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Designing and the Pilot Trial of Bivalve Molluscan Fishing Quotas on Maoming Coastal Waters of China, Northern South China Sea

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In the context of the declining fishery resources, some active management measures have been taken to strive for the sustainable development of fisheries. However, these input-oriented control management measures have not realized the expectation in alleviating the depressing depletion of fishery resources. The fishing quota (FQ) system, an output-oriented control management method, has been proved to be effective in curbing overfishing and conserving fishery resources. However, it has not been formally implemented in China until now. Thus, it is urgent to start the pilot trial on the implementation of the FQ system in China. We firstly formulated a framework for the FQ system on bivalve fisheries and then conducted an empirical analysis based on the field survey of bivalve mollusks in Maoming shallow waters, Guangdong, northern South China Sea. The species composition, dominant species, and density distribution of bivalves were analyzed. The swept-area method was used to assess the total allowable catch (TAC) of bivalves. Each step of the FQ system was discussed in depth. Results showed that a total of 45 bivalve species were identified. *Meretrix planisulcata* and *Ruditapes philippinarum* were the two dominant species. The spatial distribution of density varied largely. The estimated TAC value is 4.28×10^5 kg which can be allocated to fishermen under the regulations of the FQ system. Finally, the framework for the FQ system was improved in every step of the future procedure, including target species selection, TAC determination, quota allocation, catch report, and fishing supervision. The general framework of the FQ system in this study can also be referenced to other economically important fish or other marine organisms.

Keywords: fishing quotas, total allowable catch, field surveys, bivalve mollusks, northern South China Sea

INTRODUCTION

Marine biodiversity loss and ecosystem degradation have been two of the most challenging ecological problems in the 21st century. Marine ecosystems could have provided valuable goods and services to humans (Sinclair et al., 2002; Worm et al., 2006). However, overfishing or destructive fishing is driving a crisis that leads to undesirable changes in marine ecosystem functioning, especially in coastal ecosystems (Jackson et al., 2001; Lotze et al., 2006). A typical phenomenon is the declining fishery resources in coastal waters, which has posed a serious threat to the production of high-quality animal proteins and the livelihood of fishermen (Food and Agriculture Organization (FAO), 2009; FAO, 2011; O'Hara et al., 2021). To maintain the sustainable development of fisheries and conserve the coastal ecosystem, some active management measures, including the input control management (e.g., the permission of fishing, the reduction of fishing vessels, and career change of fishermen from fishing to culturing) and technical control management (e.g., gear restrictions, fishing size limits, and closed fishing zones), were given priority to fisheries management in most fisheries countries (Worm et al., 2009). Yet, these measures have not realized the desired target. Hence, fishery managers and researchers turned their attention to the output control management (catch shares or fishing quotas) (Costello et al., 2008; Essington, 2010; Gutiérrez et al., 2011). The quantifying of fishing quotas and implementing of the fishing quota (FQ) system have been a research hot spot for fisheries management (Håkanson and Gyllenhammar, 2005; Poos et al., 2010).

The FQ system, a typical output control management measure, is based on total allowable catches (TAC) that are determined by fishery resource surveys and scientific assessments (Branch, 2009). Once the fishermen reach their quota limits, they are obliged to stop fishing until they are issued to the next quotas. Internationally, the FQ system is mainly deployed by some developed countries. The international practice experience shows that the FQ system is one of the most effective fishery management measures. Following the FQ system, the Icelandic total productivity in the fishing industry increased by 73% more in 1995 than in 1973, which has been very successful in increasing efficiency in the fisheries (The Organization for Economic Cooperation and Development (OECD), 2017). The use of the FQ system covers a variety of marine organisms, including fish, crustaceans, siphonopods, and shellfish (Yu, 2009). The FQ system has been proved to be effective in curbing overfishing and conserving fishery resources, which has become a great progress in international fisheries management (Péreau et al., 2012). In China, fisheries management with most fishing vessels and most fishermen seem to be the most complex in the world (Huang and He, 2019). The administrative departments of fishery in China have carried out a series of measures to improve marine fishery resources, such as summer fishing moratorium, minimum mesh size regulation, fishing license system, the so-called "Double Control" system, fishery stock enhancement programs, establishment of artificial reefs, and placements of aquatic germplasm resource-protection areas, which belong primarily to the input and technical control management, whereas the effect is limited (Shen and Heino, 2014; Lyu et al., 2021; Zhang et al., 2021). In 2000, the government of China revised the Fishery Law of the People's Republic of China, making it clear that China will determine TAC and implement an FQ system (Gu, 2018). Due to the lack of basic conditions for the implementation of this system, the FQ system has been in the planning and designing stage for more than a decade. Until 2017, five pilot projects for FQ have successively been carried out in coastal waters from five provinces. During the study period of these projects, TAC is mainly determined on the data of historical catch yields from fishing logbooks (Zhao, 2020). However, the FQ system has not been formally implemented in China so far.

