Policy-driven changes in enclosure fisheries of large lakes in the Yangtze Plain: Evidence from satellite imagery

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HIGHLIGHTS

• SAR imagery makes it possible to study enclosure fisheries in the Yangtze Plain.
• First comprehensive study of the enclosure fisheries for 17 large lakes in the YP.
• Consistent decreases in the fence density were found after 2015 for most lakes.
• Similar provincial dynamics before 2015 were due to local environmental policies.
• Consistent demolition after 2015 appeared to be a response to national policy.

GRAPHICAL ABSTRACT

ABSTRACT

Enclosure fisheries have accommodated the widespread expansion of aquaculture in many lakes throughout the Yangtze Plain (YP), China, for over four decades. Such practices have increased food provision but have also triggered various detrimental environmental consequences. To restore ecosystem functions, the Chinese government recently implemented specific regulations to remove enclosure fences from lakes throughout the YP. However, little information is available on the spatial and temporal distributions of the enclosure fences, particularly in relation to the enforcement of recent policy changes. Using synthetic aperture radar (SAR) satellite images taken between 2002 and 2018, we conducted the first comprehensive assessment of the interannual changes in enclosure fences in 17 large lakes throughout the YP. Consistent decreases in fence density were found in most lakes after 2015; 15 lakes had >50% of their fences removed, while 9 lakes had >90% removed. The timing and implementation of the development and destruction of enclosure fisheries were related to government policy; before 2015, regional dynamics in enclosure fisheries were attributed to provincial policies, whereas the nearly ubiquitous fence demolition after 2015 was likely a response to national policy. This study represents remotely sensed evidence that demonstrates the importance of both local and national environmental policies and their effectiveness in mitigating ongoing human impacts on vulnerable and valuable natural resources. These findings provide valuable baseline information for future lake environmental monitoring and management.

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1. Introduction

As one of the most important components of the freshwater system, lakes have critical ecological and economic functions, such as water supply (for both residential and industrial uses), fisheries, flood control, recreation, and irrigation (Street-Perrott and Harrison, 2013; Wang et al., 2014). Extensive anthropogenic activities are considered to be the most important factor responsible for the rapid degradation of lake environments, particularly in recent decades (Hu et al., 2012b; Nanni et al., 2019; Ricaurte et al., 2017; Tao et al., 2015; Ye et al., 2013). This condition is particularly true for the lakes in China’s Yangtze Plain (YP, see Fig. 1), which is a region boasting a population of approximately half a billion people and a water surface area that accounts for ~40% of the total water in China (Wang et al., 2014). Urbanization, land reclamation, and dam construction have led to substantial decreases in the sizes of lakes (or even their disappearance) (Feng et al., 2013; Wang et al., 2014; Zhao et al., 2005), morphological changes (Fang et al., 2005; Zeng et al., 2018), and wetland degradation (Feng et al., 2016; Zhang et al., 2016). These important observations and the overall success of lake monitoring efforts have relied heavily on satellite remote sensing, which provides frequent synoptic observations at different spatial and temporal scales (Hu et al., 2012a; Ma et al., 2010; Zhang et al., 2017).

With the rapid increase in the human population after the 1960s and the subsequent high demand for protein-rich food (Hubacek et al., 2007; Peng, 2011; Poston and Duan, 2000), extensive enclosure cultures were established in many Chinese lakes in the 1970s and 1980s (see Fig. 2), leading to a pronounced increase in aquaculture production (Wang et al., 2015). In 2012, Asia generated nearly 90% of the total aquaculture production in the world, and China alone produced 62% (Waite et al., 2014). Furthermore, provinces in the Yangtze River Basin accounted for more than half of all inland aquaculture production in the country (Wang et al., 2016). However, although these fishery practices increased food provisions and economic returns (Lynch et al., 2017), they also led to numerous environmental and ecological problems, including water quality deterioration (Wang et al., 2018) and biodiversity loss (Kang et al., 2017).

