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Performance evaluation of fixed-station sampling design for a fishery-independent survey with multiple objectives

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Abstract

Fixed-station sampling design was widely used in fishery-independent surveys because of its characteristics of convenient sampling station setting, but the non-probabilistic (fixed) nature made it more uncertainty of drawing inferences on population. The performance of fixed-station sampling design for multispecies survey has not been evaluated, and we are uncertain if the design could detect the temporal trends of different populations in multispecies fishery-independent survey. In this study, spatial distribution of abundance indices for three species with different spatial distribution patterns including small yellow croaker (*Larimichthys polyactis*), whitespotted conger (*Conger myriaster*) and Fang's blenny (*Enedrias fangi*) were simulated using ordinary kriging interpolation as the "true" population distribution. The performance of fixed-station sampling design was compared with simple random sampling design by resampling the simulated "true" populations in this simulation study. The results showed that the fixed-station sampling design had the power to detect the seasonal trends of species abundance. The effectiveness of fixed-station sampling design were different in different species distribution patterns. When the species had even distribution, fixed-station sampling design could get high quality abundance data; when the distribution was uneven with heterogeneity or patchiness, fixed-station sampling design tended to underestimate or overestimate the abundance. Evidently, the estimates of abundance index based on the fixed-station sampling design must be calibrated cautiously while applying them for fisheries stock assessment and management. This study suggested that fixed-station sampling design could catch the temporal dynamics of population abundance, but the abundance estimates from the fixed-station sampling design could not be treated as the absolute estimates of populations.

Key words: computer simulation, fixed-station sampling design, precision and accuracy, ordinary kriging interpolation

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1 Introduction

Fishery-independent surveys provide reliable data on relative abundance and life history parameters for a wide range of fishery species. And the survey data are used to assess species distribution, biological interactions, and ecosystem structure and to make effective decisions for scientific fisheries managements. The quality and precision of these estimates depend, in part, on adequate sampling of all species distribution types, even it is more expensive and labor-intensive (Andrew and Mapstone, 1987; Field, 2005). One of the main goals of sampling designs is to keep a balance between estimates precision, accuracy and budget limitations.

Standardized sampling designs, at its simplest in fishery, are of two different methods: probabilistic (random) and non-probabilistic (fixed) (Bethlehem, 2009; Bonar et al., 2009). And the debate on the advantages and disadvantages of random-station versus fixed-station sampling designs has never stopped (Warren, 1994; Quist et al., 2006). The former one is commonly and typically the most statistically sound survey method for collecting fisheries data, such as simple random sampling, stratified random sampling and system sampling, as well as some more advanced sampling design derived from these traditional methods (Bonar et al., 2009; Liu et al., 2011; Yu et al., 2012; Nelson, 2014; Zhang et al., 2019; Sun and Wang, 2020). Fixed sampling can be biased by site selection, but carefully selected sampling locations can increase catches and monitor trends of target species at specific sample locations over time (Hubbard and Miranda, 1986; McClelland and Sass, 2012).

The performance of sampling design also depends on the target species distribution. Many marine species showed aggregated or patchy patterns in spatial distribution structured by water temperature, salinity, depth and other environmental variables (Mazzoni and Iglesias-Rios, 2002; Guan et al., 2017). And the spatial distribution of many populations would shift with sea-

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son and climate change as well as the fishing activities (Tang et al., 2011; Vanderwal et al., 2013; Xu et al., 2017), and changes in estimates were confounded by these distribution shift (Beare et al., 2004; Perry et al., 2005). Multispecies trawl surveys often intended to cover the range of all the populations and obtain the spatiotemporal distribution data with high precision. The sampling design was inevitably a compromise, with the distribution of target populations being most concerned in the survey.

A sound fisheries management requires information on the status of fisheries ecosystems and the impacts of various pressures such as climate change, fishing and anthropogenic perturbation on fisheries ecosystems (Pikitch et al., 2004). Further, there is increasing uncertainty in fisheries management, resulting from the impact of climate change on marine ecosystem components (Littell et al., 2011; Payne et al., 2016). These challenges and the expanding objectives for fisheries management need high quality data to provide tactical and strategic decisions on multiple spatial and temporal scales. Currently, there are considerable capacity shortfalls in data collection that are hampering effective fisheries management (Dorner et al., 2015; Graham et al., 2011; Simmonds et al., 2011). According to the considerably increasing demand for reliable survey data for scientific management, it is necessary to evaluate the performance of sampling design.

