



Remote Sensing Assessment of Marine Primary Productivity and Fishery Resources in the Daya Bay, China

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ABSTRACT

Marine primary productivity (PP) is closely related with fishery resources. This study benefited a lot by providing the reference for the use of remote sensing data to inverse PP and then to assess fishery resources in typical offshore fishery waters. The paper adopted the inversion analysis of the primary productivity (PP) in the Daya Bay, China applying the vertical generalized production model (VGPM) with ocean color and sea surface temperature (SST) provided by MODIS-Aqua. On the basis of modified VGPM model, fishery resources in the Daya Bay were evaluated according to the Tait model, Cushing model, and trophic dynamics model. Results showed that the seasonal variation of PP was obvious in the bay, the average PP reached the highest in summer ($1595.60 \text{ mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) and the second in autumn ($1274.67 \text{ mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$). The space distribution of PP decreased gradually from nearshore (greater than $1000 \text{ mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) to offshore and outside ($800 \sim 1000 \text{ mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) of the bay. As one of the most significant influencing factors to PP, chlorophyll a (Chl-a) showed similar characteristics of spatiotemporal distribution. Comparing results of different estimation models, it was found that density of fishery resources assessed by Cushing model matched well with the in-situ investigation data of fishery resources. Marine primary productivity and fishery resources in the Daya Bay were mainly influenced by Chl-a distribution, cage culture and petrochemical sewage (Liu, 2011).

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Authors' Contribution

JY designed the study, guided the entire article macroscopically and review articles. JM performed experimental work and analyzed the data. DW assisted in experiment and image processing.

Key words

Primary productivity, VGPM, Fishery resources, Daya Bay, China

INTRODUCTION

Marine primary productivity (PP) is closely related with fishery resources (Pikitch *et al.*, 2004; Chassot *et al.*, 2010). An accurate marine PP estimation model can directly provide decision-making support for fishery production and marine management, which is of great significance for resource management, carbon cycle and global climate change research. The vertical generalized production model (VGPM) was applied to the inverse analysis of marine PP (Ye *et al.*, 2015) and its main parameters could be obtained from satellite remote sensing, included sea surface temperature (SST) and ocean color (Pikitch *et al.*, 2004), the latter include chlorophyll a concentration (Chl-a), diffuse attenuation coefficient K_d (490),

Photosynthetically Active Radiation (PAR), and Euphotic Zone Depth (Zeu). Therefore, it had strong adaptability and has been widely applied to the study of marine PP. In the north of the South China Sea (SCS), fitting analysis of satellite remote sensing and surveyed data, researchers revealed the seasonal variation characteristics of PP (Tang *et al.*, 2007) and the main factors of PP temporal and spatial variation (Hao *et al.*, 2011). In coastal waters of the SCS, VGPM model was also successfully applied to the spatial and temporal distribution analysis of net primary productivity in the sea area of Shenzhen (Zhang *et al.*, 2017) and the analysis of PP seasonal variation in the Pearl River estuary (Ye *et al.*, 2015).

The assessment of fishery resources based on marine primary productivity is to estimate the amount of life matter produced by fishery organisms in a certain period of time through the energy flow of the ecosystem, which is of great significance for monitoring the ecological functions of sea areas and guiding fishery production

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(Wang *et al.*, 2005). In the middle sea area of northern Pacific Ocean, the seasonal variation of autumn cohort of squid *Ommastrephes bartramii* is closely related to the net primary productivity (Ichii *et al.*, 2011). In the Daya Bay, potential fishery production capacity estimated by PP revealed the mechanisms for maintaining the biodiversity in representative gulfs and structural and functional diversity of the ecosystems (Song *et al.*, 2012). Some models such as nutrient dynamics and Cushing model based on marine PP are also applicable in exploring the reason of fishery resource declining and the changing trend of the resources (Lu, 2006).

Daya Bay is located in the northeast SCS, a semi-closed bay surrounded by land on three sides, with zigzag shorelines, diverse habitats and rich biological resources, which is a representative offshore fishery area in the SCS (Wang *et al.*, 2006). Taking the Daya Bay as the study area, this paper adopted the inverse analysis of the marine PP based on the marine remote sensing, analyzed the spatiotemporal variation, evaluated the fishery production of the Daya Bay, explored the methods of evaluating the fishery resources in the typical fishery areas near the SCS based on the satellite remote sensing, which provided a reference for the assessment and management of offshore fishery resources in the SCS.

