and Near Infrared Radiometer type) acquired in 1987 and 1997. The dynamics of aquaculture ponds was investigated by use of high or moderate resolution remote sensing imagery in the Yellow River Delta, Pearl River Estuary, Hainan Province, and Shandong Province of China (Chu et al., 2006; Wu et al., 2006; Guan et al., 2009; Sun et al., 2010; Xu et al., 2014). Yao et al. (2016) mapped aquaculture ponds and analyzed the change using a series of Landsat data of the whole coastal region of China. Numerous effort have been devoted towards aerial estimation and mapping of aquaculture activities around the globe (Ottinger et al., 2016). All the above mentioned studies prove that remote sensing is an effective tool for providing timely and accurate information on aquaculture ponds, which is very useful for scientists and public authorities to elaborate a strategy for environmental conservation and natural resource management.

The Yellow River Delta is the youngest land in the east of China, and has the broadest, youngest and the most integrated wetland ecosystem (Li et al., 2006). Meanwhile, as one of the most active regions of land-ocean interaction among the large river deltas in the world (Cui et al., 2009a; Li et al., 2009), the Yellow River Delta has been undergoing an extensive and rapid development of land reclamation over the recent decades (Zhang et al., 2011; Wang et al., 2012a). Shengli Oil-field has more than twenty thousand wells spread all over the Yellow River Delta since 1964 (Gong et al., 2004). A large portion of wetland and wilderness has been cultivated and wide foreshore areas have been exploited as extensive shrimp ponds and salt pans (Zhou et al., 2007). These anthropogenic activities caused natural wetlands to decline by 38.6% from 2566 km^2 in 1986 to1575 km^2 in 2008 (Wang et al., 2012b) and man-made wetlands to increase by 42 116.90 ha during the period of 1976–2008 (Chen et al., 2011). Studies have been undertaken concerning changes of wetlands (Wang et al., 2012c) and its impacts on soil nutrients (Yu et al., 2012), agricultural reclamation (Han et al., 2014), the ecosystem-service value (Valdez et al., 2014), plant communities (Xiang et al., 2010), hydrology process (Li et al., 2009), and wetlands restoration (Cui et al., 2009b). However, to date, few studies have focused on tracking the spatial distribution and changes of aquaculture ponds for a long time period, which have important implications for understanding coastal environment, such as water pollution and resources overexploitation.

In this study, remote-sensing and geographic information system technologies were used to analyze a series of Landsat data from 1983 to 2015 and to characterize the spatial distribution and changes of aquaculture ponds in the Yellow River Delta. The objective of this study is to provide detailed information on the expansion of aquaculture ponds since 1983 for effectively managing land reclamation in the Yellow River Delta.

2 Materials and Methods

2.1 Study area

This study was carried out in the coastal zone of the Yellow River Delta (36°48′22″N–38°24′14″N, 117°59′20″E–120°36′55″E), located to the north of Shandong Province, including parts of Binzhou and Dongying cities, with an area of 1.17×10^4 km^2 (Fig. 1). This region is characterized by warm temperate continental monsoon climate with distinctive seasons and rainy summer. The annual average temperature is 12.1℃, the frost-free period lasts for 196 d, and the annual average precipitation and evaporation is approximately 551.6 and 1962 mm (Cui et al., 2009b), respectively, with 70% of the total precipitation occurring between May and September. The elevation is generally below 10 m except for roads

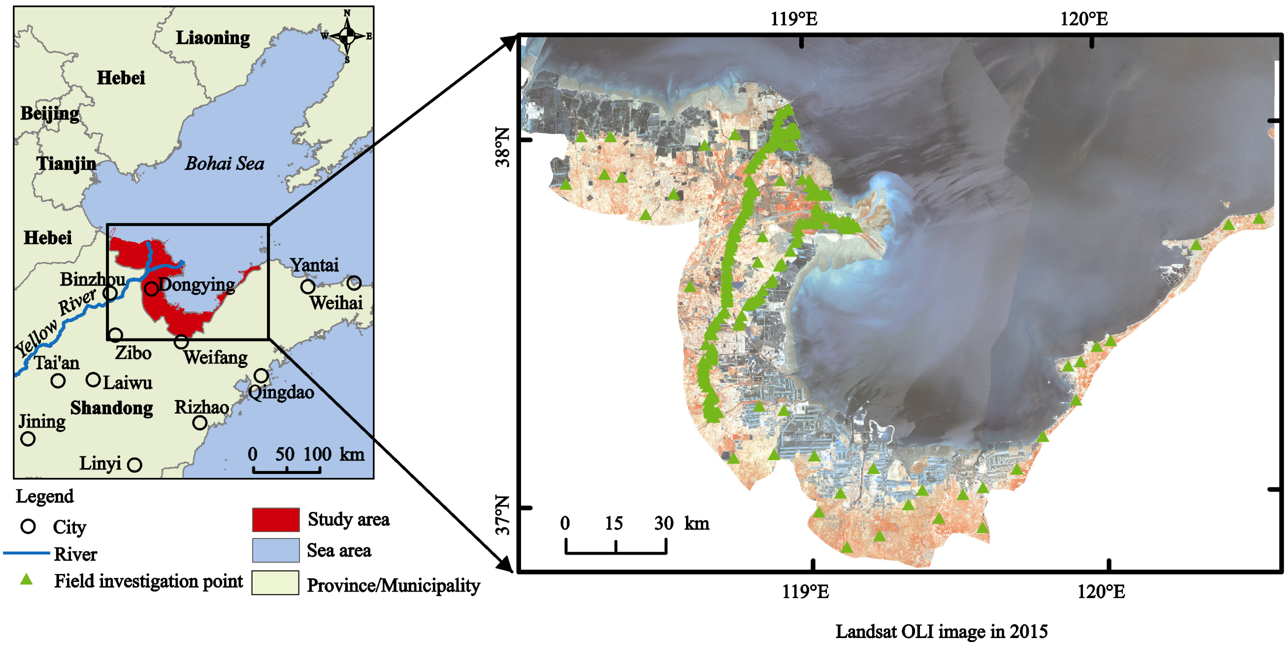

Fig. 1 Location of study area and false color composite image of Landsat Operational Land Imager (OLI) in 2015

and dikes. Due to the flat terrain and high groundwater table, this region is mainly covered by wet and saline soil, deriving from the sediment and the parent materials of loess soil (Huang et al., 2012). The natural vegetation in this area consists of salt tolerant herbs, grasses, and shrubs (Han et al., 2014). The main economic activities are agriculture, mariculture, petroleum and salt industry.

2.2 Data and preprocessing

Time series of Landsat images with a moderate resolution of 30 m/80 m were used to detect change of aquaculture ponds in the coastal region of the Yellow River Delta. Ten cloud-free scenes for years 1983, 1990, 2000, 2010 and 2015 were downloaded from the USGS Center for Earth Resources Observation and Science (http://glovis.usgs.gov/). The information on Landsat data used in this study is shown in Table 1. These images were of the highest available quality and have been precisely geo-rectified and radiometrically calibrated. For a single period, the entire region of the study area was covered using two Landsat scenes. Although the Landsat images were geo-rectified, a direct comparison among the images could not be made because the spatial resolutions and coordinate reference systems used in the images were inconsistent (Jia et al., 2016). Thus, MSS images were resampled to a pixel size of 30 m × 30 m, which is the spatial resolution of Landsat TM images. All the Landsat images were warped to the Albers projection with two standard lines. In this study, the ENVI software (ENVI, 2010) was employed to perform the re-projection, mosaic and resampling on the Landsat images.