Molluscan shellfish occur in diverse habitats and are closely related to human life with great values of ecology, economy, and culture. In terms of ecological value, as filter feeders, shellfish can not only purify water but also contribute to marine carbon sink (Chauvaud et al., 2003; Tang et al., 2011; Zhao et al., 2020). The distribution of shellfish, as the main bait source of many fish (Jaworski and Ragnarsson, 2006; Thangavelu et al., 2012) and crabs (Laughlin, 1982; Bisker and Castagna, 1987), is strongly associated with the formation and variations of fishing grounds. Due to their sensibilities to the marine environmental changes (Zhao et al., 2019; He et al., 2021; Xu et al., 2022), shellfish are regarded as the biological indicator of the quality of the waterborne or sedimental environment (Latimer and Kramer, 1997; Wang et al., 2020). In terms of economic value, shellfish are a popular food in our daily diet because of their rich nutrition (Wright et al., 2018), which has driven the economic development of shellfish harvesting, breeding, processing, and other related industries. In terms of cultural value, shellfish used to be an ancient currency. Nowadays, some shellfish have become more popular as collections and jewelry (Vaughn and Hoellein, 2018). Moreover, shellfish are sedentary benthos with high fecundity; no fishing action taken will waste the catch because of their short life cycle (Dame, 2016). As a result, shellfish have become one of the main commercial fishery targets for coastal fishermen. Nevertheless, according to the data of the China Fishery Statistical Yearbook (Fishery Bureau of Ministry of Agriculture and Rural Affairs of China, 2004-2021), the yield of wild shellfish decreased from 8.06×10^8 kg in 2003 to 3.62×10^8 kg in 2020. Therefore, the sustainable development of shellfish resources is urgent for the fisheries and livelihoods of fishermen. Research on the relevant system framework has an important reference value for its implementation in the future.

The purpose of this study is to develop a sensible framework of the FQ system and conduct a pilot trial based on the field survey data. Maoming coastal waters have a long coastline of approximately 220 km and are rich in shellfish resources with a fishing yield of 1.36×10^6 kg in 2020 (Editorial committee of Guangdong Rural Statistical Yearbook, 2021). Among shellfish resources, bivalves are a class with the largest economic value (Gosling, 2003). Therefore, this study conducted an analysis based on a survey of bivalve mollusks in Maoming shallow waters, in northern South China Sea, including the identification of bivalve species and the determination of TAC. This study provides a clue for policymakers to establish the FQ system of shellfish.

MATERIALS AND METHODS

Conceptual Framework for Fishing Quotas

A conceptual framework was designed for the FQ system based on the field survey. Accordingly, the procedure of the FQ system includes the selection of target species, determination of TAC, allocation of quotas, report of catch, and supervision of fishing (**Figure 1**).

Survey Design

The survey zone, covering nearly 3.02×10^2 km^2, is the shallow waters within 10 m of water depth in Maoming, northern South China Sea. 28 stations were set in this zone given the habitat characteristics and fishing accessibility of bivalve shellfish (**Figure 2**). In November 2020, bivalves were sampled at each station using a hydraulic clam rake (Munari et al., 2006) with a mouth width of 1.2 m and a cod-end mesh size of 20 mm. When arrived at the sampling station, the speed of the vessel was reduced to about 2 to 3 knots and the raking time was kept from 5 to 10 min. After sampling, bivalves were identified to species level (Xu and Zhang, 2008; Yang et al., 2013), weighed (total weight of species), and counted (total number of individuals).

Data Analysis

An index of relative importance (*IRI*) (Pinkas et al., 1970) was used to estimate the contribution of each bivalve species to the total catch. *IRI* was calculated using Equation 1 (Selleslagh et al., 2009):

$$IRI = (N\% + W\%) \times F\% \quad (1)$$

where *N*%, *W*%, and *F*% are the relative numbers, biomass, and frequency of occurrence, respectively. *IRI* >1,000 was considered as the dominant species and 100 <*IRI* <1000 was considered as the important species.

