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Ecological effects of artificial reefs in Daya Bay of China observed from satellite and *in situ* measurements

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Abstract

Fishery resources along China's coasts have been declining. Could those decline be alleviated by deploying artificial reefs (ARs) in suitable areas? This study investigates effects of a big project conducted in December 2007 that deployed ARs in the southwestern part of Daya Bay. The ARs cover a total dimension of 966.10 × 2850.60 m^2 and surface area of 91,500 m^2. This study analyzed the spatial and temporal variations of ecological factors, including Chlorophyll a concentrations (Chl-a), nutrients, attaching organisms and nekton resources, on and around the ARs using both satellite (Moderate Resolution Imaging Spectroradiometer, MODIS) and *in situ* data. Results showed that the potential affected area of ARs in Daya Bay reached a distance of 4.9 km in the water depth of 12.0–15.2 m. In the study area, Chl-a level reached 2.93 mg m^{-2} during the post-AR period (2008–2012), that was higher than the pre-AR period (2002–2007) (2.37 mg m^{-2}). Nekton biomass increased by 4.66–16.22 times compared with that in the pre-AR survey, and the species diversity increased by 15%–23%. This parallel trend suggested that ARs might have contribution to the increase in nekton biomass. Long-term observations shall be conducted to understand the response of phytoplankton to ARs.

Keywords: Ecological effects; Artificial reefs; Remote sensing; Daya Bay, China

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1. Introduction

Daya Bay is located at the northern part of South China Sea (SCS; Fig. 1A). The bay is shallow and semi-enclosed between 22°30′–22°50′N and 114°30′–114°50′E. It encompasses an area of approximately 600 km^2 with an irregular coastline, and the bay area has more than 50 islands (Xu, 1989). Daya Bay was one of the major aquaculture areas in Guangdong province because of the excellent water quality and rich biological resources. However, economic developments around the area has expanded rapidly in the past decades; the local permanent population doubled, and industries and establishments, such as nuclear power plants (with thermal discharge), petrochemical, printing, harbor, and tourism, expanded (Yu et al., 2007b, 2010). Along with such economic expansions, the water quality of Daya Bay has deteriorated, and the occurrence of harmful algal bloom has become more frequent (Hao and Tang,

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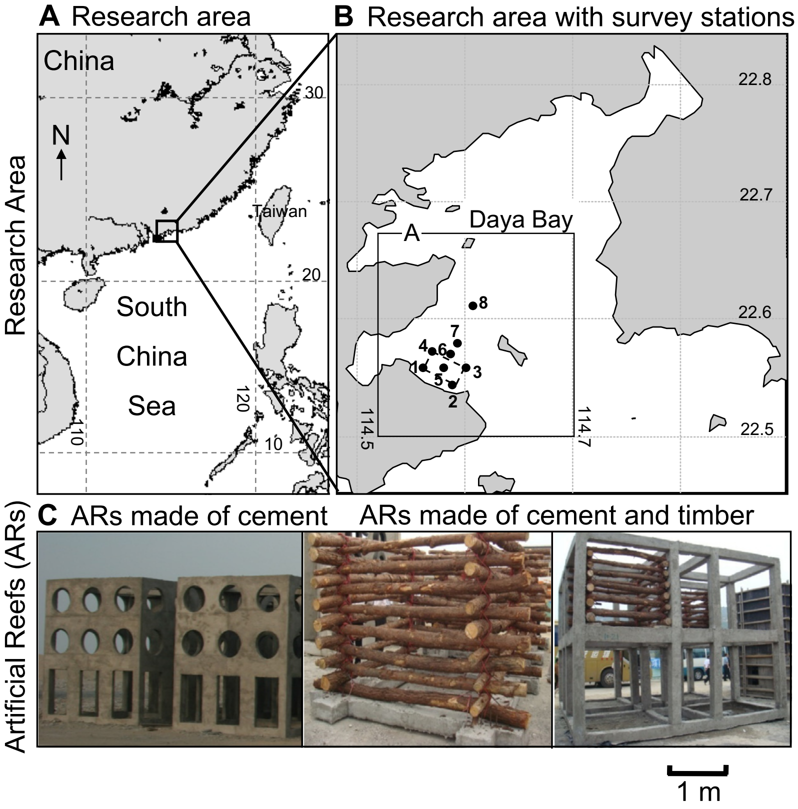

Fig. 1. Research area. (A) Location of Daya Bay. (B) Daya Bay map with the location of the ARs. The small box with dashed lines indicates the area of AR deployment. Box A shows the sample area of the satellite remote sensing data source. Black dots represent the eight survey stations. (C) Pictures of ARs deployed in Daya Bay.