In this study, ground surveys were conducted along coastal region of the Yellow River Delta during May and June 2015. The location of each sampling point was documented using global positioning system (GPS) units, with errors less than 10 m. These surveys resulted in 112 aquaculture pond points and 324 points of other land cover types. Out of those sampling points, 68

Table 1 General characteristic of employed Landsat images

Year	Path/Row	Acquisition date	Sensor	Spatial resolution (m)
1983	120/34	13 May, 1983	MSS	80
	121/34	7 July, 1983	MSS	80
1990	120/34	24 May, 1990	TM	30
	121/34	16 June, 1990	TM	30
2000	120/34	8 September, 2000	TM	30
	121/34	17 October, 2000	TM	30
2010	120/34	6 October, 2010	TM	30
	121/34	6 May, 2010	TM	30
2015	120/34	13 May, 2015	OLI	30
	121/34	4 May, 2015	OLI	30

Notes: MSS: Multi-spectral Scanner; TM: Thermatic Mapper; OLI: Operational Land Imager aquaculture ponds points and 190 other land cover points (with a minimum of 10 points per land cover type) were selected as training samples during the classification. The remaining 44 aquaculture ponds points and 134 other land cover points were used to validate the classification results for the Landsat data of the same period. The land resource map, topographic map, photos from Google earth and the historic investigation points from local experts were used to assess the classification results for the other years. The spatial distribution of field investigation points in 2015 is shown as green dots in Fig. 1.

2.3 Methods

2.3.1 Object-oriented classification

The eCognition Developer 8.64 (Definiens, 2011) was chosen to perform the object-oriented image classification for the extraction of aquaculture ponds. The workflow of extracting aquaculture ponds consisted of segmenting images, rule-building and exporting vectors. First, all bands of OLI, TM or MSS as well as the corresponding Normalized Difference Water Index (NDWI) were stacked as the input dataset for classification. Second, a multi-scale segmentation method was applied for creating image objects. Parameters for image segmentation include scale, shape, and compactness. After a 'trial and error' process for testing the segmentation parameters, the scale of first level was set at 50 for discriminating water and non-water, and the second level was set at 10 for extracting aquaculture ponds. The shape factor and compactness factor was set at 0.1 and 0.5, respectively. Third, decision tree rule-building was developed primarily based on statistical analysis of the training areas resulting from the field surveys and images (Fig. 2). Parameters such as NDWI, object based spectral attributes, rectangular fit, area and shape index were selected as key factors for rule-building. To obtain the best classification, the extraction of aquaculture ponds was confirmed by visual interpretation. Other land cover types were identified using a Nearest Neighbor classifier with training samples created from the ground survey data and images. Fourth, the extracted aquaculture ponds and other land cover types were exported as shapefiles. Aquaculture ponds were extracted for each image acquired on different acquisition dates. The threshold of each rule varied and was optimized for the best classification based on the image dates.

2.3.2 Accuracy assessment of classification

To assess the accuracy of extracting aquaculture ponds, a confusion matrix was adopted to measure the agreement between the classification result and the validation samples. The user's accuracy, producer's accuracy, overall accuracy, and Kappa coefficient were calculated. The overall accuracy shows the percentage of the points correctly identified (Rodrigues and Souza-Filho, 2011). The user's accuracy represents the likelihood that a classified object matches the ground situation. The producer's accuracy shows the proportion of object types that were correctly classified. The Kappa coefficient indicates how much the classification is apart from a random classification (Conchedda et al., 2008). The performance of the accuracy assessment was carried out with ArcGIS 10.0 (ESRI, 2010).

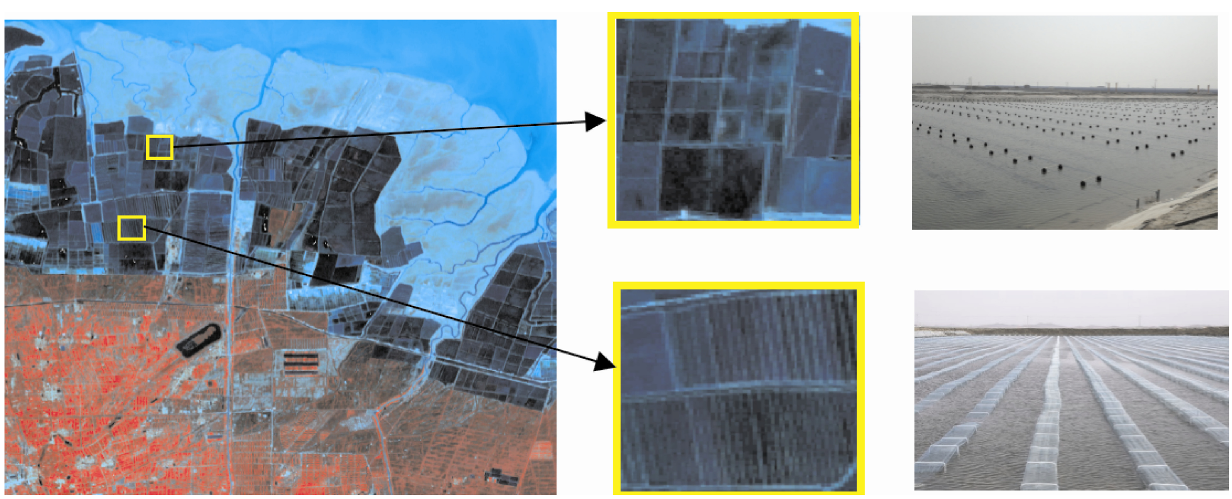

Fig. 2 Interpretation symbols of aquaculture ponds and field photos

2.3.3 Quantification of changes

Quantification of changes included three-steps: 1) the area, trend and spatial characteristics of aquaculture ponds change were obtained by analysis of the classified results using GIS, and the changes were evaluated in the following four time periods: period 1 (1983–1990), period 2 (1990–2000), period 3 (2000–2010), and period 4 (2010–2015). 2) A detailed change analysis matrix helps identify the process of change within the landscape (Zewdie and Csaplovics, 2016). Thus, the transition matrix (Zhu and Li, 2003) was employed to interpret categorical change information, which included conversions from aquaculture ponds (earlier date) to other classes (later date) and conversions to aquaculture ponds (later date) from other classes (earlier date). The transition matrix was derived from cross tabulations of classified pairs for each period by use of TABULATE command in ArcGIS (version 10.0). 3) The landscape indices are constantly adopted in the landscape ecology to show the pattern and process of the landscape change in a quantitative way (Turner and Gardner, 1991). To further investigate the change pattern of aquaculture ponds, four landscape metrics at the class level and landscape level were examined: the number of patches (NP), patch density (PD), largest patch index (LPI), and areal weighted fractal dimension (FRAC_AM). The definitions of these metrics are listed in Table 2. Based on the grid data from GIS, these indices were calculated utilizing the most commonly used landscape pattern analysis software FRAGSTATS 4.0 (UMass Landscape Ecology Lab, 2015).