The density (ind./km^2) and biomass (kg/km^2) were estimated by the swept-area method. The raking swept area per hour (*A*, km^2/h) was calculated using Equation 2, and the density and biomass (*D*, ind./km^2 or kg/km^2) were calculated using Equation 3 (Wang et al., 2017):

$$A = M \times S \times 1.852 \times 10^{-3} \quad (2)$$

$$D = \frac{W/T}{A \times C} \quad (3)$$

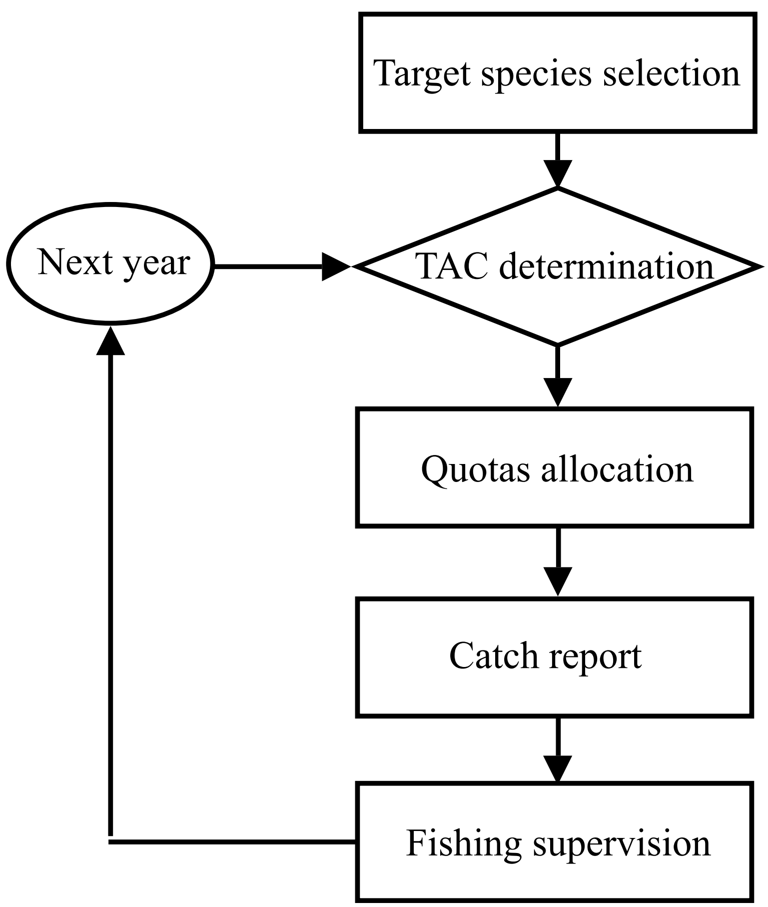

FIGURE 1 | The conceptual framework of the fishing quota system.

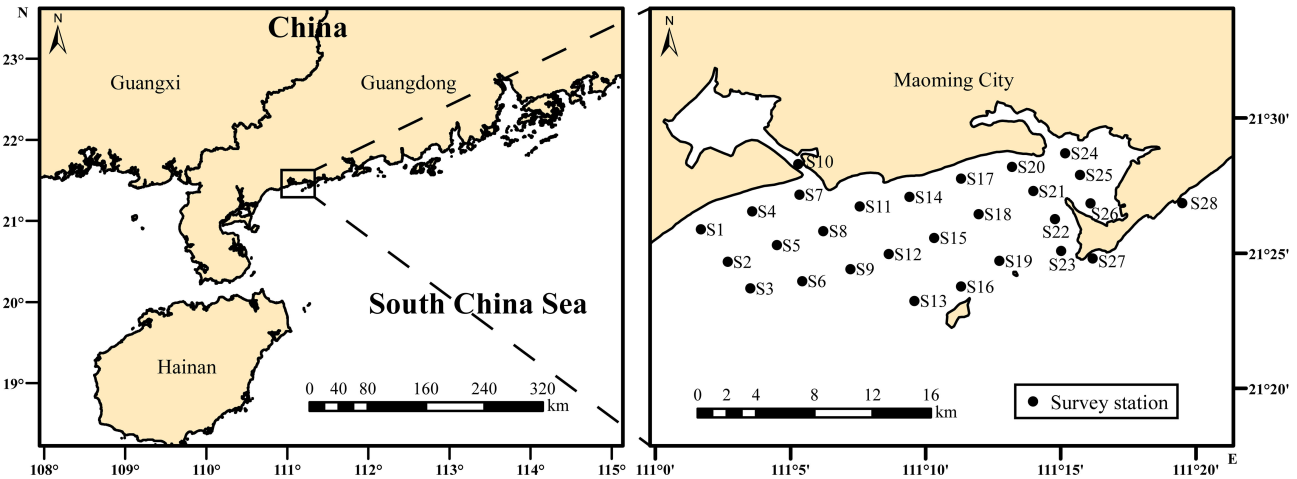

FIGURE 2 | Sampling stations of bivalves in Maoming shallow waters, northern South China Sea.

where M is the mouth width of the rake in m (here 1.2 m), S is the actual raking speed in knots at one station, 1.852 is the conversion rate of nautical miles to km, W is the catch weight of per raking at one station (kg), T is the actual raking time at one station (hours), and C is the catchability coefficient of raking, with the value of 1.0 given the weak locomotivity of bivalves.