Fishery-independent monitoring program can provide vital information for understanding the status of fishery resource and the recruitment dynamics of target species. Such a program can collect data about species density or abundance and associated environmental and spatial variables at selected sites simultaneously. In this study, the bottom trawl fishery-independent monitoring program is a quarterly survey which has monitored the fish assemblage of Shandong adjacent sea area during 2016–2017 using a fixed site sampling design.

The non-probabilistic nature of fixed sampling design would make it providing potential biased information for drawing inferences on a population. Simple random sampling design tends to yield unbiased estimates and is often used as a basic design to evaluate the survey precision, efficiency, and accuracy of other survey designs (Skibo et al., 2008; Cao et al., 2014; Li et al., 2015). The performance of fixed-station sampling design was evaluated in this simulation study. The main objectives of this study are: (1) to determine whether the fixed-station sampling design could capture the temporal dynamics of species with different spatial distribution patterns over seasons; (2) to compare the performances between fixed-station sampling design and simple random sampling design in quantifying the spatial and temporal variability in relative abundance of fish species.

2 Materials and methods

2.1 *Survey data*

Initiated in 2016, this fishery-independent monitoring program covers four seasons monitoring time series, in the coastal waters of Shandong, China. The multispecies fishery-independent survey data were collected in autumn (October, 2016), winter (January, 2016), spring (May, 2017) and summer (August, 2017). In this program, the fixed stations were chosen in a systematic fashion to spread sampling effort evenly across the study area. The survey area was divided into 15′ × 15′ grids in the inshore waters (43 sampling stations), and 30′ × 30′ grids in the offshore area (20 sampling stations) (Fig. 1). The trawl was towed for about 1 h in duration with the speed at 2–3 kn. Fish samples were identified to species, counted for abundance and measured for biological traits. The catch data in each sampling station were standardized to the relative abundance (kg/h) with the towing speed of 3 kn and duration of 1 h.

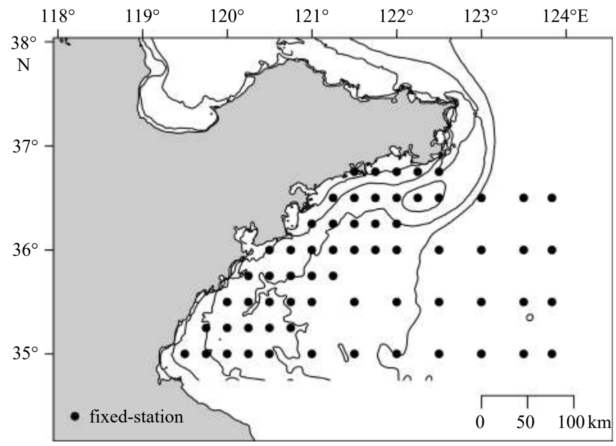

Fig. 1. Sampling stations of multispecies bottom trawl survey in the coastal waters of Shandong, China.

Intuitively, more information of species distribution will improve the understanding of the variability and be helpful in specifying models to describe their abundance. There are no significant differences among the effectiveness of different sampling designs to detect population abundance estimates for even and random spatial distribution species, and vice versa (Blanchard et al., 2008). We select different species with different spatial distribution patchiness levels as the objectives in this study to assess the effectiveness of fixed-station sampling design to detect the true trends of abundance compared with random sampling design.

As the importance of species abundance in ecology, we select species abundance index as the survey evaluation objective. Small yellow croaker (*Larimichthys polyactis*, LP), whitespotted conger (*Conger myriaster*, CM) and Fang's blenny (*Enedrias fangi*, EF) were selected as target species in this study. These three fish species are commercially or ecologically important species with different spatial distribution patterns in the waters. Fang's blenny, typically small-sized demersal fish, distributing in the Yellow Sea and Bohai Sea, is an important prey species with high abundance (Li et al., 2014). Small yellow croaker is a demersal species that is widely distributed throughout the Bohai Sea, Yellow Sea, and East China Sea, supporting important demersal fisheries with annual landing of more than 300 000 t (Guo et al., 2006; Kim et al., 2010). Whitespotted conger, a species with high economic and nutritional value, is widespread from the Northwest Pacific from the East China Sea to the coastal waters around Korea and Japan (Zhang, 2010; Kawazu et al., 2015).

The log transformation, one of the data preparation methods, can be used to make highly skewed distributions less skewed. This can be valuable both for making patterns in the data more interpretable and for helping to meet the assumptions of inferential statistics (García et al., 2000). In this study, we used log-transformed abundance as the species abundance index. Tables 1 and 2 listed the mean and coefficient of variation (CV) of abundance (log-transformed) indices as well as the presence/absence ratio of each target species based on the survey data over seasons in the coastal waters of Shandong, showing different spatial distribution patterns.