In recognition of these problems associated with enclosure fisheries, both the central government and provincial governments in China have implemented a series of large-scale programs and policies aimed at achieving sustainable development goals and ameliorating environmental degradation (Bryan et al., 2018; Fang and Kiang, 2006; Wang et al., 2015). To this end, specific regulations have recently been introduced to ban enclosure cultures, requiring a complete demolition of all enclosure fences in lakes throughout the YP (The State Council of the People’s Republic of China, 2015). Given the enormous amount of resources that have been invested, it is critical to provide regular assessments to ascertain the effectiveness of these policies and programs. However, little information is currently available regarding the spatial and temporal distributions of enclosure fences in different lakes throughout the YP region, making it difficult to assess the changes.
Fig. 2. Photos of an enclosure culture, which was used for the cultivation of freshwater fish, crab, crawfish, etc., in Chihu Lake taken in (a) January 2018 and (b) August 2018. (c) A close-up photo of an enclosure fence. (d) A schematic diagram showing the dihedral reflector effect of SAR measurements. The water-to-fence and fence-to-water scattering processes induce strong double-bounce backscattering in the SAR image.

Fig. 3. Satellite observations of enclosure fisheries. Comparison between (a) optical and (b) SAR images of Honghu Lake, demonstrating the advantages of SAR imagery in enclosure culture detection. Both images were acquired in the same year, one month apart. The linear features of the enclosure fences are evidently shown in the ENVISAT ASAR data (panel b), while these features are generally undetectable in the Landsat 5 TM images. (c) and (d) show enlarged areas of the yellow rectangles in (a) and (b), respectively. (e) shows a Google Earth high-resolution image (0.6 m) covering the blue box of (c) and (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
associated with these policies and the potential impacts on lake environments (Ouyang et al., 2016; Viña et al., 2016).

The vast spatial scale of the YP (ca. 160,000 km², see Fig. 1) (Wang et al., 2016) makes it difficult to regularly survey enclosure fisheries using traditional field investigation methods; moreover, some lakes (or lake sections) are inaccessible due to the complex morphologies of the lake bottoms. To further complicate matters, enclosure fences with widths of <5 cm are spatially unresolvable using common optical satellite remote sensing data (such as Landsat imagery, Fig. 3a & c). Although some studies have attempted to map enclosed areas with 30-m resolution optical Landsat imagery, such attempts were limited to lakes with extremely dense cultivated areas (such as Yangcheng Lake and East Taihu Lake) (Huang et al., 2017; Yang et al., 2005). Furthermore, the network structures of fences within enclosed areas are undetectable using optical datasets, thereby prohibiting any assessment of the aquaculture intensity. Although ultrahigh spatial resolution (submeter) measurements could discriminate fences from water (see Fig. 3e), the high cost and limited coverage of such measurements prevent their use in large-scale and long-term projects, such as an assessment of the YP region.

The limitations of optical remote sensing could be addressed with synthetic aperture radar (SAR) measurements, as the distributions and linear structures of enclosure fences have been revealed in SAR images (Fig. 3b & d). Unlike optical sensors, which employ reflected solar radiation, SAR instruments transmit and receive microwave signals to measure the physical properties of targets (Mattia et al., 1997; Tansey and Millington, 2001). Because the microwave backscattering process is highly sensitive to the target material, structure and orientation angle, SAR imagery has been widely used to detect objects on ocean (or water) surfaces that have significant contrast with the background, such as ships and their wakes and oil platforms (Brekke and Solberg, 2005; Gade and Alpers, 1999; Liu et al., 2018). Although the widths of fishing nets and bamboo fences are much smaller than the resolution of SAR imagery, the fence-water dihedral structure will induce significant double-bounce backscattering when the net orientation is parallel to the sensor flight direction (see Fig. 2c & d). As a result, fences can be clearly distinguished from the surrounding water. Considering the urgent need for accurate estimations of the spatial and temporal distributions of enclosure cultures, the objectives of this study are as follows: 1) quantify the areas and fence lengths of enclosure cultures using SAR images and document the long-term spatial and temporal dynamics of the changes in the enclosed fisheries in 17 large lakes throughout the YP and 2) evaluate the potential impact of policy changes on enclosure culture activities.