2010; Hao et al., 2012; Song et al., 2009; Yu et al., 2007a). Overfishing aggravates the decrease in fish stock, and increasing bottom trawling operations accelerates seabed desertification and destroys the natural habitats of marine organisms in Daya Bay (Jia and Zhuang, 2009; Wang et al., 2010). The number of fish species declined significantly, and the dominant species shifted from high-value fishes such as hairtail and pomfret in the 1980s, to low-value fishes such as sardine, anchovy, and juvenile porgy at present times (Wang et al., 2010).

Therefore, immediate measures must be implemented to protect the environment and increase the fishery resources in Daya Bay. Artificial reefs (ARs) have been utilized for different purposes in coastal management, including increasing fish abundance and diversity (Tsumura et al., 1999), recreational diving (Ditton et al., 1999), and trawling prevention (Relini, 2000). The entire AR program in the Gulf of Mexico is driven by fisheries (Addis et al., 2013), and the increase in fish around the ARs placed in the Gulf of Mexico has been well recognized and documented. Similarly, Fish Aggregating Devices (FAD) are an ancestral fishing practice that are known to locally increase local fish biomass through the attraction of fish. However, the potential benefits of ARs are recognized. Generally, ARs are poorly understood in terms of the extent to which they change the ecological environment, increase fishery resources, and whether they have a net ecological effect.

Daya Bay provides an ideal case study for the assessment of the ecological influence of ARs in bay waters, because of its shallow water depth and semi-enclosed shape. The government of Guangdong Province designated Daya Bay as an ecological demonstration zone for ARs in 2007. Since 2000, local government agencies have invested 80 million RMB to establish 100 AR areas in Guangdong coastal waters (Wang et al., 2008, 2009a). By December 2007, 2202 AR units of cement concrete and timber with a dimension of $3 \times 3\ m^2$ have been deployed in Yangmei Cove, which is located in the southwestern part of Daya Bay (Figs. 1B and C).

Marine phytoplankton is a critical indicator of ecological conditions, due to its ecological function in primary production (Chen, 2000). Chlorophyll a concentration (Chl-a) has been evaluated as a useful indicator of phytoplankton biomass (Hao et al., 2012; Yu et al., 2007a). Satellite data have likewise been utilized for Daya Bay ecological studies (Chen et al., 2003; Tang et al., 2003; Yu et al., 2007a, 2007b, 2010). The products of Moderate Resolution Imaging Spectroradiometer (MODIS) onboard aqua satellites can provide information about Chl-a on spatial and seasonal variations, which the limited number of ship stations and surveys cannot provide (Tang et al., 2005; Zhao et al., 2008). The ecological processes and possible effects from the placement of ARs in a bay ecosystem are analyzed in the present study with a particular focus on fishery resources, based on satellite remote sensing data and *in situ* investigations.

In December 2007, a big project on deploying ARs with a total dimension of 966.10 × 2850.60 m^2 and surface area of 91,500 m^2 in the southwestern part of Daya Bay, China was conducted. Could this project alleviate the decline of fishery resources and whether ARs have ecological effects? To answer this question, this study analyzed the ecological processes and possible effects resulting from the deployment of ARs in a bay ecosystem.

2. Materials and methods

2.1. Study area

The study area, including AR groups and AR potential impact area, covered an area of 4.9 km^2 with 12.0–15.2 m water depth. The AR groups were piled by AR modules through particular combinations. The total dimension of the AR groups was 966.10 × 2850.60 m^2, and the total surface area was 91,500 m^2, which was calculated according to Wang et al. (2009b). The average index of nekton biomass based on wild capture was 154 kg km^{-2} in April 2007 (pre-AR period). The main species that were caught included Gobiidae (*Chaeturichthys stigmatias*, Chaeturichthys stigmatias), Sparidae (*Sparus macrocephalus*, Black porgy), Apogonidae (*Apogon kiensis,* Band Tail Black Spot Cardinalfish), and Sciaenidae (*Argyrosomus argentatus,* White croaker).

2.2. MODIS-derived Chl-a data

MODIS is a key instrument onboard the Earth Observing System (EOS) AM (Terra) and EOS PM (Aqua) satellites that are parts of NASA's EOS. Aqua's orbit passes south to north over the equator in the afternoon, views the Earth's surface every 1–2 d, and acquires data in 36 spectral bands or groups of wavelengths.