2.2 *Simulated data*

Ordinary kriging interpolation (OKI) is one of the most com-

Table 1. Mean and coefficient of variation (CV) of abundance (unit: g) (lg-transformed) index of three target species based on the survey data in the coastal waters of Shandong, China

Species	Species codes	Spring		Summer		Autumn		Winter	
		Mean	CV	Mean	CV	Mean	CV	Mean	CV
Fang's blenny (*Enedrias fangi*)	EF	7.33	0.27	6.00	0.62	4.08	0.68	4.48	0.49
Small yellow croaker (*Larimichthys polyactis*)	LP	3.84	0.84	4.16	0.92	3.59	0.92	4.54	0.57
Whitespotted conger (*Conger myriaster*)	CM	3.23	1.06	4.10	0.92	3.32	0.99	2.26	1.29

Table 2. The presence/absence frequency and ratio of three target species based on the survey data in the coastal waters of Shandong, China

Season	CM		EF		LP	
	Presence	Absence	Presence	Absence	Presence	Absence
Autumn	34 (53.97%)	29 (46.03%)	49 (77.78%)	14 (22.22%)	37 (58.73%)	26 (41.27%)
Winter	25 (39.68%)	38 (60.32%)	56 (88.89%)	7 (11.11%)	49 (77.78%)	14 (22.22%)
Spring	32 (50.79%)	31 (49.21%)	61 (96.83%)	2 (3.17%)	39 (61.9%)	24 (38.1%)
Summer	35 (55.56%)	28 (44.44%)	49 (77.78%)	14 (22.22%)	36 (57.14%)	27 (42.86%)

monly used geostatistical interpolation methods to estimate the values at unsurveyed locations using the combination of weights and values at surveyed locations (Schabenberger and Gotway, 2005). The weights are estimated according to semi-variance among known values (Oliver and Webster, 1990; Pokhrel et al., 2013). The geostatistical interpolation method is based on the spatial autocorrelation analysis, which is often used to interpolate data at potential sampling units according to the patterns of spatial variability and is not influenced by the current survey design. In this study, we used OKI method to interpolate the species abundance index data in the four seasons, respectively. The unit size of the interpolated abundance maps was 3′ × 3′, and there were 3 800 potential sampling units in the waters. The interpolated abundance based on OKI for each specie in each sampling unit were regarded as the "true" values in the simulation study. Fixed-station sampling design and simple random sampling design were conducted based on the "true" population distribution. To quantify the accuracy of the "true" value from OKI, leave-one-out cross-validation was used to check the performance of the interpolation.

2.3 *Simulation study*

In this study, the bottom trawl surveys with fixed-station design were conducted seasonally and provided estimates of fishery species abundance for stock assessments. But it is uncertain if the fixed-station could detect the spatial and seasonal variations in abundance indices of the main fishery species with different spatial distribution patterns. Since the effectiveness of this fixed-station survey design needs to be examined, we use the random sampling design to assess the fixed-station survey design effectiveness.

As for the fixed-station sampling design, 63 stations out of the 3 800 potential sampling stations that were closest to the 63 fixed stations used in the actual settlement survey were selected. For simple random sampling design, 63 sampling stations out of the 3 800 potential sampling sites were randomly selected. Both fixed-station sampling and simple random sampling design were repeated for 1 000 times in each season. Relative estimation error (REE) and relative bias (RB) were used to measure the precision and accuracy of mean estimation values for the two sampling designs in the simulation study. The process was repeated for 100 times to capture the variability in the simulation and get the distribution of performance indices. The process of evaluating the effectiveness for fixed-station sampling design was showed in the flowchart (Fig. 2).

2.4 *Performances of the two survey designs*

REE (Eq. (1)) was used to quantify the accuracy and precision of estimated indices (Chen, 1996). RB (Eq. (2)) could estimate the accuracy and efficiency of estimated indices, indicating whether a survey design tended to underestimate or overestimate the "true" values (Paloheimo and Chen, 1996; Jiao et al., 2004).

$$\mathrm{REE}=\frac{\sqrt{\sum_{i=1}^{R}\left(Y_{i,\ \mathrm{estimated}}-Y_{\mathrm{true}}\right)^2/R}}{Y_{\mathrm{true}}}\times 100\%, \tag{1}$$

$$\mathrm{RB}=\frac{\sum_{j=1}^{R}Y_{j,\ \mathrm{estimated}}/R-Y_{\mathrm{true}}}{Y_{\mathrm{true}}}\times 100\%, \tag{2}$$

where Y_{true} was the "true" value calculated based on the "true" population, $Y_{i,\ \mathrm{estimated}}$ was the ith estimated value calculated according to resampling data, R was the number of repetitions (1 000 times in this study).