2. Materials and methods

2.1. Study area and environmental settings

With a coverage area of ~160,000 km², the YP accounts for ~18% of the total area of the downstream Yangtze Basin (Wang et al., 2016). Many freshwater lakes, most of which have shallow water depths (mean water depth of ~5 m), are distributed in this region and serve as critical water resources for human consumption and economic development. Enclosure fences, generally made of fishing nets and bamboo poles, were constructed in many of the lakes in this region (Fig. 2a & b). The waters enclosed within these fences are used for different fishery products, such as fish, crayfish, and Chinese mitten crabs (Eriocheir sinensis). The focus of this study is on the spatial and temporal dynamics of the enclosure culture activities in 17 of the largest lakes in the YP with adequate data quality for conducting an assessment (see Fig. 1). Two of the lakes (Honghu Lake and Shengjin Lake) are recognized as both Ramsar sites (Wetlands of International Importance) and national reserves in China (Ramsar, 2018). Longgan Lake is also listed as a national reserve, and two lakes (Shijiu Lake and Taihu Lake) are listed as important wetlands in China (http://www.wetwonder.org/) (Table 1).

2.2. Data preparation

Enclosure fences are generally invisible in a Landsat image, while they are shown as linear targets in SAR images (see Fig. 3b); the visibility of an enclosure fence is related to the directionality of the radar beam and the fence structure. As shown in Fig. 2c, the enclosure fences in this study area are made of fishing nets and bamboo. The net mesh size (1–2 cm) is smaller than one-third of the C-band SAR wavelength (~5.6 cm) (Garthwaite et al., 2015). Therefore, although the holes in the netting could reduce the scattering power of the radar signal, the fishing net could still induce significant fence-to-water and water-to-fence double bounces (A→B→C→D→C→D→A in Fig. 2d). The electromagnetic (EM) wave radiation from the SAR could travel through ABCD (or in the opposite direction) and then back to the satellite instrument. This EM transmission process is known as the dihedral backscattering effect, which causes a significant signal contrast between the target and background objects. In particular, such a signal contrast could be obvious when the background is a smooth water surface, which has a backscattering echo that appears to be much lower than those from other features. Although high-resolution commercial satellite data (such as Rapid Eye, IKONOS, and QuickBird) may be able to resolve small-scale fences, their high cost and limited data coverage prevent their use in large-scale and long-term assessments of enclosure fishery activities in the YP region.

To explore the temporal and spatial dynamics of enclosure culture activities over the past two decades, SAR data covering the YP area from three satellite instruments, namely, the Environmental Satellite (ENVISAT) advanced synthetic aperture radar (ASAR), European Remote Sensing (ERS) SAR and Sentinel-1 SAR, were obtained from the European Space Agency (ESA) and Eolisa software (version 9.7.2). The three data types are multilook and ground-range products that are operated in the C-band (i.e., 5.331 GHz, 5.3 GHz and 5.405 GHz, respectively). The spatial resolutions of the datasets are similar: 30 × 30 m for ENVISAT ASAR, 26.3 × 30 m for ERS SAR and 20 × 22 m for Sentinel-1 SAR.