In this study, MODIS-derived Chl-a data were used to investigate the changes in Chl a concentration. Spatial resolution satellite data of 1 km × 1 km were used because the AR groups (966.10 × 2850.60 m^2) were larger than 1 km^2 and their potential affected area reached to several kilometers. A total of 3845 daily Chl-a images (1 km × 1 km spatial resolution) were obtained from July 2002 to December 2012 (http://oceancolor.gsfc.nasa.gov/). ASCII format data were derived from MODIS Chl-a products for the AR area (of box A in Fig. 1B) by using the MATLAB 7.0.1 software package. These data were then processed into monthly values, and linear regression analysis was performed. To remove the season signal, monthly Chl-a anomalies were also calculated based on the monthly Chl-a minus the monthly mean Chl-a that was averaged for 11 years (2002–2012) (Fig. 2). Finally, the increase in Chl-a after the deployment of ARs was calculated based on the average of each month from 2008 to 2012 minus the average of the same month from 2002 to 2007 and compared with the monthly average Chl-a over the 2002–2007 period. To understand Chl-a distribution in the study area, Chl-a data sets were processed into monthly average images by using Grid Analysis and Display System (GrADS) for two periods, namely, pre-AR (2002–2007) and post-AR (2008–2012) (Fig. 3).

2.3. In Situ observations

Eight survey stations were equally spaced in the study area. Station 5 was at the center of the AR groups. Four of these eight stations were set on the boundary of the AR groups, and they were at a distance of 1.5 km from the center of AR groups (indicated using the numbers 1, 2, 3, and 4 in Fig. 1B). The other four were set at a distance of 0, 1.3, 1.6, and 4.9 km (indicated using the numbers 5, 6, 7, and 8 in Fig. 1B) from the center of the AR groups. The water depth at each station is shown in Table 1. The time and purpose of each field investigation are shown in Table 2. Research teams from South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences conducted studies on the overall ecology and environment of the study area (Jia et al., 2011).

All *in situ* data obtained through a series of research cruises were measured following the national standard methods (SOC, 2007). Water temperature varied seasonally, because Daya Bay is a shallow bay with a mean water depth of 11 m, and that homogeneously thermocline was not observed throughout the water column (Yin et al., 2006; Yu et al., 2010). Water samples were collected from the surface layer at less than 5 m, the middle layer at 5–10 m, and the bottom layer at more than 10 m. Sampling depth was measured *in situ* by using a YSI 6600 multi-parameter water quality monitor. Chl-a was tested via the fluorescence spectrophotometric method after acetone (90% v/v) was extracted in the dark for 24 h at 4 °C. The nutrients utilized in this study include inorganic nitrogen ($TIN = NO_3—N + NO_2—N + NH_4—N$, $molL^{-1}$) and phosphate ($PO_4—P$, $molL^{-1}$). The TIN/P ratio was calculated using the following formula: TIN ($molL^{-1}$)/$PO_4—P$ ($molL^{-1}$).

Nekton investigations were conducted through bottom trawling around the AR groups area (Stations 1, 2, 3, and 4) to indicate the nekton resource status in the study area and diving survey in the artificial reef's modules where bottom trawling cannot be conducted. The nekton stock biomass (in weight) was calculated via the swept area method (Gunderson, 1993; Zhan, 1995). The species diversity of nekton in the study area was calculated in terms of nekton species (in number), which was used to divide the study area (4.9 km^2). The increase in the percentage of the nekton species diversity was calculated with the following equation, $[(N_i—N_1)/N_1] \times 100\%$, where the Ni is the species diversity during the post-AR period, and N_1 is the species diversity in April 2007 (pre-AR period).

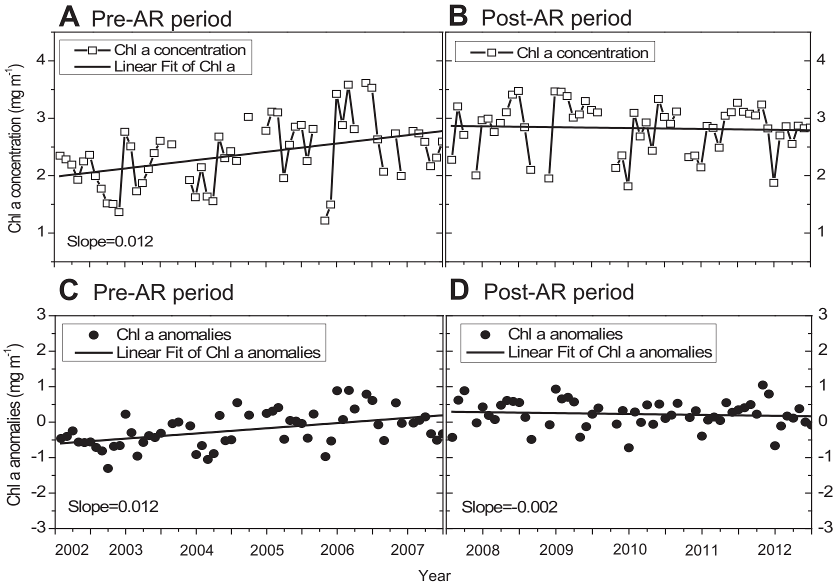

Fig. 2. (A) Time series of monthly mean Chl-a from 2002–2007. (B) Monthly mean Chl-a from 2008–2012. (C) Monthly Chl-a anomalies from 2002–2007. (D) Monthly Chl-a anomalies from 2008–2012.