MATERIALS AND METHODS

Research area

The survey of fishery resources and ecological environment was conducted according to the station location, in May 2015 (spring), August (summer), September (Autumn) and January (winter) (Fig. 1).

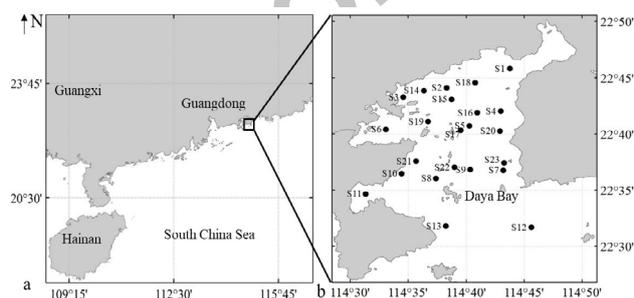


Fig. 1. Research area and survey stations.

Data from satellite remote sensing

The data was from level 2 product in MODIS-AQUA NASA (<https://oceancolor.gsfc.nasa.gov/>). The spatial resolution is 1Km, temporal resolution is day, and the time period is from 2013 to 2016. The satellite remote sensing data were extracted with the help of SEADAS

7.3(NASA Goddard Space Flight Center, USA), MatLAB 9.0 (MathWorks, USA) and ArcGIS 9.3 (Environmental Systems Research Institute, USA) was applied for the visual processing.

Survey data

The data of fishery resources and environment were from the fishery resource and ecological environment survey of the Daya Bay carried out by South China Sea Fisheries Research Institute during May 2015 (spring), August (summer), September (autumn) and January (winter). The survey methods were referred from GB17378-2007 and GBT12763.6-2007 (Standardization Administration, 2007a, b). The details are listed in Table I. Bottom trawler was used for the survey, with the total power 254Kw, total weight of 108t, equipping with ROYALRV-680GP GPS system and JKC Radar, trawling once for each station, averaging 0.25 h each time at 2.5 knots.

Table I. Survey season, station, species and category.

Season survey	Number of station	Species of catch	Survey category
spring	10	Fish Crustaceans Cephalopods	Number of species, Catch (Kg)
summer	17	Fish Shrimps Crabs Squilla Cephalopods	Number of species, Catch (Kg), Catch numbers (ind)
autumn	10	Fish Crustaceans Cephalopods	Number of species, Catch (Kg)
winter	17	Fish Shrimps Crabs Squilla Cephalopods	Number of species, Catch (Kg), Catch numbers (ind)

Estimation of primary productivity

Inversion of marine primary productivity based on VGPM model (Kameda and Joji, 2005):

$$PP_{eu} = 0.66125 P_{opt}^B \frac{E_0}{E_0 + 4.1} \cdot Z_{eu} \cdot C_{opt} \cdot D_{irr} \dots (1)$$

where, PP_{eu} represents primary productivity in euphotic layer ($\text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), P_{opt}^B represents maximum rate of carbon sequestration in water column (mg

$C \cdot \text{mg} \cdot \text{Chl-a}^{-1} \cdot \text{h}^{-1}$), E_0 represents photosynthetically active radiation in sea surface PAR ($\text{mol quanta} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), acquired from the OC product in MODIS-Aqua; Z_{eu} represents depth of euphotic layer (m), C_{opt} represents Chl-a content (Chlorophyll a, Chl-a, $\text{mg} \cdot \text{m}^{-3}$) of the water column P_{opt} where the maximum rate of carbon sequestration is, acquired from the OC product in MODIS-AQUA; D_{irr} represents the Photoperiod (h), acquired from Shenzhen Government OBSERVATORY (<http://www.szmb.gov.cn/twt/>). Maximum rate of carbon sequestration in water column (P_{opt}^B) (Liu *et al.*, 2012):

$$P_{opt}^B = \frac{0.071 \times T - 3.2 \times 10^{-3} \times T^2 + 3.0 \times 10^{-5} \times T^3}{C} + (1.0 + 0.17 \times T - 2.5 \times 10^{-3} \times T^2 + 8.0 \times 10^{-5} \times T^3) \quad (2)$$

Depth of euphotic layer (Z_{eu}) (Tang *et al.*, 2007):

$$Z_{eu} = \frac{2.784}{K_d(490)} \quad \dots(3)$$

Chlorophyll fitting

The regression analysis of Chlorophyll a concentration in the filed survey and Chl-a extracted by MODIS-Aqua in the same period showed good fitting effect, $R^2 = 0.92$ (Fig. 2).