The ENVISAT ASAR data from the entire mission (i.e., from 2002 to 2012) covering the study region were downloaded. Images with the highest quality for individual lakes (e.g., with the largest signal contrast between the water background and fence boundaries and minimum aquatic vegetation mixing) were selected. Because the observational frequency of ENVISAT ASAR is unpredictable and the data availability is not consistent over time, ERS SAR data were used as a supplementary dataset for the ENVISAT ASAR observational period. However, although at least one valid observation was available for most years between 2002 and 2012 for these lakes, high-quality data were not found for some lakes in certain years. More frequent and timely SAR observations have been provided by the recently launched Sentinel-1 satellite with a temporal resolution of 6 days. High-quality data between February 2015 and May 2018 were obtained from the Sentinel-1 SAR instrument, which made it possible to quantify short-term (i.e., seasonal) changes in enclosure culture patterns.

The SAR images were converted from the original slant range coordinate system into a geographic coordinate system and were then geocoded using the Sentinel Application Platform (SNAP) software (version 6.0) provided by the ESA. As lake boundaries are not evident in SAR images due to interferences from some onshore linear features (e.g., paddy fields), water masks were first delineated using Landsat 8 Operational Land Imager (OLI) images for all the selected lakes; then, the water masks were used to extract the lake areas from the SAR measurements. The Landsat 8 OLI data were obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/) during the wet season to ensure maximum lake inundation levels. The normalized difference water index (NDWI) (McFeeters, 1996) and corresponding lake-specific thresholds were used to determine the water masks from the Landsat 8 OLI images. The enclosure fences in Taihu Lake can be found in only the eastern areas of the lake, and thus, the boundary for
Taihu Lake was confined to this region (denoted as East Taihu Lake in this study).

The enclosure fences of several lakes were identifiable in recent high spatial resolution images (submeter) from Google Earth (https://earth.google.com). The enclosure features delineated from these images were used to validate the results of the SAR observations.

To examine whether the changes in the enclosure areas and related policies impacted the fishery industry in the YP, the annual total aquaculture production levels of three provinces (i.e., Jiangsu, Anhui and Hubei) were obtained from the provincial statistical yearbooks between 2000 and 2017. These data, which were released by the local provincial governments, include annual productions from both the total lake fisheries and the portion of enclosure aquaculture (available only since 2002) throughout the province. The surface areas of the examined lakes account for 18.0% of the total lake area in Hubei (538.3 km² out of 2983.5 km²), 80.0% of the total lake area in Anhui (999.2 km² out of 1250.0 km²) and 41.3% of the total lake area in Jiangsu (2478.1 km² out of ~6000.0 km²). The lakes located in Jiangxi Province (Chihu 32.27 km² out of ~6000.0 km²). The lakes located in Jiangxi Province (Chihu 32.27 km² out of ~6000.0 km²). The lakes located in Jiangxi Province (Chihu 32.27 km² out of ~6000.0 km²).

### Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Lon.</th>
<th>Lat.</th>
<th>Province</th>
<th>Area (km²)</th>
<th>Protection status a</th>
<th>FD (km²/m²)</th>
<th>APEC (%)</th>
<th>Date</th>
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<td>0.68</td>
<td>1.18</td>
<td>0.18 1.38 – – – – – – –</td>
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</table>

Note: a Ramsar: Wetlands of International Importance; NNR: national nature reserve; IW: important wetlands in China; U: unprotected.

Theoretically, due to the pronounced signal contrast between bright fishery features and the provincial aquaculture production (omitted) lines due to a low signal contrast were manually delineated. For example, false positive lines caused by noise or contamination due to vegetation were removed, and false negative (omitted) lines due to a low signal contrast were manually delineated. The above procedures, as shown in Fig. 4, were conducted for every SAR image over each individual lake, and enclosure patterns were obtained for all 17 selected lakes. The lengths of the enclosure fences in the lakes were estimated as the total length of the converted polyline elements, and the enclosure aquaculture areas were represented as the total areas of the polygons converted from the polylines. Sporadic concurrent high-resolution (submeter) images from Google Earth were used to validate the performance of the SAR-delineated fences in terms of the fence lengths (i.e., polyline lengths) and enclosed areas (i.e., polygon areas) (see discussion).