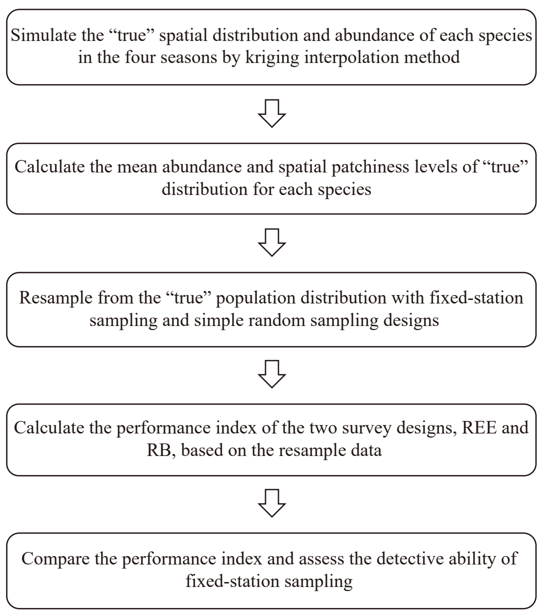

Fig. 2. The flowchart of evaluation of the performance for fixed-station sampling design.

In this study, the fixed stations were chosen in a systematic fashion to spread sampling effort, so the mean equation is $\bar{X}=\sum_{k=1}^{n} X_k/n$ based on fixed-station, which is same with the equation based on simple random sampling design. Where X_k was the abundance value in the *k*th sampled site.

As the formula shows, the REE values could reflect the difference between resampling results and true value for every species over seasons and measure both bias and variation in the evaluation. And the RB values could measure the estimation bias. Therefore faced with alternative estimators for a given objective, it is generally reasonable to use the one with the smallest REE and RB values.

3 Results

3.1 *Model evaluation*

The adjusted R^2 values of leave-one-out cross-validation for three target species over seasons runs varied from 0.072 to 0.490. There was a positive relationship between predicted and observed abundance values (Fig. 3). EF fitted better (R^2: 0.12–0.49), while LP in spring and winter fitted worse (R^2=0.072 and 0.089, respectively).

3.2 *Predicted distribution of target species*

The predicted abundance (log-transformed) distributions by OKI method were different for the three target species during the four seasons. The abundance distribution of EF was chosen as an example to show the performance of OKI in predicting the spatial distribution of fish species abundance (Fig. 4). The spatial distribution of Fang's blenny abundance varied over different seasons. The abundances in spring and summer were higher than those in autumn and winter. The hotspots with high abundance distributed evenly throughout the survey area in spring, however the hotspots occurred in the deeper waters in summer. The abundance was low in the shallow waters in autumn, and low in the waters between 35.5°N and 36°N in winter (Fig. 4). The abundance distribution of LP and CM were set in supplementary materials (Figs S1 and S2).

In order to evaluate the effectiveness of fixed-station sampling design in capturing the temporal variability of abundance index, the probability density distribution of the observed and simulated abundance indices were calculated, respectively. As for the same species in each season, the two probability density distribution range was similar, but the positions of peak-value in probability density distribution for observed data were different from those for simulated data, and the probabilities of the peak values in observed data were less than those for simulated data (Fig. 5).

3.3 *Mean abundance indices*

The mean log-transformed abundance indices based on fixed-station sampling and simple random sampling designs showed similar trends for three selected fish species in different seasons (Fig. 6). However, the deviations of estimates for the fixed-station sampling were much greater than those for the random sampling design. The fixed-station sampling would underestimate or overestimate the abundance indices of the fish populations in some seasons. The mean abundance indices from simple random sampling were the same with those from the "true" value, suggesting that the random sampling design could yield unbiased estimates for the target fish species. However, the random sampling design yielded a larger variance than that of the fixed-station sampling design.