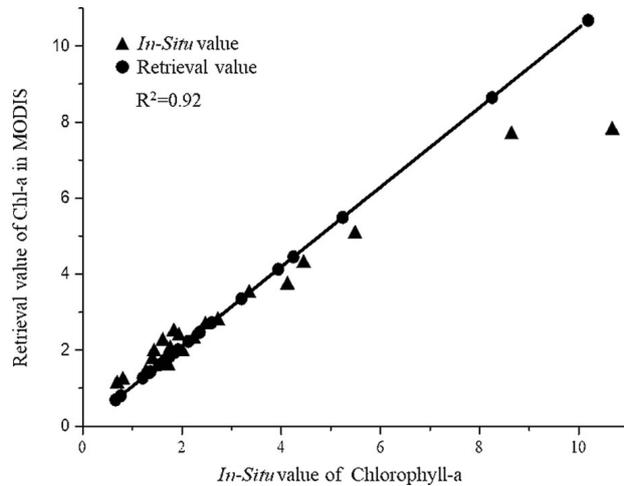


Fig. 2. The relationship between *in-situ* Chlorophyll a concentration and MODIS-derived Chl-a.

Fisheries resources assessment

Tait model (Luo, 1993)

The efficiency μ is 0.015 when the primary productivity of coastal waters is transformed into the tertiary organisms (fishery resource) (Lu *et al.*, 2002; Wang *et al.*, 2005). Estimation formula of fishery yield in the Daya Bay was estimated by the following formula.

$$Y_T = \mu \times t \times S \times PP_{eu} \quad (4)$$

Where, Y_T represents fishery production (t), μ

represents biotransformation efficiency, t represents conversion coefficient, S represents sea area (km^2), PP_{eu} ($\text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) represents primary productivity.

Cushing model (Cushing, 1971)

The carbon emission of the tertiary organism is equal to the half of the 1% primary carbon production and 10% secondary carbon production.

Estimation formula of fishery yield in the Daya Bay was based on Cushing model:

$$Y_C = t \times S \times \frac{0.01PP_{eu} + 0.1SPP_{eu}}{2} \quad (5)$$

Where, Y_C represents fishery production (t), t represents conversion coefficient, S represents sea area (km^2), PP_{eu} ($\text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) represents primary productivity (primary carbon production), SPP_{eu} ($\text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) represents secondary productivity (secondary carbon production).

Trophic dynamics model (Fei, 1980)

The food energy flow theory was applied to estimate fishery production in Daya Bay.

$$B = Q \times E^n \quad (6)$$

where, B represents fishery production (t), Q represents Phytoplankton production ($\text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), E represents ecological efficiency, n represents biotrophic level.

According to Tait, Cushing and trophic dynamics model, the fishery resource density in the Daya Bay area is calculated.

Stock density acquired by in-situ survey

Stock density by trawling survey is expressed as resource density, referring to sea area sweeping method (Ding, 1980; Guan *et al.*, 2013).

$$D = \frac{C}{qa} \quad (7)$$

Where, D , resource density (kg/km^2); C , fishery production per hour by trawling ($\text{kg}/\text{net} \cdot \text{h}$); a , sampling area per hour by net ($\text{km}^2/\text{net} \cdot \text{h}$); q , net capture rate (0.5).

RESULTS

Seasonal distribution of PP, Chl-a and SST

In terms of seasonal distribution, PP of the Daya Bay reached the highest in summer, took the second place in spring and autumn, and reached the lowest in winter. The spatial distribution of PP showed that high value of PP was mainly in the coastal and northern waters within the bay ($>1000 \text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), the low value mainly appeared in the estuary ($<900 \text{mg C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$). The seasonal distribution of Chl-a was similar with that of PP, which reached the highest in summer, took the second place in autumn

and winter and reached the lowest in spring. The spatial distribution of Chl-a showed that the value in the inner bay was higher than that in the outside bay (Fig. 3). High value of Chl-a (above $9 \text{ mg} \cdot \text{m}^{-3}$) was mainly in the north of the Daya Bay and the low value in the middle and mouth of the Daya Bay. The SST value was the highest in the summer, the second in autumn and spring, the lowest in winter. The spatial distribution of SST within the bay was even.