2.4. Assessment of enclosure culture changes

Two parameters were estimated in addition to the lengths and areas of the enclosure cultures for each lake to examine the dynamics of the corresponding aquaculture activities. The first parameter is the fence density (FD), which is represented as the ratio between the length of the enclosure fences and the lake size (see Table 1). The second parameter is the area percentage of enclosure culture (APEC), which is defined as the percentage of the total lake area (i.e., the lake size) that is covered by the enclosure culture area. The FD represents the intensity of enclosure culture activities. A key step in estimating FD and APEC is the normalization against the lake area, and such a process is conducted to
make it possible to compare the enclosure cultivation status between different lakes; otherwise, the original length or area values could differ by orders of magnitude.

For each year during the ENVISAT and ERS data periods (i.e., from 2002 to 2012), the mean values of the extracted lengths and areas of the enclosure cultures in each lake were estimated to represent the annual conditions. Sufficient data were available for Sentinel-1 SAR to estimate the seasonal values between 2015 and 2018. Then, the corresponding annual/seasonal FD and APEC values were also estimated by normalizing the inundation areas for the different lakes.

3. Results

3.1. Interannual dynamics of enclosure culture activities

The interannual changes in the spatial distributions of the fishery networks in two typical lakes (i.e., Honghu Lake and Gehu Lake) in the YP are demonstrated in Fig. 5. On June 18, 2004, the total fence length and enclosure area were 1619.88 km and 231.10 km², respectively; these values decreased to 1331.63 km and 152.10 km², respectively, on March 4, 2012 (Fig. 5a). Likewise, a remarkable decline was observed for Gehu Lake, in which more than half of the total fence length and associated enclosure culture area dismantled between 2005 and 2017 (Fig. 5b). Such substantial changes were found for all 17 examined lakes, but the patterns diverged remarkably among the different lakes (Fig. 6). For most of the lakes, both the fence lengths and enclosure areas peaked during the first few years of the study period (before 2008) and decreased to their lowest values in the most recent years. In contrast, Caizi Lake and Shijiu Lake demonstrated distinct changes in their enclosure fishery activities (Fig. 6i & p), and no observable decreases were found in recent years. The change patterns of the fence length generally mimicked the changes in the aquaculture areas for all lakes throughout the observational period.

Except for Caizi Lake and Shijiu Lake, the most recent FDs for most lakes decreased dramatically relative to their historic maxima (Table 1 and Fig. 7). Fence constructions were almost completely removed from some lakes (e.g., Daye Lake, Shengjin Lake, Xiliang Lake), for which the recent FDs dropped below 0.1 km/km². In addition, the recent FDs for more than half of the lakes (10 out of 17) fell below 1 km/km², whereas four lakes (Shijiu Lake, Gehu Lake, East Taihu Lake and Yangcheng Lake) remained above 2 km/km², and the largest value...
was observed in East Taihu Lake (3.67 km/km²). Similarly, the recent APEC values also decreased when compared with the corresponding historic maxima. Except for Caizi Lake, Shijiu Lake and Chihu Lake, the recent APEC values of most lakes decreased to <30%; 10 of the lakes exhibited APEC values below 10%, and 4 lakes had values between 10% and 30%. The coefficients of variation (CVs) of the recent FD and APEC also increased compared with the corresponding historic maxima; the recent APEC CV (1.38) was even higher than the corresponding FD (1.18), indicating inconsistent changes between FD and APEC.

3.2. Similarities among the enclosure culture activities in the same province

Considerable similarities were also found among the temporal patterns of the enclosure cultures in the same administrative units (see Fig. 6). Specifically, the most extensive enclosure fisheries of the five lakes in Hubei Province (Changhu Lake, Honghu Lake, Xiliang Lake, Futou Lake and Daye Lake) were observed at the very beginning of the observation period (i.e., 2002), and the aquaculture activities of these lakes (except for Honghu Lake) remained stable until 2016. Long fence lengths and large enclosure areas were also observed initially in 2002 in the lakes located in Jiangsu Province (Changdang Lake, Gehu Lake, Taihu Lake and Yangcheng Lake); these values decreased dramatically in 2008 and subsequently reached steady low levels. In contrast, all the lakes in Anhui Province (Huangda Lake, Pohu Lake, Shengjin Lake, Caizi Lake, Nanyi Lake, Longgan Lake, and Shijiu Lake) demonstrated steadily increasing fence lengths and enclosed areas between 2002 and 2009.