3 Results

3.1 Spatial and temporal dynamics of aquaculture ponds

The confusion matrix is presented in Table 3, including user's accuracy, producer's accuracy, overall accuracy and the Kappa coefficient of the classification results. Overall classification accuracy for years 1983, 1990, 2000, 2010 and 2015 was 85% or higher, and kappa coefficients were 0.80 or higher. Classification errors were observed because aquaculture ponds and salt field had similar regular shape and spectral characteristics and hard to separate. The accuracy assessment for mapping aquaculture ponds indicated that aquaculture ponds had a relatively high producer's and user's accuracy and our mapping results are consistent with those obtained from field investigation sites.

Results from the image classification in the study area from 1983 to 2015 are shown in Fig. 3. The main land cover types in 1983 were cropland and natural wetlands,

Table 2 Definitions of landscape metrics

Index	Symbol	Definition	Formula
Number of Patches	*NP*	Number of patches divided by area	$NP = n_i$ n_i = number of patches in the landscape of patch type (class) i
Patch density	*PD*	Density of patches divided by area	$PD = n_i/A$ A = total landscape area (m^2)
Largest Patch Index	*LPI*	The percentage of total landscape that is made up by the largest patch	$LPI = \frac{\text{Max}(a_1,...,a_n)}{A} \times 100$ a_i = area of patch i (m^2)
Area weighted fractal dimension	*AMFD*	Mean patch fractal dimension with the addition of individual patch area weighting applied to each patch	$AMFD = \sum_{j=1}^{n}\left[\left(\frac{2\ln(0.25P_{ij})}{\ln a_{ij}}\right)\left(a_{ij} / \sum_{j=1}^{n} a_{ij}\right)\right]$ a_{ij} = area of patch ij (m^2) p_{ij} = perimeter (m) of patch ij

Table 3 Accuracy of land cover classification results

Type	Aquaculture ponds				
	1983	1990	2000	2010	2015
PA (%)	88.2	87.5	90.3	96.7	96.1
UA (%)	83.5	88.0	85.0	93.5	98.0
Overall accuracy (%)	85.0	87.0	86.0	90.0	92.0
Kappa coefficient	0.80	0.82	0.83	0.88	0.93

Notse: PA represents producer's accuracy; UA represents user's accuracy

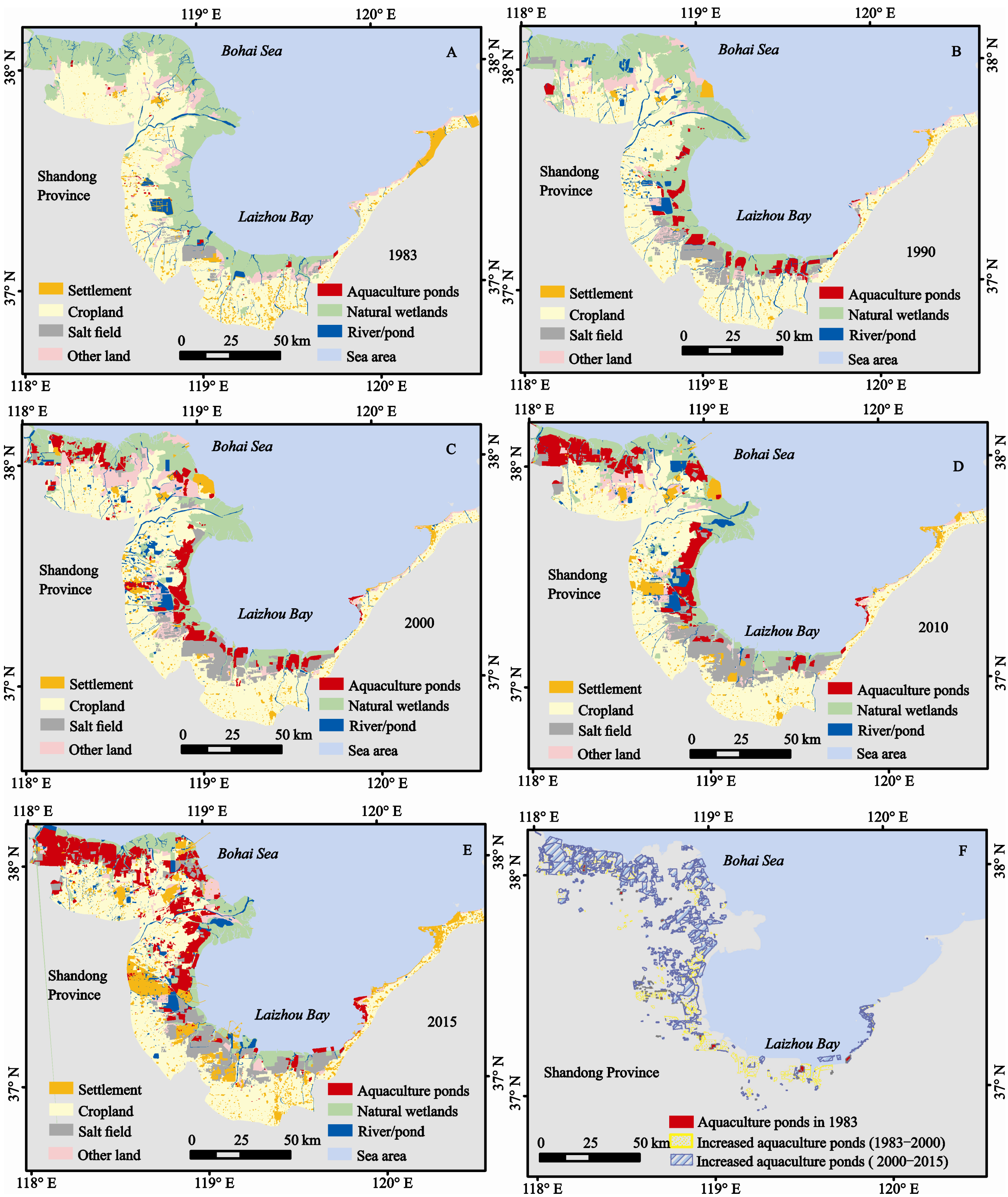

Fig. 3 Land cover classification of study area and changes of aquaculture ponds between 1983 and 2015. (A) Aquaculture ponds and other land cover types in 1983, (B) Aquaculture ponds and other land cover types in 1990, (C) Aquaculture ponds and other land cover types in 2000, (D) Aquaculture ponds and other land cover types in 2010, (E) Aquaculture ponds and other land cover types in 2015, (F) Aquaculture ponds changes during 1983–2015

accounting for 52% and 32% of the whole study area, respectively. In 1983, the coastal region of this study area was generally covered by natural wetlands, mainly including salt marsh, freshwater marsh and mudflat in this study (Fig. 3A). The expansion of aquaculture ponds occurred initially from the south bank of Laizhou Bay (Fig. 3B). During the period of 2000–2015, numerous patches of aquaculture ponds expanded to the north of the Yellow River Estuary (Figs. 3C–3F).