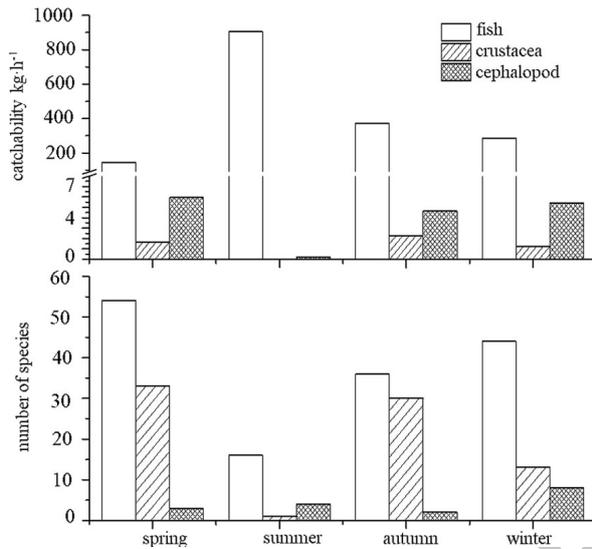


Fig. 3. Seasonal variations of catchability and number of species.

Fisheries resources assessment

Marine primary productivity was used to assess the fishery resources and further evaluate fishery resource density, with the help of Cushing, Tait and trophic dynamics model. Results showed that the fishery resource density evaluated by Cushing model was the closest to the fishery resource density surveyed *in-situ*. The fishery resources achieved the highest in summer, which matched with the seasonal distribution of fishery resource density obtained by *in-situ* survey. Tait and trophic dynamics model followed (Fig. 4).

DISCUSSION

Seasonal variation of fishery resources

Fishery resources mainly included fishes, crustaceans and cephalopods in daya bay. seasonal variation of catch rate was different significantly, showing the characteristic of highest in summer, then in autumn, winter and spring orderly, while fishes were captured the most, then cephalopods and crustaceans orderly in all seasons. catch rate of fishes ranked first, with few cephalopods

were captured and almost zero crustaceans especially in summer. Seasonal variation of number of species of fishery resources appeared that the value is highest in spring and lowest in summer, with autumn ranked second. Comparing catchability with number of species, value of catchability was lowest, but the highest number of species in spring, showing the opposite trend exactly in summer and similar tendency between autumn and winter. Catchability of cephalopod is stronger than that of crustacea, while number of crustacea was higher than cephalopod except summer. Fish were the most important component ecological types of all seasons in Daya Bay (Fig. 2).

Spatiotemporal variation of primary productivity in the Daya Bay

The spatiotemporal distribution of PP was affected by Chl-a in the Daya Bay, showing the same tendency with that of Chl-a, and the two presented a significant positive correlation (Le *et al.*, 2013). The results showed that the value of the PP was the highest in summer, the second in autumn and winter. High value of PP appeared in the north of the Daya Bay, consistent with the Liu's research (Liu *et al.*, 2012), probably connected with the rich nutrition and high phytoplankton utilization efficiency (Qiu *et al.*, 2005). Additionally, due to the effect of seasonal thermocline (Yin *et al.*, 2006), the northerly marine current clustered the nutrition into the north of the bay, with the nutrition supply outside the bay, resulting the highest Chl-a value in summer, relatively lower Chl-a in other seasons (Lu, 1990; Qiu *et al.*, 2005). The value of the Chl-a in the inner bay and nearshore was higher than that in the outside bay and off-shore. It might be affected by the cage culture, thermal emission (Yu *et al.*, 2010) from nuclear power plant and petrochemical sewage (Wang *et al.*, 2011) and human activities (Wu and Wang, 2007). Daya Bay was affected by human activities included thermal plume from nuclear power stations (Yu *et al.*, 2010), cage culture in the Aotou waters in the bay (Liang *et al.*, 2017), and etc., partly resulted to higher Chl-a near shore in summer and autumn than that in the offshore. Moreover, petrochemical sewage has threatened the health of marine ecosystem seriously. The seasonal distribution of PP in the Daya Bay was positively correlated with the fishery resources density. In summer, higher PP brought higher fishery production, providing sufficient bait source for fishery organisms. In autumn, the amount of fishery resources decreased due to the increase of fishing intensity (Yu *et al.*, 2017a) after summer fishing moratorium (Mao *et al.*, 2017).