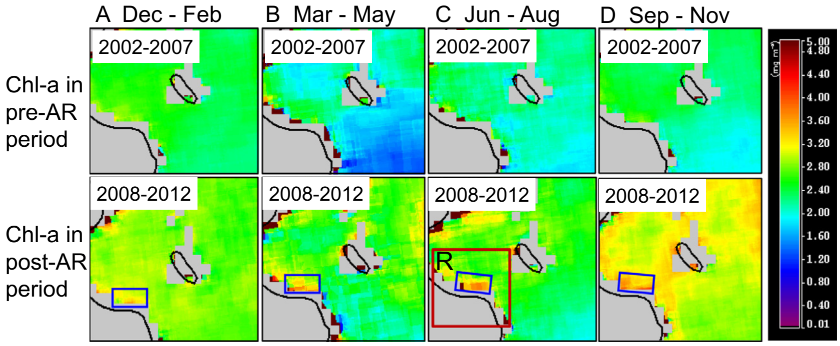

Fig. 3. Comparison of seasonal Chl-a distribution during the pre-AR (2002–2007) and post-AR (2008–2012) periods. (A) Winter (December to February). (B) Spring (March to May). (C) Summer (June to August). (D) Autumn (September to November). The blue box indicates the location of the ARs. Box R with the red line is amplified in Fig. 7B to show the distribution of Chl-a in the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A scuba diver sampled the organisms that were attached on the reef modules with a quadrat of 0.01 m^2, because the thinnest part of AR modules was 0.2 m. The organisms attached on the AR modules were sampled at three water depths: the upper layer at 6 m, the middle layer at 8 m, and the lower layer at 10 m. The data from the three layers were averaged to determine the overall status of the organisms attached on the AR modules.

2.4. Computational fluid dynamics numerical simulation

The flow field around the AR units was simulated using a computational fluid dynamics (CFD) numerical simulation software called ANSYS FLUENT (http://www.ansys.com/). The numerical model was based on the law of conservation of mass and momentum. Seawater was set as an incompressible fluid, and the governing equations were continuous and were Navier–Stokes equations (Landau and Lifshitz, 1999). This CFD has a wide application in fluid mechanics and can be compared to the experiments (Baloch, et al., 1995; Zhang and Ko, 1996).

Table 1
Water depth at each station.

Station	1	2	3	4	5	6	7	8
Water depth (unit: m)	12.0	12.6	13.6	13.1	13.5	15.2	14.3	12.8

3. Results

3.1. Variations in annual Chl-a from 2002–2012

The time series of the monthly mean Chl-a from July 2002 to December 2012 (Fig. 2) shows that the minimum and maximum Chl-a were 1.22 (April 2006) and

Table 2
Survey time and purpose.

Survey time			Chl-a, nutrients, nekton	Attaching organism
Pre-AR period	2007	April	√	
Post-AR period	2008	March	√	
		April		√
		May	√	
		July		√
		August	√	
		September		√
		October		√
		November	√	
		December		√
	2009	May	√	

3.61 mg m^{-3} (November 2006), respectively. The linear regression analysis performed on monthly Chl-a in the pre-AR period (2002–2007) revealed an ascending trend at a rate of 0.012 mg m^{-3} per month (Fig. 2A). During the post-AR period (2008–2012), Chl-a was at a relatively high level with most Chl-a being higher than 2.0 mg m^{-3} (Fig. 2B). The average values of monthly Chl-a were 2.37 mg m^{-2} during the pre-AR period and 2.93 mg m^{-2} during the post-AR period, respectively.

We also compared the monthly Chl-a anomalies in the pre-AR (Fig. 2C) and post-AR (Fig. 2D) periods. During the pre-AR period (2002–2007), Chl-a anomalies ranged from −1.21 (June 2004) to 1.93 (August 2006, Fig. 2C). During the post-AR period (2008–2012), Chl-a anomalies ranged from −0.72 (June 2010) to 1.04 (April 2012, Fig. 2D). For the entire observation period (2002–2012), the trend identified via linear regression analysis based on Chl-a anomalies shifted from positive to negative. The slope of linear regression decreased from 0.012 (2002–2007) to −0.002 (2008–2012) (Figs. 2C and 2D).

3.2. Increase in seasonal Chl-a in post-AR period

The seasonal variations in Chl-a in the pre-AR (2002–2007) and post-AR (2008–2012) periods were compared (Fig. 3). Chl-a in the post-AR period was higher than that in the pre-AR period in each season by 0–0.5 mg m^{-3}. High Chl-a was observed in the study area during the post-AR period (the blue box in Fig. 3 indicates the location of AR deployment). The Chl-a reached its maximum from June to August (Fig. 3C) and spread onto the entire bay from September to November (Fig. 3D).