Land cover of the study area has experienced significant changes related to human influences during the past 32 years. In brief, the area of cropland and natural wetlands greatly decreased and the area of aquaculture ponds, settlement and salt field increased. The area of aquaculture ponds within the study area increased continuously over the 32 years, from 40.38 km^2 in 1983 (0.4% of the total area) to 1406.89 km^2 in 2015 (16% of the total area) (Fig. 4). The net increase of aquaculture ponds was 1366.51 km^2 during the 32-year period. In the four periods of this study, the growing rate of aquaculture ponds varied with a particularly rapid increase occurring between 2010 and 2015, from 11% to 16% of the total area and being 93.5 km^2 per year.

3.2 Land conversions contributed to expansion of aquaculture ponds

Based on the transition matrix of the four different periods, land conversions contributed to the expansion of aquaculture ponds were identified and characterized in Fig. 5. From 1983 to 2015, natural wetlands were the largest cover type that was changed to the aquaculture ponds, and accounted for 55% of the gain area of aquaculture ponds. Especially in period 1 and period 2, natural wetlands accounted for 72% and 71% of the gain area of aquaculture ponds, respectively. Natural wetlands converted to aquaculture ponds in period 1, period 2, period 3 and period 4 were 251.1, 364.2, 305.3 and 195.8 km^2, respectively. In period 3, the percentage of natural wetlands occupying the gain area of aquaculture ponds dropped but the area of natural wetlands changed to aquaculture ponds was still large. In period 4, cropland was the largest source for the expansion of aquaculture ponds. The area of cropland changed to aquaculture ponds was 251.5 km^2, accounting for 37% of the increased aquaculture ponds in this period.

Besides natural wetlands, cropland was another main source for the expansion aquaculture ponds from 1983 to 2015. An increasingly large amount of cropland was transformed into aquaculture ponds. The percentage of cropland changed to aquaculture ponds accounted for 9%, 17%, 11% and 37% of the gain area of aquaculture ponds in period 1, period 2, period 3 and period 4, respectively. The transition matrix for the period of 1983 to 2015 also reveals the dynamics of the gain area of aquaculture ponds and the total percentage of natural wetlands and cropland contributed to the increase of aquaculture ponds (Fig. 6). It can be observed that the combined percentage of natural wetlands and cropland converted to aquaculture ponds has declined from 88% in period 2 to 67% in period 4. The total area of other

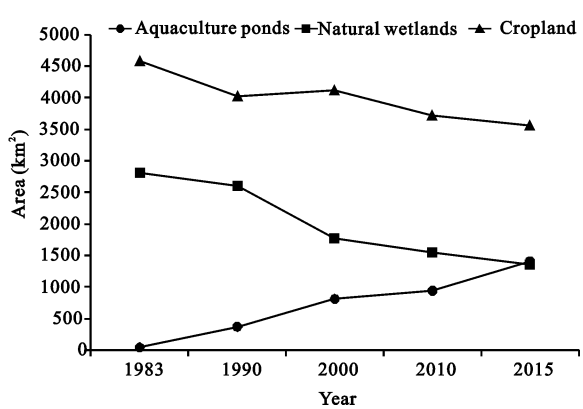

Fig. 4 Area changes of aquaculture ponds, natural wetlands and cropland from 1983 to 2015

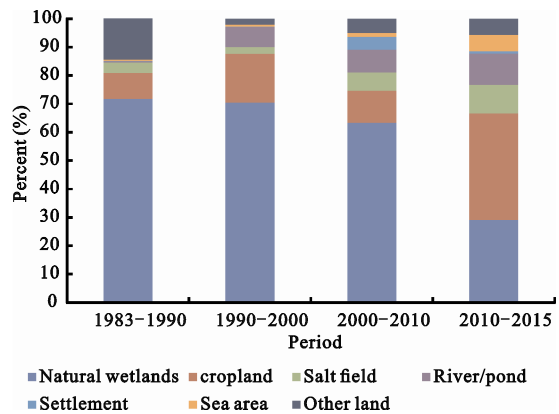

Fig. 5 Contributions of different land covers to the expansion of aquaculture ponds.

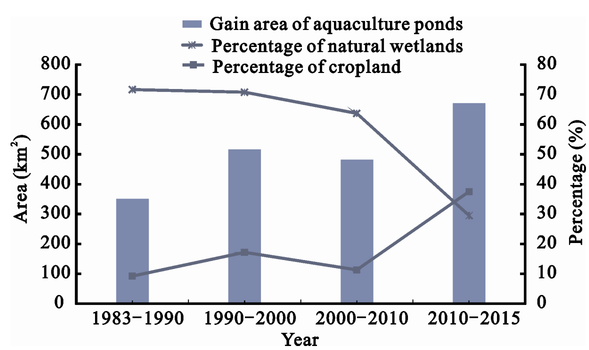

Fig. 6 Gain area of aquaculture ponds and the percentage contribution of natural wetlands and cropland

land cover types contributed to the increase of aquaculture ponds increased from 1983 to 2015.

3.3 Landscape pattern change of aquaculture ponds

The variation of the four landscape pattern indices for aquaculture ponds in the study area is illustrated in Table 4, and the evolution process of landscape pattern was analyzed chronologically.

The number of patches (NP) for aquaculture ponds in the coastal region of the Yellow River Delta has an obviously rising trend since 1983, ranging from 56 to 268 and suggesting an increased area and landscape heterogeneity. The patch density (PD) for aquaculture ponds has a slightly rising change during the study period. The largest aquaculture pond patch of the total landscape area (LPI) continuously increased over time, particularly in the last 15 years (2000–2015), implying that larger and combined patches occurred in the study area. Fractal analysis mainly emphasizes the autocorrelation of patches and a larger value indicates a more complicated shape (Ren, 2008). The overall area weighted fractal dimension (AMFD) of aquaculture ponds in the study area is relatively low. This means the aquaculture pond patch is not complicated in shape. The AMFD series have slightly increased in the past 32 years, which indicates the landscape pattern for the aquaculture pond patches has turned to be more and more complicated.

Landscape pattern indices at landscape level for the whole study region and at class level for natural wetlands were calculated and listed in Table 5. For the whole region, NP and PD increased as well as LPI and AMFD declined, which indicates the landscape pattern for the whole region has turned to be more fragmented and the impacts of human activities on the landscape pattern were stronger than before. Natural wetlands showed an opposite trend of NP, PD and LPI compared with aquaculture ponds. For natural wetlands, NP, PD and LPI decreased and AMFD have slightly increased in the past 32 years. The change trend of landscape indices reflects the loss, fragmented and complicated shape of natural wetlands patches.