The estimated bivalve production (P) was calculated using $P = D \times A_s$, with A_s the area of the survey zone (here 3.02×10^2 km^2). Finally, 80% of the estimated production was chosen as TAC for bivalves given the economics and sustainability.

RESULTS

Species Composition and Dominant Species of Bivalves

A total of 45 bivalve species belonging to 29 genera, ten families, and six orders were identified from the 28 stations sampled (**Table 1**). The bivalve species that occurred most frequently were from Veneroida (27 species), which accounted for 60.0% of the total number of bivalve species, followed by Arcoida (14 species), which accounted for 31.1%. The other four orders had one species for each. According to the *IRI* score, *Meretrix planisulcata* and *Ruditapes philippinarum* were the dominant bivalve species, constituting 50.1% of the total catch by biomass and 67.7% by numbers. There were eight important bivalve species, constituting 37.3% of the total catch by biomass and 21.7% by numbers.

Density Distribution and TAC of Bivalves

Both the distributions of density and biomass varied largely in the survey zone (**Figure 3**). The density value ranged from 0 ind./km^2 to 3.72×10^6 ind./km^2, with an average of 3.43×10^5 ind./km^2. The biomass values ranged from 0 kg/km^2 to 1.40×10^4 kg/km^2, with an average of 1.77×10^3 kg/km^2. Both the maximum values of density and biomass were in S7, while no bivalves were sampled in S23, S26, and S27. The estimated bivalve production was 1.03×10^8 ind. or 5.35×10^5 kg in the survey zone. To be conservative, TAC of bivalves was 8.28×10^7 ind. or 4.28×10^5 kg.

Frame Improvement and Current Completion Status of the Bivalve FQ System

The conceptual framework of the bivalve FQ system was improved (**Figure 4**). There were five steps in the FQ system frame. For step 1, the species composition of bivalves was analyzed after the field survey, and dominant species were determined by using the *IRI* index. The target species of bivalves was selected by the value of species. For step 2, the density distribution and estimated production were analyzed by the swept-area method and numbers or biomass. The TAC of bivalve was determined. For step 3, free fishing like Olympic competition (FFOC), community quotas (CQ), individual vessel quotas (IVQ), and individual transferable quotas (ITQ) can be used for quota allocation of bivalves. For step 4, the traditional and electronic fishing logbooks can be used for the catch report of bivalves. For step 5, the port inspection, maritime inspection, and punishing for illegal behavior can be used for fishing supervision of bivalves. In the end, the procedure of the bivalve FQ system can be cycled next year. To sum up, Step 1 and Step 2 were completed. Step 3, Step 4, and Step 5 were conceived, although it still needs more time before they are implemented.

DISCUSSION

Selection of Target Species

Target species selection is the beginning in the process of implementing the FQ system. In general, target species selection

TABLE 1 | Species composition and *IRI* values of bivalves from Maoming shallow waters in November 2020.