Month-to-month comparisons of the average Chl-a from 2002–2007 and 2008–2012 showed a systematic increase in Chl-a during the 2008–2012 period with Chl-a ranging from 0.27–0.80 mg m^{-3} (Fig. 4, no data for April 2008 to 2012). For the entire observation period, Chl-a increased by 10.79%–27.06% in 2008–2012 compared with that in 2002–2007 (Fig. 4). The largest percentage of increase was concentrated in the period from September to November.

3.3. Environmental condition of the study area

In situ Chl-a and DIN/P ratio at the surface and bottom layers during the pre-AR and post-AR surveys (average value of five post-AR surveys) were compared for the four stations along the cross section (Stations 5, 6, 7, and 8 in Fig. 1B). The post-AR survey data were higher than those

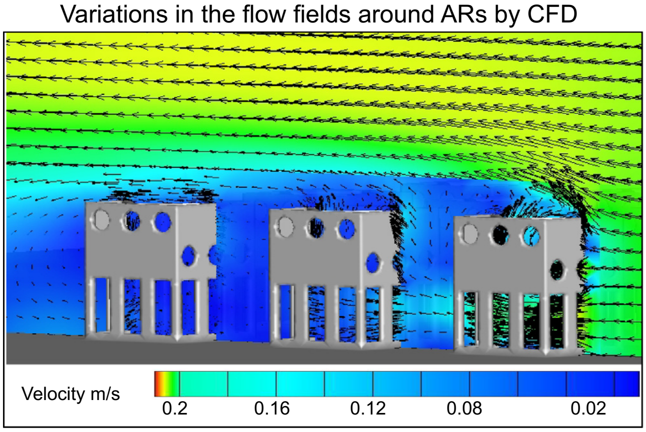

Fig. 5. Numerical simulation of computational fluid dynamics to show the variations in the flow fields around ARs.

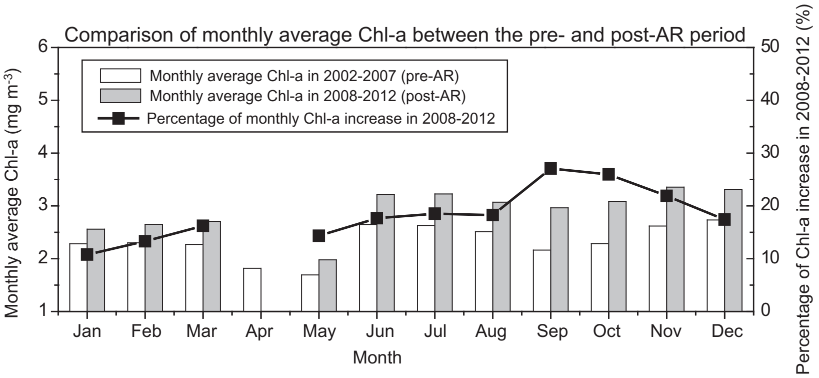

Fig. 4. Comparison of monthly average Chl-a in the two periods (2002–2007 and 2008–2012). The percentage of Chl-a increase during the post-AR period (2008–2012) is indicated with a quadrat. No data are available for April 2008–2012.

of the pre-AR survey for the surface layer and the bottom layer. Chl-a decreased gradually with increasing distance from the central part of the ARs (Figs. 6A and B). Chl-a in the post-AR surveys were higher than that in the pre-AR survey in each station, particularly for the bottom Chl-a (Fig. 6A). The DIN/P ratio was low before AR deployment (pre-AR survey), came close to the Redfield value, and then achieved standard values of 10–20 after AR deployment (Fig. 6B). During the post-AR surveys, the surface and bottom DIN/P ratios were close and remained at a constant range in each station (Fig. 6B). Moreover, the DIN/P ratio at the center of the ARs (Station 5) was closer to the Redfield value than those from farther stations (Stations 6, 7, and 8; Fig. 6B).

3.4. *Attaching organisms and nekton resources in the AR water*

After the deployment of ARs in December 2007, the attaching organisms on the ARs were investigated five times in April, July, September, October, and December 2008 (Fig. 6C). The species diversity of attaching organisms appeared to be changing seasonally, with the variation of their sizes and biomass. The species (in number) of the attaching organisms varied from 26 (December) to 45 (September) in different seasons, and the density ranged from 747.98 ind m^{-2} (September) to 311.25 ind m^{-2} (July). The biomass (in wet weight) of the attaching organisms decreased from spring (April) to summer (July) and gradually increased before reaching the maximum of 540.32 g m^{-2} in winter (December).

The nekton biomass (in weight) and the species diversity in the study area increased after the ARs were deployed in December 2007 (Fig. 6D). In the pre-AR survey (April 2007), the nekton biomass was 154.04 kg km^{-2}, and the species diversity in the study area was 14.9 species km^{-2}. In the post-AR surveys, the biomass increased by 4.66–16.22 times that of the pre-AR survey and varied from 871.80 kg km^{-2} (May 2008) to 2652.99 kg km^{-2} (May 2009). The species diversity increased by 15%–23% and ranged from 17.14 (March 2008) to 18.37 (May 2009) species km^{-2} (Fig. 6D).