Table 4 Spatial pattern indices and their processes for aquaculture ponds

Year	NP	PD	LPI	AMFD
1983	56	0.0047	0.06	1.05
1990	99	0.0082	0.35	1.06
2000	100	0.0083	0.46	1.08
2010	159	0.0094	1.52	1.10
2015	268	0.0222	1.73	1.11

Notes: NP-Patch number; PD-Patch density; LPI-Largest Patch index; AMFD-Area weighted fractal dimension

Table 5 Spatial pattern indices for the whole region and natural wetlands

Type	Year	NP	PD	LPI	AMFD
Landscape	1983	2371	0.197	19.2	1.156
	2015	3421	0.284	13.7	1.147
Natural wetlands	1983	192	0.0053	1.69	1.116
	2015	170	0.0047	1.06	1.117

4 Discussion

4.1 Expansion of aquaculture ponds in coastal region of the Yellow River Delta

China has a long history of coastal reclamation in river delta areas in relation to the coastal defense and has continuously reclaimed coastal wetlands at a large scale for conversion to agricultural, urban, and industrial uses since the 1950s (Temmerman et al., 2013; Wang et al., 2014). The coastal reclamation had been changed from mainly agricultural land to the aquaculture pond and then to unused water surface in the coastal region of China from 1980 to 2010 (Gao et al., 2014). In the Yellow River Delta, the main types of reclamation include construction of reservoirs and harbors, aquaculture, salt field and agriculture. From 1976–2015, man-made wetlands increased by 2891 km^2, which were primarily ascribed to the expansion of aquaculture ponds and salt field (Chen et al., 2017). Ma et al. (2015) reported that the area of aquaculture ponds was the largest among all the coastal land reclamation in the Yellow River Delta during 1990–2008. In this study, the classification results show that aquaculture ponds in the coastal region of the Yellow River Delta kept rising from 1983 to 2015 with an average speed of 42.70 km^2 per year. The fastest expansion of aquaculture ponds occurred in the period of 2010–2015, and the area increased by 467.52 km^2 with a rate of 93.5 km^2 per year. If not considering the period of 2010–2015, the increased area of aquaculture ponds from 1990–2000 was the largest. Xu et al. (2014) revealed that the coastal aquaculture area of Shandong Province had increased from the late 1980s to 2010 and the increased area of aquaculture ponds in the same period was the largest, which is consistent with our results. In addition, the increase rate of aquaculture ponds in the coastal region of Yellow River Delta also has the same change trend as that of the whole coastal region of Shandong Province, which slowed down after year 2000.

The study area occupied more than 10 counties of Binzhou and Dongying cities, Shandong Province, but the change of aquaculture ponds in those counties was obviously different. The area of aquaculture ponds in Zhanhua County, Laizhou City, Kenli County and Dongying City kept rising from 1983–2015, except that the trend for Laizhou City had a turning point in 2010 but its overall changing trend is still increasing (Fig. 7). In fact, Zhanhua County, Kenli County and Dongying City were located in the north of the Yellow River Estuary, south bank of Bohai Bay. Combined with Fig. 3F, it can be seen that the increased aquaculture ponds were mostly distributed in the north of the Yellow River Estuary after 2000. Meanwhile, Weifang City, Shouguang City, Guangrao County, and Changyi City also showed an identical changing trend of aquaculture ponds (Fig. 8). The area of aquaculture ponds of those cities increased from 1983 and had a turning point in 2000 or 2010. Finally, the area of aquaculture ponds in 2015 was still larger than that of 1990 in each county with the exception of Weifang City. From Fig. 3F, the increased aquaculture ponds after 2000 could be ignored in the south of the Yellow River Estuary. Generally speaking, the distribution of aquaculture ponds of the study area shifted toward to the north-west of this coastal region, which is also consistent with a previous study for the coastal region of Shandong Province (Xu et al., 2014). The reason for this spatial change was the expansion of salt field in the south bank of Laizhou Bay. ‘Salt field of Laizhou’ was an important export base for solar salt. Large stocks for salt production were found in Laizhou City in 2005. Much area in the south bank of Laizhou Bay were turned into salt field according to the spatial analysis between land cover data of 2010 and 2015 in this study.

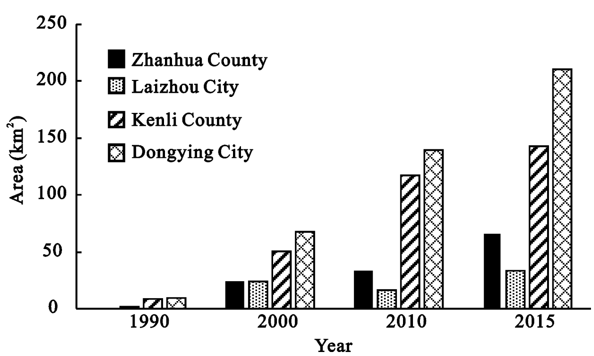

Fig. 7 Area changes of aquaculture ponds in Zhanhua, Laizhou, Kenli, and Dongying City

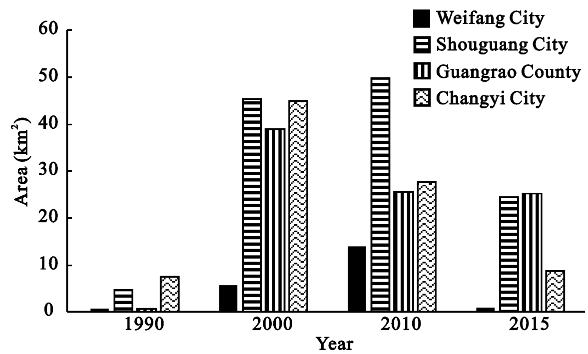

Fig. 8 Area changes of aquaculture ponds in Weifang, Shouguang, Guangrao, and Changyi cities

With the rapid economic development of coastal regions, the demand for land has become stronger and wetland reclamation has become a common phenomenon. In the coastal region of the Yellow River Delta, about 1116.4 km^2 natural wetlands (including salt marsh, freshwater marsh and mudflat) have been transformed into aquaculture ponds since 1983. Liu et al. (2008) found that mudflat decreased and a large proportion of it was turned into aquaculture ponds in the Yellow River Delta from 1990s. Sun et al. (2011) and Li et al. (2011) concluded that the expansion of aquaculture ponds was significantly correlated with the decrease of natural wetlands. In this study, natural wetlands, especially mudflat, were main sources of increased aquaculture ponds. Similar to the development modes of aquaculture in the Pearl River Estuary (Sun et al., 2010), there are two modes for the expansion of aquaculture ponds in the Yellow River Delta: ‘mudflat to aquaculture ponds’ and ‘arable land to aquaculture ponds’. In the period of 2010–2015, cropland contributed to 37% of the increase of aquaculture ponds and was the largest source of the expansion of aquaculture ponds. Since 1980s, aquaculture reclamation activities experienced rapid development, mostly depending on abundant mudflats in the coastal region of the Yellow River Delta. Driven by rapid economic development, population, and urbanization, harbors and built up areas (including airports, oil industry and infrastructure) grew rapidly after 2000. The built up in the coastal region is mostly transformed from aquaculture ponds and mudflat areas. Meanwhile, consumers’ demand for mariculture products is not only a high quality requirement, but also a shift from seasonal demand to perennial demand, which is significantly higher than the economic benefits of cropland (Yao et al., 2016). Therefore, reclamation areas for aquaculture ponds were changed from coastal mudflats to cropland inland.

4.2 Environmental impacts of aquaculture ponds expanding

From a human health point of view, future aquaculture will be of utmost importance in terms of global protein supply, economic trade, and food security (Beveridge et al., 2013). However, the rapid expansion of aquaculture has transformed large areas of valuable coastal environments (Pattanaik and Narendra Prasad, 2011) and inevitably produces negative effects on the coastal environment.