SN	Latin name	Order	Family	Genus	*IRI*
1	*Meretrix planisulcata*	Veneroida	Veneroidae	*Meretrix*	2868
2	*Ruditapes philippinarum*	Veneroida	Veneroidae	*Ruditapes*	1071
3	*Tapes belcheri*	Veneroida	Veneroidae	*Tapes*	379
4	*Scapharca inaequivalvis*	Arcoida	Arcoidae	*Scapharca*	247
5	*Meretrix meretrix*	Veneroida	Veneroidae	*Meretrix*	219
6	*Macridiscus aequilatera*	Veneroida	Veneroidae	*Macridiscus*	184
7	*Scapharca anomala*	Arcoida	Arcoidae	*Scapharca*	171
8	*Anomalodiscus squamosus*	Veneroida	Veneroidae	*Anomalodiscus*	166
9	*Meretrix lusoria*	Veneroida	Veneroidae	*Meretrix*	112
10	*Anadara kagoshimensis*	Arcoida	Arcoidae	*Anadara*	101
11	*Paratapes undulatus*	Veneroida	Veneroidae	*Paphia*	78
12	*Scapharca labiosa*	Arcoida	Arcoidae	*Scapharca*	60
13	*Scapharca satowi*	Arcoida	Arcoidae	*Scapharca*	48
14	*Scapharca indica*	Arcoida	Arcoidae	*Scapharca*	37
15	*Dosinia biscocta*	Veneroida	Veneroidae	*Dosinia*	22
16	*Lioconcha fastigiana*	Veneroida	Veneroidae	*Lioconcha*	15
17	*Meretrix lyrata*	Veneroida	Veneroidae	*Meretrix*	13
18	*Trisidos tortuosa*	Arcoida	Arcoidae	*Trisidos*	3
19	*Codakia tigerina*	Lucinida	Lucinidae	*Codakia*	3
20	*Trisidos kiyonoi*	Arcoida	Arcoidae	*Trisidos*	3
21	*Scapharca broughtonii*	Arcoida	Arcoidae	*Scapharca*	3
22	*Moerella iridescens*	Veneroida	Tellinidae	*Moerella*	2
23	*Scapharca cornea*	Arcoida	Arcoidae	*Scapharca*	2
24	*Mactra aphrodina*	Veneroida	Mactridae	*Mactra*	1
25	*Solidicorbula erythrodon*	Myoida	Corbulidae	*Solidicorbula*	1
26	*Soletellina diphos*	Veneroida	Psammobiidae	*Soletellina*	1
27	*Scapharea globosa*	Arcoida	Arcoidae	*Scapharca*	1
28	*Perna viridis*	Mytiloida	Mytilidae	*Perna*	1
29	*Dosinia japonica*	Veneroida	Veneroidae	*Dosinia*	<1
30	*Dosinia cumingii*	Veneroida	Veneroidae	*Dosinia*	<1
31	*Clausinella calophylla*	Veneroida	Veneroidae	*Clausinella*	<1
32	*Potiara pilula*	Arcoida	Arcoidae	*Potiarca*	<1
33	*Scapharca gubernaculum*	Arcoida	Arcoidae	*Scapharca*	<1
34	*Gari truncata*	Veneroida	Psammobiidae	*Gari*	<1
35	*Anadara antiquata*	Arcoida	Arcoidae	*Anadara*	<1
36	*Nitidotellina minuta*	Veneroida	Tellinidae	*Nitidotellina*	<1
37	*terocardia elliptica*	Veneroida	Veneroidae	*terocardia*	<1
38	*Crassostrea rivularis*	Pterioida	Ostreidae	*Crassostrea*	<1
39	*Angulus emarginatus*	Veneroida	Tellinidae	*Angulus*	<1
40	*Hiatula chinensis*	Veneroida	Psammobiidae	*Hiatula*	<1
41	*Vepricardium coronatum*	Veneroida	Cardiidae	*Vepricardium*	<1
42	*Dosinia troscheli*	Veneroida	Veneroidae	*Dosinia*	<1
43	*Tellinides timorensis*	Veneroida	Tellinidae	*Tellinides*	<1
44	*Apolymetis meyeri*	Veneroida	Tellinidae	*Apolymetis*	<1
45	*Pinguitellina pinguis*	Veneroida	Tellinidae	*Pinguitellina*	<1