When the maximum FDs were colour-coded into three different levels (low: <2 km/km²; medium: ≥2 and <4 km/km²; and high: ≥4 km/km²), as shown in Fig. 1, the lakes in the same provinces generally fell into the same levels. For example, while the lakes with the highest FDs (i.e., high-level lakes) were nearly all found in the lower

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**Fig. 6.** Long-term changes in the SAR-derived enclosure fence lengths and corresponding fishery areas for the 17 examined lakes. The scale changes along the horizontal axis, where the points before and after 2015 (separated with a dashed yellow line) represent the annual mean and seasonal (quarterly) mean values, respectively. Seasonal variations in the fishery features before 2012 were nonsignificant. The absence of data in some years before 2012 was due to the absence of high-quality SAR imagery to extract enclosure fences, and the data gap between 2012 and 2015 was due to the unavailability of SAR observations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
YP region of Jiangsu Province (except for Honghu Lake), the low-level lakes with the smallest FDs (i.e., ≤2 km/km²) were observed only in Anhui Province. In contrast, the FD maxima of the upper YP lakes located in Hubei Province were classified as medium-level lakes (except for Honghu Lake).

4. Discussion

4.1. Responses of enclosure culture activities to national and provincial level policies

The most striking finding from the long-term SAR observations was a substantial removal of enclosure cultures from most of the examined lakes after 2015. The consistent demolition of enclosure fences appears to have been a response to related national policies enacted for “the overall plan for institutional reform to promote ecological progress”, which was announced by the State Council of China in 2015 (The State Council of the People’s Republic of China, 2015). The ultimate goal of this plan was to protect the natural environment and ensure long-term sustainability through reductions in human interference. Therefore, this plan intended to completely remove all the constructed fishery fences in lakes throughout the YP to preserve the original ecological functions of those lakes.

The SAR images suggest that the efficiency of enforcing these regulations evidently differed among the examined lakes, as demonstrated by the relative differences between the maximum and recent values of the APEC and FD (Fig. 7). By the end of the observational period, the national-level policy appeared to work well for most lakes. Eight of the lakes showed relative differences of >90% between the recent and maximum values for both the APEC and FD. The maximum decrease occurred in Daye Lake, for which the enclosure facilities were completely removed (i.e., relative differences = 100%). Most of the lakes (15) experienced decreases exceeding 50% in their enclosure cultures after 2016. However, >75% of the fishery structures remained in Shijiu Lake and Caizi Lake by the second quarter of 2018, suggesting that the enforcement of the national-level policy may have been delayed in these two lakes.

The response time of the national-level policy implementation can be clearly reflected through the percentage of removed enclosure areas (PREA) during different seasons between 2005 and 2018 (Fig. 8). In general, the demolition of fencing began initially in the upper YP (Hubei Province), where the PREA values increased dramatically by the first quarter of 2017. Specifically, Daye Lake appeared to
be the first lake to respond to the national policy, as the PREA in this lake began to increase after the second quarter of 2016, and the structures were completely removed (i.e., PREA = 100%) by the third quarter of the same year. In contrast, the response times of the lakes in the middle YP region were much longer, as the demolition did not start until 2018. In particular, no actions had been taken in Caizi Lake and Shijiu Lake in response to the national policy by the end of the observational period (i.e., second quarter of 2018), as demonstrated by the stable PREA values between 2015 and 2018. The reason for the remaining facilities may be related to the late response of the local governments or the long negotiation time between the authorities and the local fishermen, as the removal of the fences could tremendously reduce the income of fishermen.