3.5. *Flow field change around the ARs*

The ANSYS FLUENT model predicted that after the ARs are deployed to the seabed, the flow field changes when water current passes the ARs. Significant local upwelling and eddy flow fields generated at the front and back of the ARs, respectively. A geometric shaded area, which was a shadow region generated from the AR modules (Liu et al., 2013), was distributed within and around the reef (Fig. 5).

4. Discussion

4.1. *Increase in Chl-a and variation in nutrients associated with ARs*

In shallow waters, large ARs are expected to mimic natural upwelling and carry up nutrients into the water column, which may result in phytoplankton growth. In this

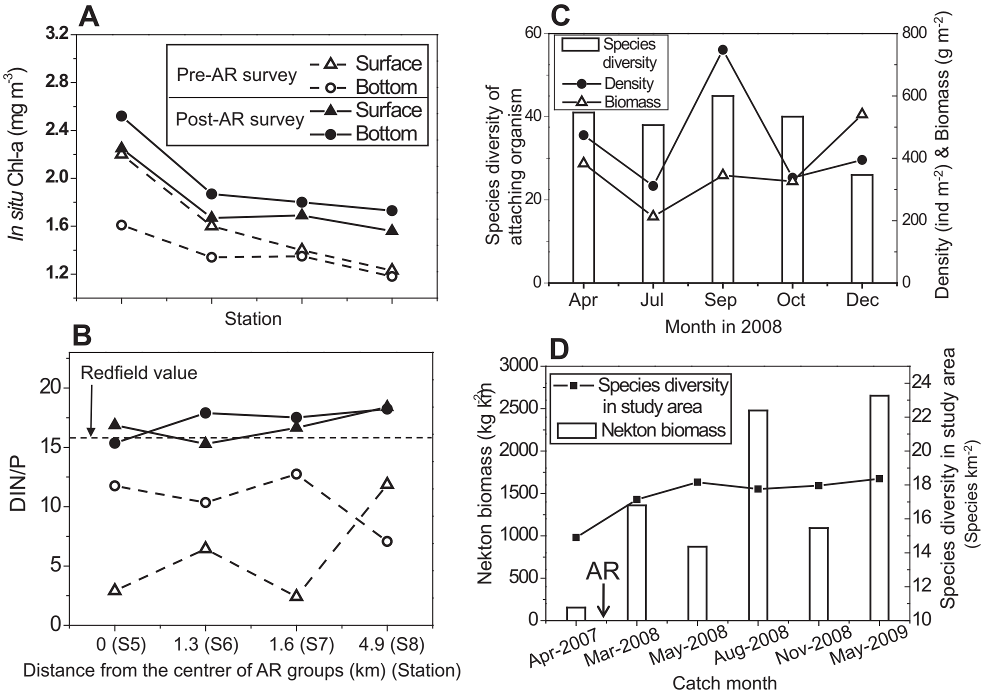

Fig. 6. *In situ* observation results. (A) Chl-a in each station for surface and bottom water samples in the pre-AR and post-AR surveys. (B) Ratio of DIN/P ($TIN = NO_3{-}N + NO_2{-}N + NH_4{-}N$, $molL^{-1}$. $P{-}PO_4$, $molL^{-1}$). (C) Species, density and biomass (in wet weight) of attaching organisms on the ARs. (D) Nekton biomass (in weight, kg km^{-2}) and total species of catch in the AR water. The arrow indicates the time when ARs were deployed.

study, variations in Chl-a suggested variations in the primary production of the study area. In terms of time, variations in Chl-a from 2002–2007 (pre-AR period) showed a different trend than during the 2008–2012 (post-AR period). Given human developments, the uses and degradations described in the introduction and the primary productivity prior to AR deployment were responses to natural variability and human activities around the bay (Figs. 2 and 3). Monthly Chl-a increased during the pre-AR period (2002–2007) and maintained a high level during the post-AR period (2008–2012) (Figs. 2A and B). The monthly Chl-a anomalies decreased slightly (Figs. 2C and D). These results showed that phytoplankton concentration was slightly higher after AR development. High Chl-a was observed in the study area from December to August (Figs. 3A, B, and C) and spread to the entire bay from September to November (Fig. 3D). This finding is in agreement with the result of the comparison of monthly Chl-a (Fig. 4). In terms of space, the increase in bottom Chl-a in the center of the ARs (Station 5 in Fig. 1B) was larger than that in the farther stations (Stations 6, 7 and 8 in Fig. 1B) (Fig. 6A). Both results indicated that Chl-a variations during the pre- and post-AR periods may be associated with ARs.