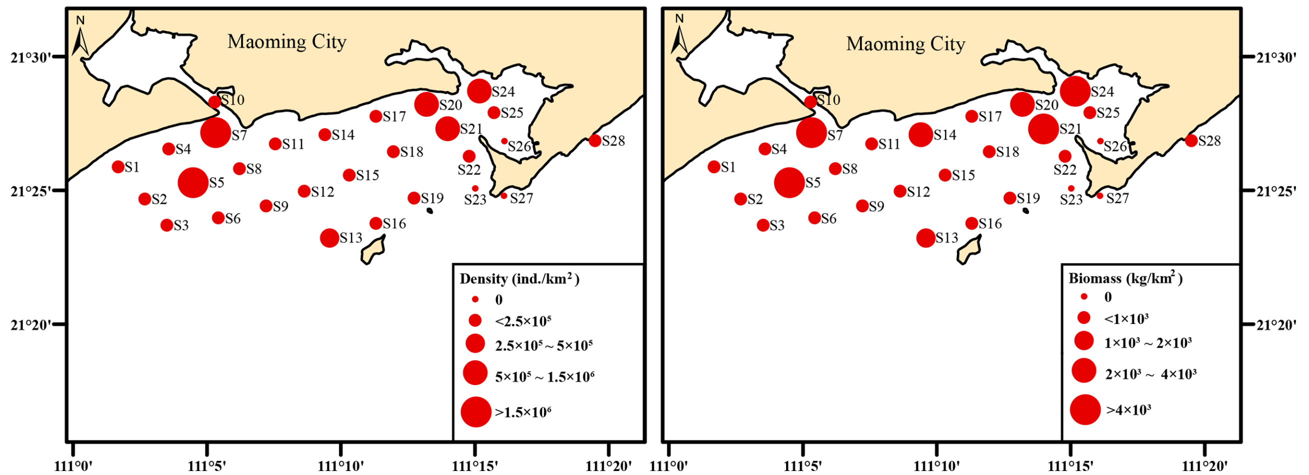

FIGURE 3 | The distribution of density and biomass of bivalves in Maoming shallow waters, northern South China Sea.

follows four principles: (1) Species has high economic value, large catch, and small bycatch. (2) Species needs to be conserved due to its severe declining resources. (3) Species needs to be adjusted due to the competition from different fishing grounds. (4) Species is used commonly by multiple countries or regions (Zhao, 2020). In the preliminary stage of the implementation of the FQ system, it follows mainly the first principle, also giving priority to the single species with fast growth, short life cycle, and small migration range (Harlyan et al., 2021). In this study, bivalve species composition and dominant species can be used as a reference to select the optimum species. There were 45 bivalve species, but most of them were of low economic value or no economic value. Further, only *M. planisulcata* (*IRI* = 2,868) and *R. philippinarum* (*IRI* = 1,071) were the dominant species. The reason why *M. planisulcata* was the first dominant species is that its number was large; however, its individual weight was smaller than that of *R. philippinarum*. To our knowledge, local fishermen tend to discard them because *M. planisulcata* belong to the bycatch. So, if a single-species FQ system

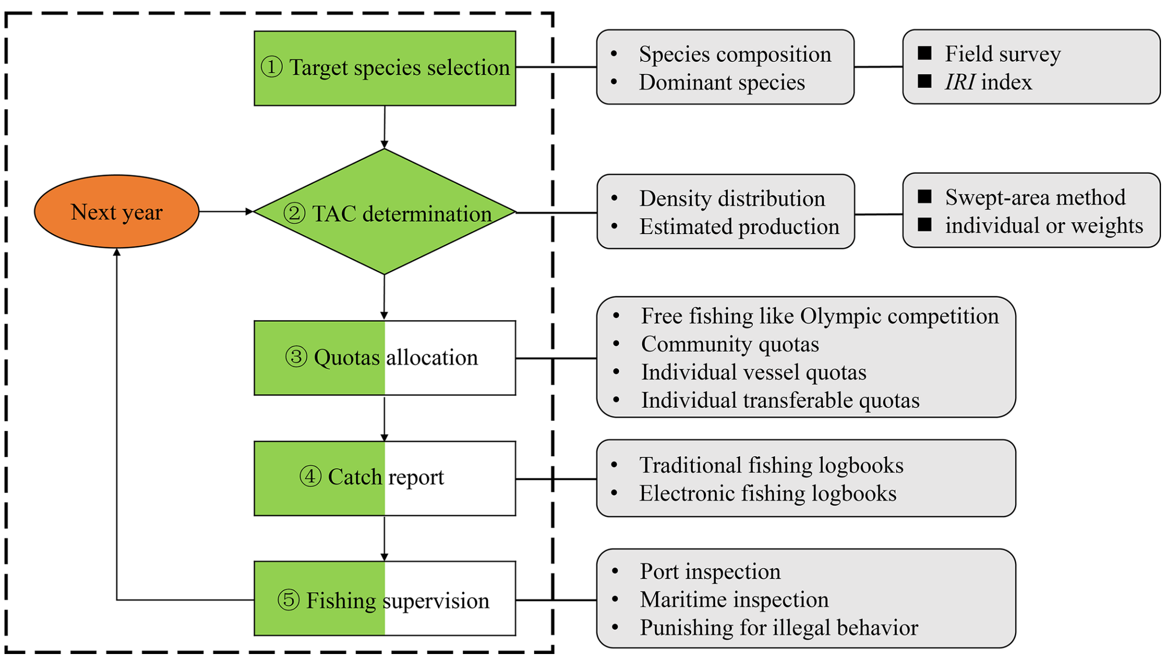

FIGURE 4 | The frame improvement of the bivalve FQ system and current perform status (the filled green color represents the degree of completion, respectively).

for bivalves needs to be implemented, the optimum species is *R. philippinarum* with higher value. The single-species FQ system is relatively easy to implement in the preliminary stage, which can accumulate more experience for the implementation of a multiple-species FQ system in the future.