Fishery resource assessment based on remote sensing in the Daya Bay

In this paper, fishery resource density evaluated by

Cushing model fitted best with the fishery resource density surveyed in situ, where Tait model and trophic dynamics model differed greatly from the fishery production investigated in situ, thus the latter two models are not applicable to assess the fishery production in Daya Bay (Fig. 5). It is likely that the key parameter of fishery resources estimated by Cushing model is organic carbon content of resource organisms, which is close to the carbon content of fishery resources in the study sea area. In South Fujian-Taiwan shoal, the deviation between the fishery resources estimated by Cushing model and the fishery resources investigated in situ was only 5.44% (Xiao, 2003); off the coast of Fujian, relative error was about 5% between the fishery production estimated by Cushing model and that surveyed in situ (Li and Lu, 2008). The research have shown that the fishery resource density estimated by Tait model is more suitable for Daya Bay than Cushing model (Song *et al.*, 2012), This is because the average conversion efficiency of primary productivity to secondary productivity is 30%. However, A large proportion of this is caused by jellyfish plankton, which is difficult to transfer C to higher trophic levels, which seriously affects the estimation of resource density (Song *et al.*, 2009), This phenomenon of the latter cannot be expressed in the model, which results in the deviation of fishery resources density caused by the high average ecological efficiency of Cushing model. In

this study, the ecological efficiency of 0.15 was selected in the calculation of secondary productivity. Although it may lead to underestimate of secondary productivity in Daya Bay, it can avoid the impact of jellyfish plankton on fishery resources assessment to a certain extent. The results also show that the Cushing model used in this paper has a good effect on the assessment of fishery resources. The accuracy of trophic dynamics model eva is mainly controlled by the parameter n of fishery resources nutrition level. If it is not set properly, it will lead to a large deviation between the assessment results and the real situation. In the evaluation results in the 1990s, Wang *et al.* (2005) believed that the fishery resources had undergone structural changes at that time. Therefore, the trophic level was taken as 2.5, and good results were achieved. However, in recent years, due to the increase of offshore fishing intensity, the fishery resources in Daya Bay have shown a trend of miniaturization and low value (Wang *et al.*, 2010). In this study, the trophic dynamics model shows that it overestimates fishery resources, which is probably due to the further reduction of the trophic level of fishery resources. In the future, the study on the assessment of fishery resources in Daya Bay should focus on the different ecological efficiency among different trophic levels, and the parameters in Cushing model should be modified to adapt to the local specific population structure.