Rising heterogeneity and fragmentation of landscape features occurred in the coastal region of Yellow River Delta with growing aquaculture ponds areas. The temporal trends of certain landscape indices, such as steadily rising NP and PD clearly indicate landscape shifting and fragmentation of landscape pattern (Sui et al., 2015). The conversion of natural wetlands to more profitable aquaculture ponds and its seaward expansion has caused loss and fragmentation of wetland habitats. The degradation of coastal wetlands alters the natural tidal system, decreases sedimentation rates and affects fisheries (Kuenzer et al., 2011).

Water pollution has arisen with the development of aquaculture industry causing negative ecological impacts on the surrounding environmental (Ottinger et al., 2016). Untreated wastewater discharged into adjacent coastal water is a key environmental concern in aquaculture (Cao et al., 2007) and that could cause subsequent release of high loads of nutrients (nitrogen and phosphorus) and suspended solids into nearby estuaries and coastal waters (Islam et al., 2004).

Chen and Qiu (2014) has demonstrated that aquaculture activities considerably contribute to land subsidence which is a major threat to low lying coastal areas (Kuenzer and Renaud, 2012; Renaud et al., 2013). Higgins et al. (2013) analyzed interferometric ALOS-Palsar and Envisat-ASAR data of the coastal area of the Yellow River Delta in China and showed that this region has undergone tremendous land subsidence with a sinking rate of 250 mm per year which is mainly attributed to increased groundwater pumping as a result of rising freshwater demands by aquaculture (Ottinger et al., 2013).

4.3 Uncertainties in mapping aquaculture ponds

The spatial resolution of Landsat data clearly is a limiting factor for the identification of single aquaculture ponds which have generally quite small, simple geometric forms (Ottinger et al., 2016). Landsat images such as MSS (80 m), TM (30 m) and OLI (30 m) at different spatial resolution were used in this study and the different spatial resolutions could be the initial error source for the classification. Although MSS data (80 m × 80 m) acquired in the year of 1983 were resampled to a pixel size of 30 m × 30 m, it cannot be truly resampled to this smaller spatial resolution. As a result, patches in the classification map of 1983 are relatively coarser than other maps. Small patches of aquaculture ponds in 1983 have been either neglected or recognized as large ones, which also causes errors of landscape indices. Meanwhile, with a Landsat image at 30 m resolution a pond with a spatial extent of 50 m × 50 m would be covered by approximately four pixels. Small aquaculture ponds would be either neglected or identified as other types since a coarser resolution pixel may be a mixture of different surface features.

Furthermore, the accuracy assessment of historical data has always been a difficulty for remote sensing mapping since the historical data for validation is hardly obtained quantitatively (Janssen and Vanderwe, 1994). In this study, field surveys were carried out in 2015 to collect ground truth points for classification and validation. Ground truth points from Google Earth high-resolution images were used for the accuracy assessment of year 2010. For years 1983, 1990 and 2000, the historical data for validation were collected from published papers or local residents and experts, some of them may not be highly accurate. Therefore, uncertainties caused by different sources of validation data are expected in mapping aquaculture ponds for a long time series.

Another uncertainty stems from the inconsistency of acquisition time for remote sensing data. Landsat imagery has been widely used to map land use/land cover. However, frequent cloud cover and the long re-visit time (16 days) of Landsat make it difficult to obtain cloud-free images in the same season or same tidal level period, especially near the sea area. Aquaculture ponds mapping results derived from different acquisition date of images would lead to errors when comparison was carried out for different years. During low tides and high tides, the extent of mudflat is different because the inundated area is influenced by tidal water. Aquaculture ponds are mostly converted from natural wetlands, especially mudflat being located in the intertidal zone. The extraction of aquaculture ponds are inevitably affected by the condition of tidal water. Our study was aimed at measuring aquaculture ponds that were visible in the Landsat images, but submerged aquaculture ponds at high tides may not be accurately mapped.

5 Conclusions

An object-oriented classification method was applied to Landsat MSS/TM/OLI data for mapping aquaculture ponds and conducting the change analysis of the aquaculture ponds area over the three decades (1983–2015). The overall accuracy of mapping aquaculture ponds is higher than 85%, which is sufficient for analyzing landscape spatial pattern on the scale of 1∶100 000. Areal dynamics, land conversions contributed to the expansion of aquaculture ponds, and changes in the landscape metrics were examined in this study.

From the period of 1983–2015, the areal extent of the aquaculture ponds in the coastal region of Yellow River Delta showed a significant increasing trend, the net change and the rate of increase was 1366.51 and 42.70 km^2 per year, respectively. The largely growing aquaculture ponds in the study area could be linked to coastal reclamation politics and rapid economic development since 1980s. The fast increase occurred during the period of 2010–2015 and 1990–2000. The prevalent land conversion occurred in natural wetlands, especially mudflat, and cropland which were turned into aquaculture ponds. The spatial analysis indicated that the patches of aquaculture ponds primarily expanded from the south bank of Laizhou Bay to the north of the Yellow River Estuary during 2000–2015. The landscape metrics analysis showed an increase in the quantity and complexity of aquaculture ponds patches from 1983–2015. The study area has undergone a sharp expansion of aquaculture ponds, which led to the loss of large areas of valuable coastal and inland environments. Uncontrolled and uncoordinated development of aquaculture has caused serious environmental degradation of coastal regions, such as habitat loss and fragmentation, water pollution and land subsidence, *etc*. There is urgent need to maintain a sustainable coastal environment. The results from this study provide baseline data and valuable information for efficiently planning and managing aquaculture practices and for effectively implementing adequate regulations and protection measures.

References

Alonso-Pérez E, Ruiz-Luna A, Turner J et al., 2003. Land cover changes and impact of shrimp aquaculture on the landscape in the Ceuta coastal lagoon system, Sinaloa, Mexico. *Ocean & Coastal Management*, 46(6–7): 583–600. doi: 10.1016/S0964-5691(03)00036-X

Beveridge M C M, Thilsted S H, Phillips M J et al., 2013. Meeting the food and nutrition needs of the poor: the role of fish and the opportunities and challenges emerging from the rise of aquaculture. *Journal of Fish Biology*, 83(4): 1067–1084. doi: 10.1111/jfb.12187

Cao L, Wang W M, Yang Y et al., 2007. Environmental impact of aquaculture and countermeasures to aquaculture pollution in China. *Environmental Science and Pollution Research*, 14(7): 452–462. doi: 10.1065/espr2007.05.426

Chen C L, Qiu G H, 2014. The long and bumpy journey: Taiwan’s aquaculture development and management. *Marine Policy*, 48: 152–161. doi: 10.1016/j.marpol.2014.03.026

Chen Jian, Wang Shiyan, Mao Zhanpo, 2011. Monitoring wetland changes in Yellow River Delta by remote sensing during 1976–2008. *Progress in Geography*, 30(5): 585–592. (in Chinese)

Chen Lin, Ren Chunying, Wang Can et al., 2017. Dynamic of coastal wetlands of the Yellow River Delta for 6 periods. *Wetland Science*, 15(2): 179–186. (in Chinese)

Chu Zhongxin, Zhai Shikui, Sun Ge et al., 2006. Surveying area changes of plain reservoirs and aquafarms in the Yellow River Delta with remote sensing data. *Marine Sciences*, 30(8): 10–12. (in Chinese)

Conchedda G, Durieux L, Mayaux P, 2008. An object-based method for mapping and change analysis in mangrove ecosystems. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63(5): 578–589. doi: 10.1016/j.isprsjprs.2008.04.002

Cui B S, Tang N, Zhao X S et al., 2009a. A management-oriented valuation method to determine ecological water requirement for wetlands in the Yellow River Delta of China. *Journal for Nature Conservation*, 17(3): 129–141. doi: 10.1016/j.jnc.2009.01.003

Cui B S, Yang Q C, Yang Z F et al., 2009b. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecological Engineering*, 35(7): 1090–1103. doi: 10.1016/j.ecoleng.2009.03.022

Daily G C, 1997. *Nature’s Services*: *Societal Dependence on*

Natural Ecosystems. 4th ed. Washington, DC: Island Press, 412.