Determination of TAC

TAC determination is the important precondition of the FQ system, which directly affects the implementation effect of the FQ system (Branch, 2009). If TAC is set too high, the resource depletion may be exacerbated. Whereas if it is too low, resources may be wasted. To our knowledge, TAC is determined based on the data of scientific surveys and fishing statistics. For the data of fishing statistics, previous studies used some models to assess the maximum sustainable yield (MSY) of fishing species (Brodziak and Ishimura, 2011; Martell and Froese, 2013), and in terms of the principle that the catch needs to be lower than the increase of fishery resources, TAC needs to be less than MSY to maintain sustainable development (Mace, 2001; Acheson et al., 2015). Using the models, more than 5 years of continuous fishing statistical data are required to provide a more accurate assessment of MSY. However, the long-term data of most fishery stocks have poor availability. In this study, based on the scientific survey, the swept-area method was used to estimate the bivalve production and determine the TAC value. This way is suitable for the stocks that lack the long-term fishing data. For the TAC value, TAC by weights (4.28×10^5 kg) is more suitable for use than that by individuals (8.28×10^7 ind.) due to the habitual use of weight. In addition, the density distribution of bivalves was analyzed in this study, but results showed that there were no significant geographical differences. If the density is concentrated within a certain range, it is recommended that the FQ system is mainly applied to this range to facilitate management. The survey tool in this study is a hydraulic clam rake. Munari et al. (2006) compared the effects of three raking tools (manual rake, hydraulic rake, and conveyor rake) on the benthic community, and results showed that manual raking and hydraulic raking have mild disturbances but unlikely to have persistent effects on biota. They suggested that clam fishermen should be allowed to use the hydraulic rake due to its relative efficiency. However, in China, rakes are the banned fishing facilities. Considering the problems of fishermen's livelihood, it is worth thinking about whether the hydraulic rake should be locally (and legally) used. Additionally, more selective and eco-friendly fishing tools need to be developed.

Allocation of Quotas, Report of Catch, and Supervision of Fishing

After determining TAC, fair and equitable allocation of quotas is the key to stimulating fishermen to comply with the FQ system. Well-designed quota allocation can help prevent fisheries collapse (Costello et al., 2008). In terms of whether the quotas are allocated to fishermen and whether the quotas are allowed to transfer, FQ can be divided into four types (Ding, 2019): FFOC, CQ, IVQ, and ITQ. For FFOC, fishermen can catch competitively until the TAC limit value was reached. Although this way has low management costs, it does not solve the competitive fishing mind of fishermen. Moreover, this way may make fishermen to compete for catch regardless of the risks, such as bad weather (Long, 2010). What is more, a large number of catches coming to the market at the same time will affect the prices, which leads to lower incomes for fishermen. For CQ, quotas are first allocated to different communities which are formed by fishermen, and then each community committee allocates the quotas to the members according to their own regulations. However, it is not applicable in Maoming sea areas due to the scattering of local traditional fishermen. For IVQ, quotas are allocated to the fishing vessels that meet the requirements. This is an appropriate type to allocate at present. The owner of the vessel can apply to the local department of fishery at first. The requirements are as follows: (1) Applicants must have a household register certificate in Maoming city. (2) Applicants must have a marine fisheries fishing license. (3) Applicants must have a fishing vessel with the equipment of life-saving, communication, and positioning system. After that, TAC will be allocated distributed averagely according to the number of fishing vessels who meet the requirements and granted the special fishing license of bivalve shellfish. For ITQ, the quota holders can transfer their quotas. To make the quota holders adapt to the new management system, it is recommended to forbid them to transfer the quotas at the beginning of the FQ system. Waiting until conditions mature, ITQ can be allowed. For ITQ, attention should be paid to prevent the concentration of quotas into few people, which may lead to a monopoly of the market (Eythórsson, 2000).

Fishermen must record truthfully their fishing yields in the logbooks, because this is the only approach to know if TAC is reached. Traditional logbooks are printed on paper, which is easy to lose and get damaged. In recent years, with the development of science and technology, the technology of using smart devices to record fishing information has become mature (Oviedo and Bursztyn, 2017). Fishermen can use a specialized software in mobile phones to report their fishing yields. Electronic fishing logbooks make it easy to collect and store the data of fishing and locations, so TAC can be monitored in time (Zhao, 2020). In view of the differences in age and literacy rate among fishermen, the traditional or electronic fishing logbooks should be chosen one accordingly.