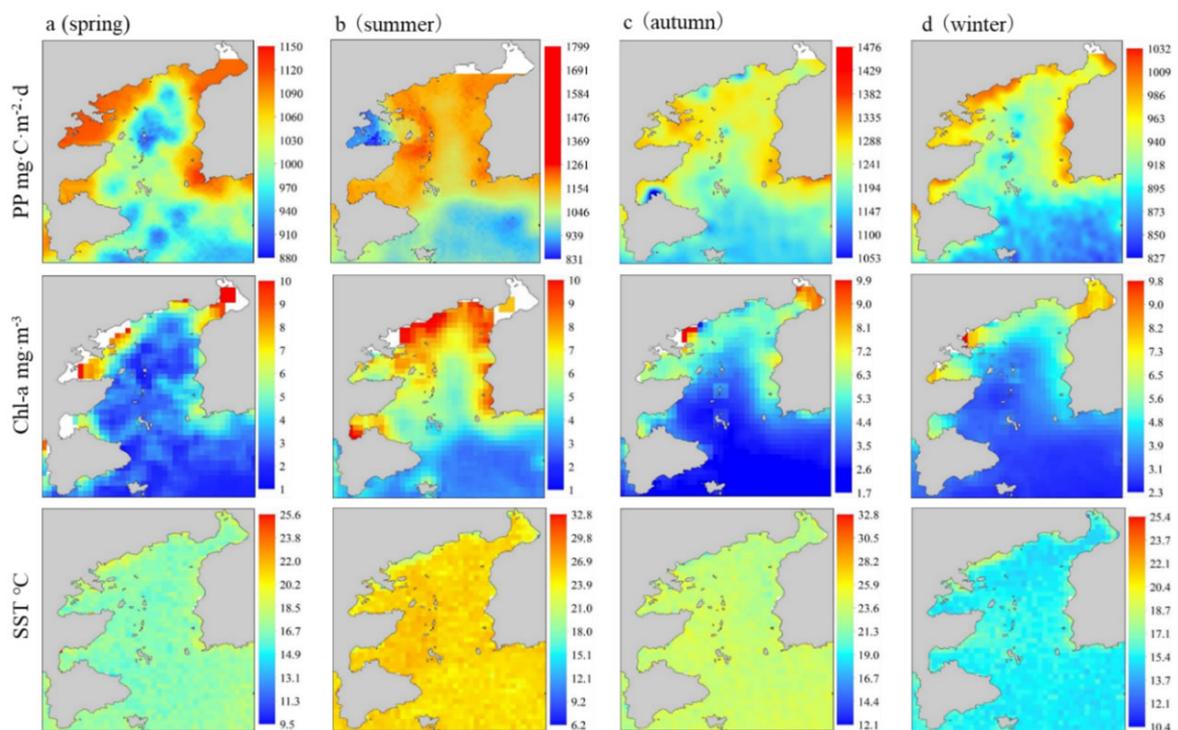


Fig. 4. Seasonal variations of PP, Chl-a and SST.