Duan H B, Zhang H, Huang Q F et al., 2016. Characterization and environmental impact analysis of sea land reclamation activities in China. *Ocean & Coastal Management*, 130: 128–137. doi: 10.1016/j.ocecoaman.2016.06.006

ENVI. 2010. ENVI User's Guide: Version 4.8. Boulder, CO, USA: Research Systems, Inc.

Environmental Systems Research Institute (ESRI). 2010. ArcGIS 10.0. Redlands, CA, USA: Environmental Systems Research Institute (ESRI).

Fuchs J, Martin J L M, Populus J, 1998. Assessment of tropical shrimp aquaculture impact on the environment in tropical countries, using hydrobiology, ecology and remote sensing as helping tools for diagnosis. DRV/RA/RST/98-05. Available at: http://archimer.ifremer.fr/doc/00132/24357

Gao Zhiqiang, Liu Xiangyang, Ning Jicai et al., 2014. Analysis on changes in coastline and reclamation area and its causes based on 30-year satellite data in China. *Transactions of the Chinese Society of Agricultural Engineering*, 30(12): 140–147. (in Chinese)

Gong Yuling, Wang Lingshu, Liu Shaowen et al., 2004. Distribution characteristics of terrestrial heat flow density in Jiyang depression of Shengli Oilfield, East China. *Science in China Series D*: *Earth Sciences*, 47(9): 804–812. doi: 10.1360/03yc0062

Guan Xuebin, Zhang Cuiping, Jiang Jusheng et al., 2009. Remote sensing monitoring of aquaculture and automatic information extraction. *Remote Sensing for Land & Resources*, (2): 41–44. (in Chinese)

Han G X, Xing Q H, Yu J B et al., 2014. Agricultural reclamation effects on ecosystem CO_2 exchange of a coastal wetland in the Yellow River Delta. *Agriculture*, *Ecosystems and Environment*, 196: 187–198. doi: 10.1016/j.agee.2013.09.012

Hazarika M K, Samarakoon L, Honda K et al., 2000. Monitoring and impact assessment of shrimp farming in the east coast of Thailand using remote sensing and GIS. *International Archives of Photogrammetry and Remote Sensing*, 33: 504–510.

Higgins S, Overeem I, Tanaka A, Syvitski J P M, 2013. Land subsidence at aquaculture facilities in the Yellow River delta, China. *Geophysical Research Letters*, 40: 3898–3902. doi:org/10.1002/grl.50758

Hoeksema R J, 2007. Three stages in the history of land reclamation in The Netherlands. *Irrigation and Drainage*, 56(S1): S113–S126. doi: 10.1002/ird.340

Huang L B, Bai J H, Chen B et al., 2012. Two-decade wetland cultivation and its effects on soil properties in salt marshes in the Yellow River Delta, China. *Ecological Informatics*, 10: 49–55. doi: 10.1016/j.ecoinf.2011.11.001

Islam M S, Sarker M J, Yamamoto T et al., 2004. Water and sediment quality, partial mass budget and effluent N loading in coastal brackishwater shrimp farms in Bangladesh. *Marine Pollution Bulletin*, 48(5–6): 471–485. doi: 10.1016/j.marpolbul.2003.08.025

Janssen L L F, Vanderwel F J M. Accuracy assessment of satellite-derived land-cover data-a review. *Photogrammetric Engineering & Remote Sensing*, 60(4): 419–426.

Jia M M, Liu M Y, Wang Z M et al., 2016. Evaluating the effectiveness of conservation on mangroves: a remote sensing-based comparison for two adjacent protected areas in Shenzhen and Hong Kong, China. *Remote Sensing*, 8(8): 627. doi: 10.3390/rs8080627

Kennish M J, 2001. Coastal salt marsh systems in the U.S.: a review of anthropogenic impacts. *Journal of Coastal Research*, 17(3): 731–748.

Kuenzer C, Bluemel A, Gebhardt S et al., 2011. Remote sensing of mangrove ecosystems: a review. *Remote Sensing*, 3(5): 878–928. doi: 10.3390/rs3050878

Kuenzer C, Renaud F, 2012. Climate and environmental change in river deltas globally: expected impacts, resilience, and adaptation. In: Renaud F et al. (eds.). *The Mekong Delta System*: *Interdisciplinary Analyses of a River Delta*. Dordrecht: Springer, 7–46. doi: 10.1007/978-94-007-3962-8_2

Li S N, Wang G X, Deng W et al., 2009. Influence of hydrology process on wetland landscape pattern: a case study in the Yellow River Delta. *Ecological Engineering*, 35(12): 1719–1726. doi: 10.1016/j.ecoleng.2009.07.009

Li Yunzhao, Yu Junbao, Han Guangxuan et al., 2011. Dynamic evolution of natural wetlands in Yellow River Delta and related driving factors. *Chinese Journal of Ecology*, 30(7): 1535–1541. (in Chinese)

Li Zhenghai, Wang Haimei, Liu Shurun et al., 2006. Analysis about the biodiversity of Yellow River Delta. *Ecology and Environment*, 15(3): 577–582. (in Chinese)

Liu Jian, Chen Shang, Xia Tao et al., 2008. Analysis on changes of wetland landscape in Yellow River Delta and influences on ecosystem services. *Advances in Marine Science*, 26(4): 464–470. (in Chinese)

Ma Tiantian, Liang Chen, Li Xiaowen et al., 2015. Quantitative assessment of impacts of reclamation activities on coastal wetlands in China. *Wetland Science*, 13(6): 653–659. (in Chinese)

Ma Z J, Melville D S, Liu J G et al., 2014. Rethinking China's new great wall. *Science*, 346(6212): 912–914. doi: 10.1126/science.1257258

Ottinger M, Kuenzer C, Liu G H et al., 2013. Monitoring land cover dynamics in the Yellow River Delta from 1995 to 2010 based on Landsat 5 TM. *Applied Geography*, 44: 53–68. doi: 10.1016/j.apgeog.2013.07.003

Ottinger M, Clauss K, Kuenzer C, 2016. Aquaculture: relevance, distribution, impacts and spatial assessments-a review. *Ocean & Coastal Management*, 119: 244–266. doi: 10.1016/j.ocecoaman.2015.10.015

Pattanaik C, Narendra Prasad S, 2011. Assessment of aquaculture impact on mangroves of Mahanadi delta (Orissa), East coast of India using remote sensing and GIS. *Ocean & Coastal Management*, 54(11): 789–795. doi: 10.1016/ j.ocecoaman.2011.07.013

Ren Chunying, 2008. *Landscape Dynamics of Farming-Pastoral Ecotone in the West Songnen Plain and Its Impact on Soil Properties*: *A Case Study in Tongyu County*, *Jilin Province*.