The upwelling effects caused by the ARs extended to both vertical and horizontal directions. The potentially affected distance of ARs reached to 4.9 km in waters of 12.0–15.2 m depth in Daya Bay (Figs. 6A and B). This influencing distance varied seasonally and reached the maximum in September (Fig. 3). Chl-a in Daya Bay was influenced by multiple factors, such as thermal plume from nuclear power plants, aquaculture, industries, and etc. (Hao et al., 2012; Yu et al., 2007a, 2007b, 2010). Long-term observation shall be conducted to understand the phytoplankton response to ARs.

After the deployment of ARs, the nutrition changed and become close to the Redfield value, which was more appropriate for phytoplankton growth, especially in the central part of ARs (Station 5 in Figs. 1A, 6A, and B). This finding indicated that the deployment of ARs partly caused the nutrition variations in the study area, which changed the direction and velocity of flow in the study area (Fig. 5; Falcão et al., 2009).

4.2. Ecological effects of ARs in Daya Bay

The ARs in Daya Bay modified the pre-existent bottom and pelagic ecosystems through physical (flow-field modification and increased surface area) and ecological (nutrients variation and increased reef biota) processes (Fig. 7). Upwelling and eddy flow fields that were generated around the ARs enhanced the nutrients in the water column and consequently enhanced phytoplankton growth, which might have attracted fish (Figs. 5, 7B and D). Chl-a in the AR-deployed area was higher than that in the adjacent water (Figs. 2–4, 6A, and 7B), which suggests an increase in phytoplankton biomass in the study area. This phytoplankton biomass aggregation around the ARs promoted nutrient regeneration, which traps drifting organic materials and favors the accumulation of marine organisms and

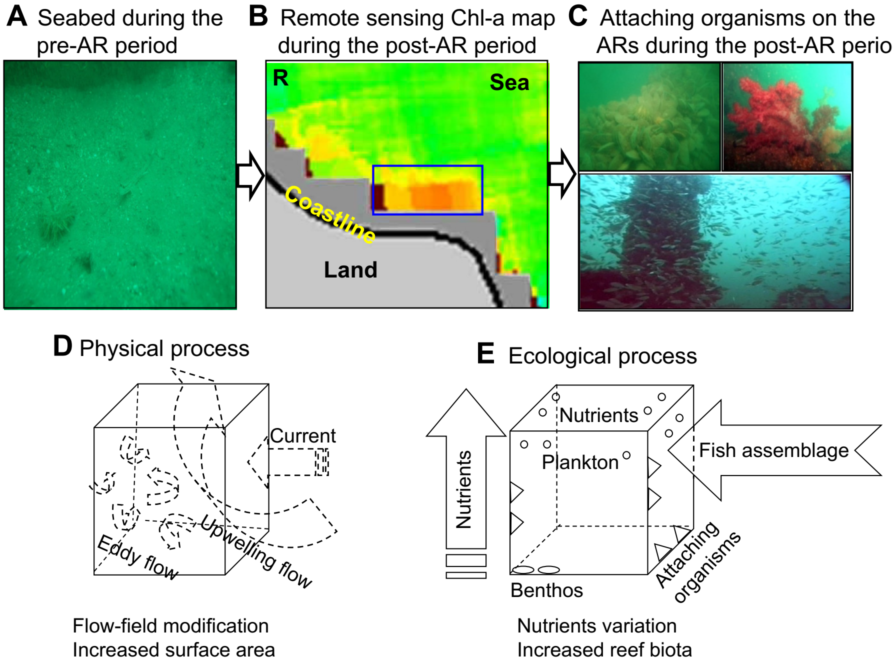

Fig. 7. Diagram of the physical and ecological process around the ARs. (A) Photo of seabed during the pre-AR period. (B) Monthly average Chl-a image during the post-AR period (amplified from box R in Fig. 3). (C) Photos of ARs with attaching organisms and fish. (D) Physical process during the post-AR period: flow-field modification and increased surface area. (E) Ecological process during the post-AR period: nutrients variation and increased reef biota.

planktons (Figs. 6 and 7; Falcão et al., 2007; Kirke, 2003). Given the modification of flow fields and the increase in surface area in AR modules, nutrients varied and reef biota (such as plankton and attaching organisms) accumulated because of the flow-field modification and increase in surface area in the AR modules, and a habitat that was rich in bait for fish was eventually developed (Fig. 7). After five months in April 2008, the attaching organisms on ARs multiplied. The species diversity increased from 0 to 41, and the biomass (in wet weight) increased from 0 g m^{-2} to 383.08 g m^{-2}. Species diversity and density reached their 2008 maximum in September, although the biomass fluctuated slightly until December 2008 where the biomass reached the maximum (Fig. 6C). This AR biota may be a response to the increasing primary production, because monthly Chl-a also reached the peak value in the same period (September to November 2008, see Figs. 3 and 4). The increase in species diversity and biomass of attaching organisms was also an improvement in the fishery resources. This phenomenon was used as a case study by observing the increase in reef biota in the Daya Bay waters for three years and comparing with one set of pre-deployment data in April 2007. Further research on the correlation between specific organisms with specific fish species would be conducted to understand the ecological effects of ARs.