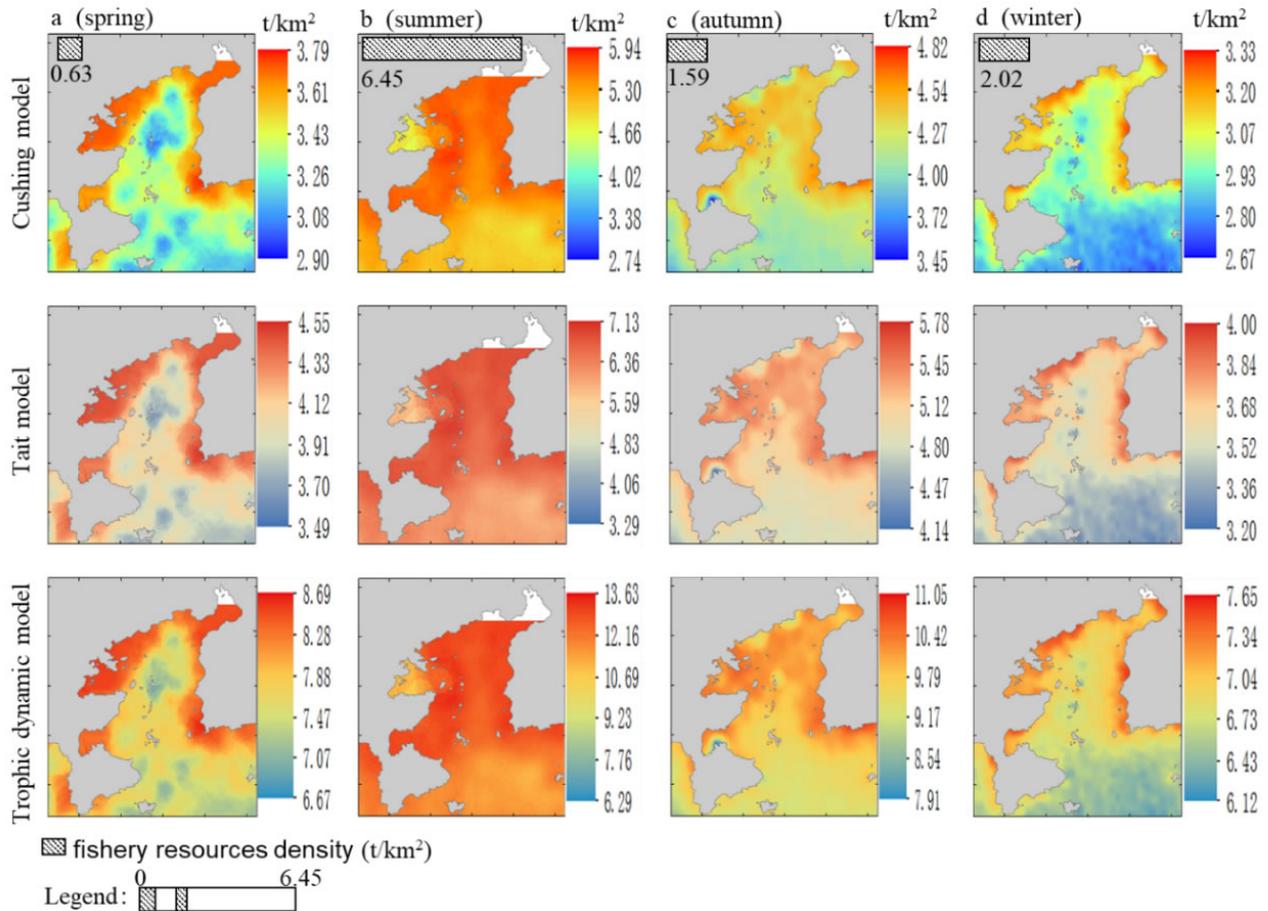


Fig. 5. Fishery resource density from models and surveys.

The seasonal distribution characteristics of fishery resource density evaluated by Cushing model based on primary productivity is basically consistent with actual survey results. In summer, resource density surveyed was slightly higher than the evaluation results of Cushing model, and in autumn, winter and spring, the resource density surveyed was slightly lower than the evaluation results of Cushing model. This was related to the selective use of biological resources by human activities. In summer, summer fishing moratorium allowed the fishery organisms to recover in the coastal waters of South China Sea (Yu *et al.*, 2018). In autumn, after the summer fishing moratorium, the resource density of *in situ* survey was slightly lower than that of Cushing model because of the increasing fishing intensity. The influence of human factors was not taken into account in Cushing model. In Egong Bay, a typical offshore fishing waters in the South China Sea, the ecosystem communities were stable during the summer fishing moratorium, however, the ecosystem communities in autumn was unstable due to the increasing

fishing intensity (Yu *et al.*, 2017b). In spring, young populations of *Trachurus japonicus* and *Parargyrops edita* occupying the Daya Bay probably reduced the actual catch (Wang *et al.*, 2010), resulting in the lower fishery resource density by *in-situ* investigation than the estimated fishery resource density by Cushing model.

Sustainable development of fishery resources

Taking season as time scale, fishery resource density evaluated by Cushing model was higher than fishery resource density by investigation except summer. On one hand, ecological environment was under great pressure in the Daya Bay due to the excessive disturbance of human beings. The environment that fishery organisms depend on for survival was deteriorating, the interaction between biological community and ecological environment led to the decrease of biological community diversity. The research showed that difference of benthic animal productivity was closely related to the influence of human activities in the Daya Bay. Fishery resources have an obvious trend of

miniaturization and low value (Du *et al.*, 2008, 2009). On another hand, overfishing was another important factor in the decline of fisheries in the Daya Bay which has been overexploited, updated and replenished slowly. Therefore, it is necessary to take measures to protect fishery resources, control fishing boats strictly and advocate pelagic fishing. There are abundant cephalopod fishery resources in waters of the continental shelf of the South China Sea, providing feasibility for the development of pelagic fishery (Li *et al.*, 2016). Fishing moratorium should be extended appropriately to protect spawning groups and young fishes, recovery time of fishery resources should be sufficient. The types of fishing moratorium should be expanded to increase the types of fishery resources (Yu *et al.*, 2017a). Construction of marine ranching restored the habitat to some extent, and played a positive role in the conservations and proliferation of fishery resources. (Wang *et al.*, 2019). Value-added release of different niche species should be carried out and spatial heterogeneity of fishery communities should be fully taken into account and the release of one-way species should be transferred to the value-added release based on ecosystem balance (Li *et al.*, 2011; Yu *et al.*, 2015), aiming to maintain ecosystem balance while expanding the types of fishing moratorium.

CONCLUSIONS

This study analyzed spatiotemporal distribution of the primary productivity and fishery resource density in the Daya Bay, according to the data from remote sensing and survey information on fishery resource. The research showed that fishery resource density estimated by Cushing model fitted well with the survey results. The temporal and spatial distribution of primary productivity and fishery resources is related with Chl-a, cage culture and nuclear power plant thermal emission, petrochemical emissions and other factors. In this study, only OC, SST and other ecological environmental factors obtained by satellite remote sensing were chosen. Marine current, plankton, proliferation were considered as important factors, which may have influence on primary productivity and fishery resources, aiming to analyze the distribution of primary productivity and fishery resources accurately in the Daya Bay.

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Statement of conflict of interest

The authors have declared no conflict of interest.

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