In addition to the national policy-induced demolition of fishery structures after 2015 for most of the examined lakes in the YP, the similarities among the interannual change patterns between 2002 and 2015 within the same administrative units are likely linked to the policies enacted at the local (i.e., provincial) level. The fishery in Hubei Province experienced rapid development before 2000, which was possibly due to several promotional provincial regulations in the 1990s ("Hubei Province Fisheries Management Implementation Measures") (Standing Committee of the Hubei Provincial People's Congress, 1990). Therefore, the densest enclosure fences were found in the lakes of Hubei Province in the first year, and the most extensive enclosure in the YP region (APEC maximum of ~99.9%) was also found in this region (Honghu Lake). The harmful impacts of extensive enclosures were subsequently recognized by the local government, who released a number of policies and regulations in 2007 to control such fishery activities in lakes throughout Hubei Province (People's Government of Hubei Province, 2007, 2008). However, these actions led to only slight decreases in the enclosed areas of Honghu Lake from 2004 to 2010 (see Fig. 6b). The substantial demolition of fences was not apparent until the national policy was in place, showing the importance of the national policy.

The enclosure cultures in the lakes of Anhui Province were underdeveloped at the beginning of the study period (i.e., 2002), but substantial increases were observed for all lakes in this region between 2002 and 2009. Such a consistent increase in this province may also be associated with a provincial policy enacted in 2004 ("the Anhui Fishery Industry Development Plan (2003-2007)" ) (People's Government of Anhui Province, 2004) aimed at enhancing fishery production throughout Anhui Province to meet the increased demand for high-profit products (such as Chinese mitten crabs: *Eriocheir sinensis*). Fences were widely demolished in most lakes after the national policy was implemented.

Over the last century, aquaculture has fully developed in Jiangsu Province, which is the most urbanized region in the YP (Wang et al., 2015). In particular, Chinese mitten crabs, a product cultivated mainly in the enclosed areas in many lakes of this region, have been very popular in China (e.g., Yangcheng Lake, Taihu Lake), leading to high FD and APEC values even in the first year of 2002. Rapid decreases in enclosed areas and fence lengths were observed in the lakes in Jiangsu Province in 2008; these reductions were also attributed to the enactment of local policy. Specifically, a severe drinking water crisis occurred in Wuxi in 2007 due to contamination from extensive algae blooms in Taihu Lake (Guo, 2007). Subsequently, the Jiangsu provincial government announced a series of regulations to control the potential aquaculture pollution (People's Government of Jiangsu Province, 2008), thereby requiring the removal of enclosure culture facilities from several major lakes (including Eastern Taihu Lake, Gehr Lake, and Changdang Lake). The enforcement of this policy appeared to be effective within this province, as demonstrated by the considerable decreases in fence lengths and enclosed areas in all lakes (see Fig. 6).

4.2. Impacts of enclosure fisheries and related policies on aquaculture productions

The national policies announced by the State Council of China in 2015 appeared to have driven not only substantial decreases in the enclosure areas in lakes throughout the YP but also evident declines in both the total provincial production from lake fisheries and the production from lake enclosure fisheries (enclosure fishery data in 2017 are not available for Hubei Province) (see Fig. 9). The interannual fluctuations in fishery production from enclosure cultures showed considerable temporal agreement with the remotely sensed dynamics of fence facilities. For example, a substantial increase in lake enclosure fishery production occurred in Anhui Province from 2005 to 2006 (Fig. 9b); this increase was primarily associated with policy-promoted enclosure areas in regional lakes at the same time (Figs. 6 & 9a). Additionally, an even greater increase was found in the total production of lake fisheries in Anhui after the fishery industry development plan was implemented. On the other hand, when the FDs in the lakes in Jiangsu Province decreased after the pollution control plan was enacted in 2008, both the production from lake fisheries and the lake enclosure fisheries demonstrated steady decreases (Fig. 9a & b). In contrast, although the conservation plan of Hubei Province that was executed in 2007 led to a sharp