4.3. Fish attraction and reproduction in the AR water

This study showed that ARs enhanced local nekton biomass and diversity in Daya Bay, which is located in the northern South China Sea. This enhancement was induced through fish attraction, and several studies have also indicated that this enhancement was through reproduction (Fowler and Booth, 2012; McGowan et al., 2014). The ARs provided additional habitats that improved the environmental carrying capacity, the species diversity, and the biomass of artificial reef biota (Booth and Fowler, 2013; Pickering and Whitmarsh, 1997). With a hollow structure, ARs can expand the surface area for the growth of attaching organisms. AR waters can develop a bait-abundant field, which will attract migratory fish and facilitate larval retention (Figs. 6 and 7). Additional surface area with increased reef pile size helps attain the maximum fish biomass (Jan et al., 2003). Considering that the natural habitat has disappeared in Daya Bay (Jia and Zhuang, 2009; Wang et al., 2010), ARs can provide a suitable habitat and spawning ground for larval and juvenile fish (Figs. 6C and 7C). In Daya Bay, ARs had significant attraction effects on *Plectorhynchus cinctus*, *Lutjanus argentimaculatus*, and *Sebastiscus marmoratus*. The attraction effects were connected to available rooms and shade spaces (Zhou et al., 2010, 2011, 2012).

In addition to the attraction effect, ARs can allow the production of new fish biomass and ongoing recruitment through reproduction. Relevant studies observed that egg clusters, pairings, and egg laying occur at the ARs (Pickering and Whitmarsh, 1997). The biomass and species diversity of nekton in August 2008 were relatively high and are in agreement with Chl-a variations (Fig. 3C), which indicates that the ARs may provide additional environmental carrying capacity.

A diagram is presented in Fig. 8 to model the biota enhancement processes that ARs generate. After the deployment of ARs, the flow fields around the ARs changed, the nutrients were then enhanced, and the TIN/P ratio increased. The nutrients fertilized the phytoplankton in the mixed layer with an increase in Chl-a, which enhanced the primary production in the AR water. Zooplankton later fed on phytoplanktons, and planktivores consumed both. Subsequently, attaching organism and fish fed on these plankitivores. Both feedings enhanced fish biomass and species in the AR water (Fig. 8). Therefore, ARs have important functions in the enhancement and recruitment of coastal fishery. The diet of the fish species sampled in the study area and the implantation of their biomass increase will be explored in further studies.

5. Summary

This study, as the first time, investigate ecological effects of ARs in China using both satellite remote sensing and

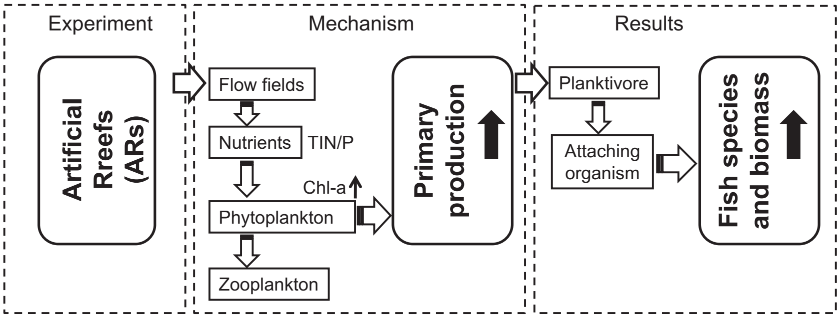

Fig. 8. Fish-enhancement mechanism in the study area. (1) Experiment indicates the deployment of ARs in the test area. (2) Mechanism indicates variations in flow fields, nutrients, phytoplankton, and zooplankton and the increase in primary production in the AR water. (3) Response of planktivore and attaching organisms on the ARs and increase in fish species and biomass.

shipboard monitoring data. Combining the two data sets provide important information for reliability checks to assess the ecological effects of ARs.

ARs exhibit ecological effects in both vertical and horizontal directions, reaching 4.9 km distance in the water depth of 12.0–15.2 m in Daya Bay. Three years after the deployment of ARs, the nekton biomass increased by 4.66–16.22 times of that in the pre-AR survey, and the species diversity of nekton in the study area also increased by 15%–23%. These phenomena are related to variations in nutrients, increase in Chl-a, and occurrences of attaching organisms after AR deployment. It is necessary to conduct long-term observations to understand ARs ecological response and to identify suitable reference sites.

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