Beijing: Graduate University of Chinese Academy of Sciences. (in Chinese)

Renaud F G, Syvitski J P M, Sebesvari Z et al., 2013. Tipping from the Holocene to the Anthropocene: how threatened are major world deltas? *Current Opinion in Environmental Sustainability*, 5(6): 644–654. doi: 10.1016/j.cosust.2013.11.007

Rodrigues S W P, Souza-Filho P W M, 2011. Use of multi-sensor data to identify and map tropical coastal wetlands in the Amazon of Northern Brazil. *Wetlands*, 31(1): 11–23. doi: 10.1007/s13157-010-0135-6

Spalding M, Blasco F, Field C, 1997. World Mangrove Atlas. Okinawa, Japan: International Society for Mangrove Ecosystem.

Sui X, Chen L, Chen A et al., 2015. Assessment of temporal and spatial landscape and avifauna changes in the Yellow River wetland natural reserves in 1990-2013, China. *Ecological Engineering*, 84: 520–531. doi: 10.1016/j.ecoleng.2015.09.035

Sun Xiaoyu, Su Fenzhen, Zhou Chenghu et al., 2010. Analyses on spatial-temporal changes in aquaculture land in coastal areas of the Pearl River Estuarine. *Resources Science*, 32(1): 71–77. (in Chinese)

Sun Xiaoyu, Su Fenzhen, Lv Tingting et al., 2011. Analysis of temporal-spatial changes in wetlands over the Yellow River Estuary. *Resources Science*, 33(12): 2277–2284. (in Chinese)

Suzuki T, 2003. Economic and geographic backgrounds of land reclamation in Japanese ports. *Marine Pollution Bulletin*, 47(1–6): 226–229. doi: 10.1016/S0025-326X(02)00405-8

Temmerman S, Meire P, Bouma T J et al., 2013. Ecosystem-based coastal defence in the face of global change. *Nature*, 504(7478): 79–83. doi: 10.1038/nature12859

Tian B, Wu W T, Yang Z Q et al., 2016. Drivers, trends, and potential impacts of long-term coastal reclamation in China from 1985 to 2010. *Estuarine*, *Coastal and Shelf Science*, 170: 83–90. doi: 10.1016/j.ecss.2016.01.006

Turner M G, Gardner R H, 1991. *Quantitative Methods in Landscape Ecology*. New York: Springer-Verlag.

UMass Landscape Ecology Lab. FRAGSTATS: spatial pattern analysis program for categorical maps. Available at: http://www.umass.edu/landeco/research/fragstats/fragstats.html. 2015-06-12.

Valdez C V, Ruiz-Luna A, Berlanga-Robles C A, 2014. Effects of land use changes on ecosystem services value provided by coastal wetlands: recent and future landscape scenarios. *Journal of Coastal Zone Management*, 19(1): 418–424. doi: 10.4172/2473-3350.1000418

Virdis S G P, 2014. An object-based image analysis approach for aquaculture ponds precise mapping and monitoring: a case study of Tam Giang-Cau Hai Lagoon, Vietnam. *Environmental Monitoring and Assessment*, 186(1): 117–133. doi: 10.1007/s10661-013-3360-7

Wang M J, Qi S Z, Zhang X X, 2012b. Wetland loss and degradation in the Yellow River Delta, Shandong Province of China. *Environmental Earth Sciences*, 67(1): 185–188. doi: 10.1007/s12665-011-1491-0

Wang W, Liu H, Li Y Q et al., 2014. Development and management of land reclamation in China. *Ocean & Coastal Management*, 102: 415–425. doi: 10.1016/j.ocecoaman.2014.03.009

Wang X G, Lian Y, Huang C et al., 2012a. Environmental flows and its evaluation of restoration effect based on LEDESS model in Yellow River Delta wetlands. *Mitigation and Adaptation Strategies for Global Change*, 17(4): 357–367. doi: 10.1007/s11027-011-9330-x

Wang Yongli, Yu Junbao, Dong Hongfang et al., 2012c. Spatial evolution of landscape pattern of coastal wetlands in Yellow River Delta. *Scientia Geographica Sinica*, 32(6): 717–724. (in Chinese)

Wu Yanjun, Zhang Jinghong, Tian Guanghui et al., 2006. A survey to aquiculture with remote sensing technology in Hainan Province. *Chinese Journal of Tropical Crops*, 27(2): 108–111. (in Chinese)

Xiang J, Wang Q F, Wu G et al., 2010. Formation of plant communities of the newly created wetland in Modern Yellow River Delta. *Procedia Environmental Sciences*, 2: 333–339. doi: 10.1016/j.proenv.2010.10.038

Xu Yuanjing, Zhang Zengxiang, Wang Xiao et al., 2014. Remote sensing monitoring and temporal variation analysis of coastal aquaculture in Shandong Province in the recent three decades. *Journal of Geo-Information Science*, 16(3): 482–489. (in Chinese)

Yao Yunchang, Ren Chunying, Wang Zongming et al., 2016. Monitoring of salt ponds and aquaculture ponds in the coastal zone of China in 1985 and 2010. *Wetland Science*, 14(6): 874–882. (in Chinese)

Yu J, Wang Y, Li Y et al., 2012. Soil organic carbon storage changes in coastal wetlands of the modern Yellow River Delta from 2000 to 2009. *Biogeosciences*, 9(6): 2325–2331. doi: 10.5194/bg-9-2325-2012

Zewdie W, Csaplovics E, 2016. Identifying categorical land use transition and land degradation in northwestern drylands of Ethiopia. *Remote Sensing*, 8(5): 408. doi: 10.3390/rs8050408

Zhang T, Li Q, Yang X M et al., 2010. Automatic mapping aquaculture in coastal zone from TM imagery with OBIA approach. *Eighteenth International Conference on Geoinformatics*, Beijing. 1–4. doi: 10.1109/GEOINFORMATICS.2010.5567961

Zhang T T, Zeng S L, Gao Y et al., 2011. Assessing impact of land uses on land salinization in the Yellow River Delta, China using an integrated and spatial statistical model. *Land Use Policy*, 28(4): 857–866. doi: 10.1016/j.landusepol.2011.03.002

Zhou W Z, Tian Y Z, Zhu L F, 2007. Land use/land cover change in Yellow River Delta, China during fast development period. *Proceedings of the SPIE 6679*, *Remote Sensing and Modeling of Ecosystems for Sustainability IV*. San Antonio, CA: SPIE, 66791I. doi: 10.1117/12.734015

Zhu G R, Xie Z L, Xu X G et al., 2016. The landscape change and theory of orderly reclamation sea based on coastal management in rapid industrialization area in Bohai Bay, China. *Ocean & Coastal Management*, 133: 128–137. doi: 10.1016/j.ocecoaman.2016.09.016

Zhu Huiyi, Li Xiubin, 2003. Discussion on the index method of regional land use change. *Acta Geographica Sinica*, 58(5): 643–650. (in Chinese)