![Fig. 8. PREA values calculated as (maximum APEC-current APEC)/maximum APEC) between 2005 and 2018, where each column represents a lake, and each cell represents a seasonal PREA value. The lakes from left to right are consistent with the positions of the lakes from west to the east in the YP. Cells with missing data are shaded in white.](image-url)
decrease in the total lacustrine fishery production, enclosure fishery production remained stable during the observational period. This finding may have been due to the ineffective implementation of regional policies or the limited fraction (18.0%) of examined lakes in this province. Statistically, most of the lakes in Hubei and Anhui (8 out of 12) showed significant correlations \( (p < 0.05) \) between the enclosure areas and total provincial production from lake fisheries during the observational period (see Fig. 9c). In contrast, the enclosure areas of all lakes in Jiangsu Province (4) showed a significant \( (p < 0.05) \) correlation with the provincial production from lake enclosure fisheries.

4.3. Limitations and implications

The spatial distributions of enclosure cultures and the long-term dynamics in the YP lakes were documented using SAR images from three satellite missions. Concurrent ultrahigh spatial resolution images from Google Earth were used to validate the SAR-extracted enclosure features. The two sets of observations independently exhibited enclosure fences with very similar spatial distributions, and the relative differences in the delineated fence lengths and enclosure areas were < 10% (Fig. 10). Moreover, we compared the extracted results with several consecutive Environmental Satellite (ENVISAT) ASAR images taken within a year; the relative differences were within 5% for the different lakes in terms of the FD, APEC, fence length and enclosure area. Because

Fig. 9. Policy-induced changes in fishery production in different provinces. (a) Chronology of major provincial and national fishery-related policies in the YP after 2002. (b) Annual fishery production estimates (solid lines indicate production from enclosed fisheries, and dashed lines indicate the total production from lakes) in different provinces. (c) Correlations between the enclosed area of each lake and fishery production (from both enclosed fisheries and total fisheries) of the province where the lake is located. Statistically significant correlations are annotated with an asterisk (*).
examined throughout the YP. Such information appears to be valuable for lake management, as is inferred from the strong linkages between the interannual changes in fence structures and regional and national policies. Moreover, once additional relevant datasets are collected in the future, knowledge of enclosure areas and their changes over time will enable an evaluation of the potential impacts of these special human activities on water quality and ecological functions. Furthermore, as the Yangtze River Economic Belt has constituted one of the concentrations of the key national strategic development plans of China (Zhang et al., 2010), the continuation of efforts similar to those in the current study are essential to guarantee the effective implementations of related policies in the YP region. Finally, enclosure cultures or similar cultivation activities are present not only within the YP but also vastly across other freshwater and coastal ecosystems of China and other countries (Phillips et al., 2010; Wang et al., 2015; Zeng et al., 2010). Consequently, the proposed approach could be employed in these regions to fill critical gaps in the knowledge needed to assess and monitor fishery activities and ecosystem functions (Ottinger et al., 2016; Pettorelli et al., 2018).

5. Conclusions

The distributions and dynamics of the enclosure culture areas in 17 large lakes throughout the YP were systematically quantified and analyzed for the first time using satellite SAR time series data. Notably, this information is difficult to characterize using optical satellite images and is intensively laborious using traditional field surveys. Enclosure cultures were widespread throughout the studied lakes in the early 2000s, but such practices rapidly disappeared following provincial and national policy changes, showing the effective implementation of policies in the YP. The results of this study provide the first baseline datasets of the distributions and dynamics of the enclosure cultures in 17 large lakes throughout the YP, representing a valuable resource for future lake environmental monitoring and restoration within the YP region, as well as in other lacustrine and coastal regions experiencing similar aquaculture development.

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Notes

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References