On the whole, the fishing supervision includes the following aspects: (1) Port inspection. The fishing target species of FQ must be landed at the designated port. In the meantime, the port information officers collate the data of sales and logbooks every day and ensure the authenticity of data. To prevent the actual fishing yields exceeding the upper limit of quotas, the quota holders will be warned when their yields are close to the limit (Yu, 2009). (2) Maritime inspection. On the one hand, the fishery administration department can track the position of fishing vessels through the vessel monitoring system. On the other hand, it can carry out routine and surprise inspection at sea to check whether there are maritime sales. Besides, the following vessel observers should be dispatched without day to record and supervise the production status. (3) Punishing for illegal behavior. To prevent illegal production, harsh punishment

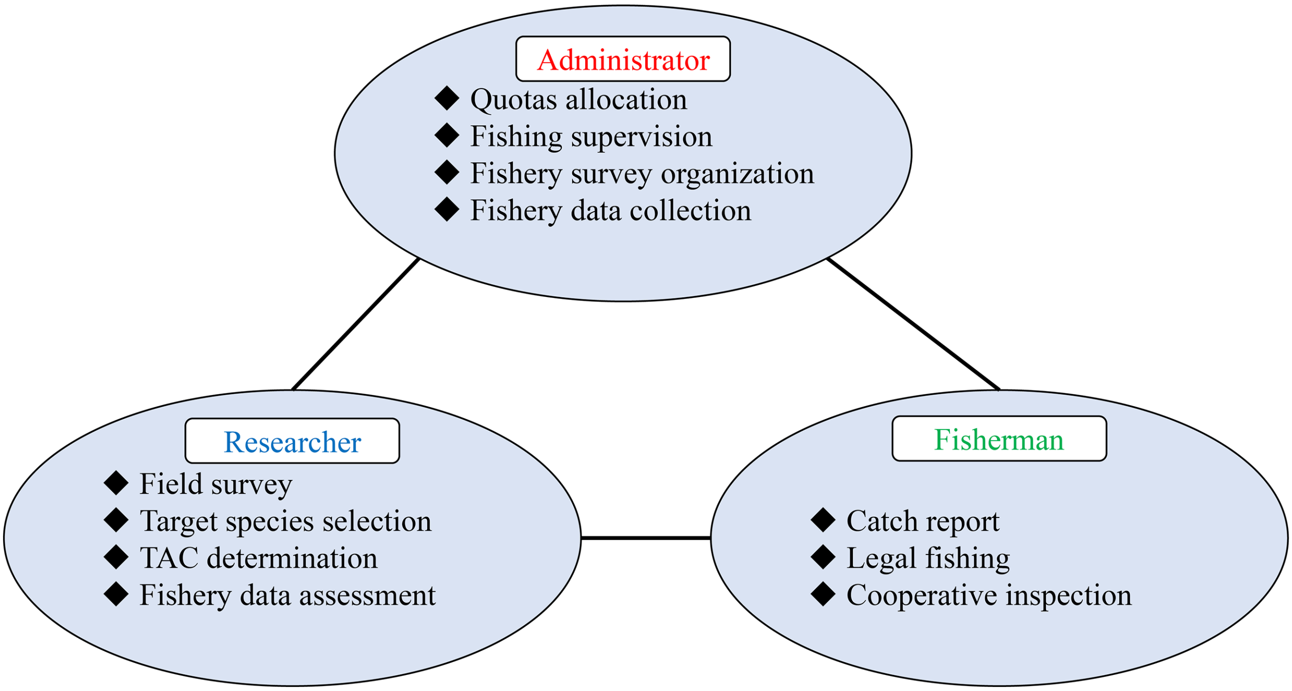

FIGURE 5 | The respective responsibilities of administrators, researchers, and fishermen under the FQ system.

with fines and special license revocation should be imposed on violators (**Figure 5**) (Zhao, 2020).

CONCLUSION

In summary, we made the practical framework for the FQ system of bivalve fisheries based on the field survey. Our findings not only contribute to the establishment of the FQ system in China but also serve as a guideline for implementing a formal FQ system for bivalve molluscan fishing quotas in the near future. Further research is needed to understand the fishermen's approbation degree of this system through questionnaires.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The animal study was reviewed and approved by the Animal Experimental Ethics Committee of Guangdong Ocean University, China.

AUTHOR CONTRIBUTIONS

SL and XW conceived the study. SD, KL, and JZ conducted the field and laboratory work, assisted the identification of the species, and participated in the data analysis. SL drafted the manuscript. XW revised the manuscript. All authors contributed to the article and approved the submitted version.

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