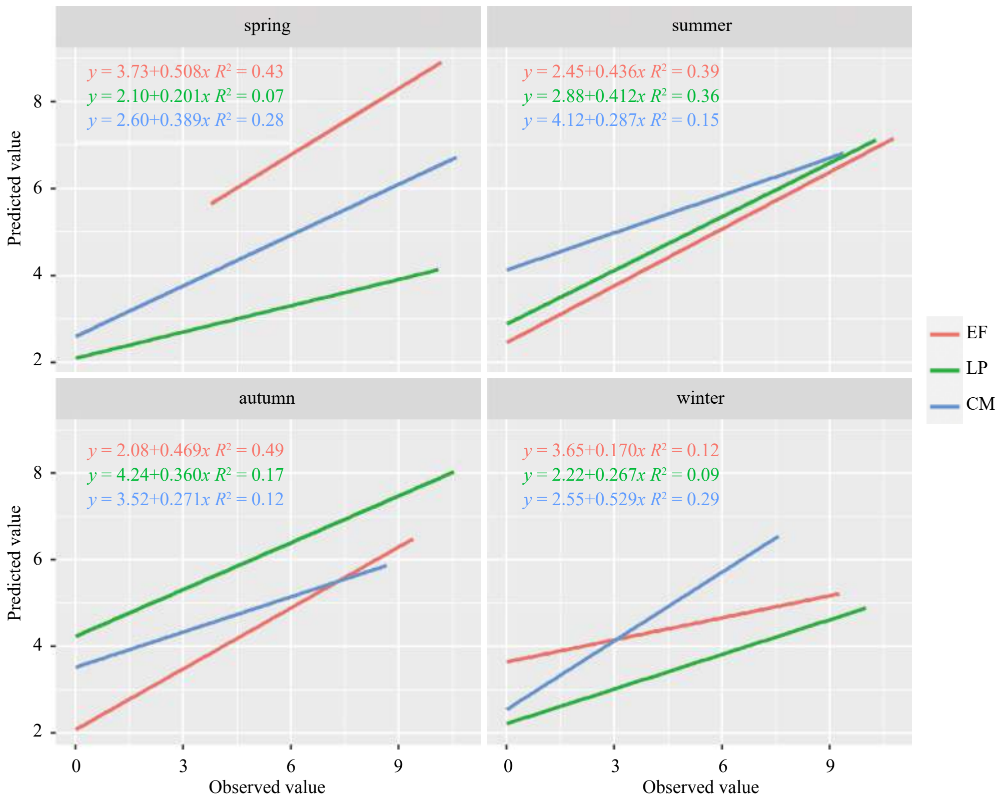

Fig. 3. Leave-one-out cross-validation based on OKI comparing the predicted versus observed log-transformed abundance of target three species.

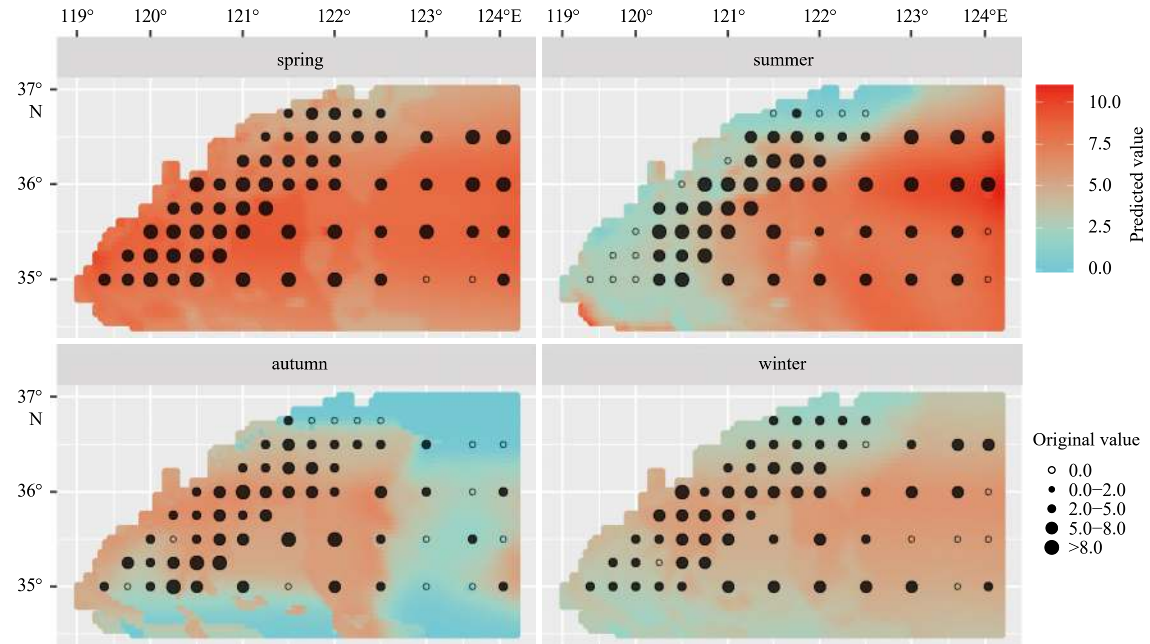

Fig. 4. Mapping abundance (log-transformed) distribution of Fang's blenny using spatial interpolation method based on survey data. The black dot was the original abundance (log-transformed) in each sampling station.

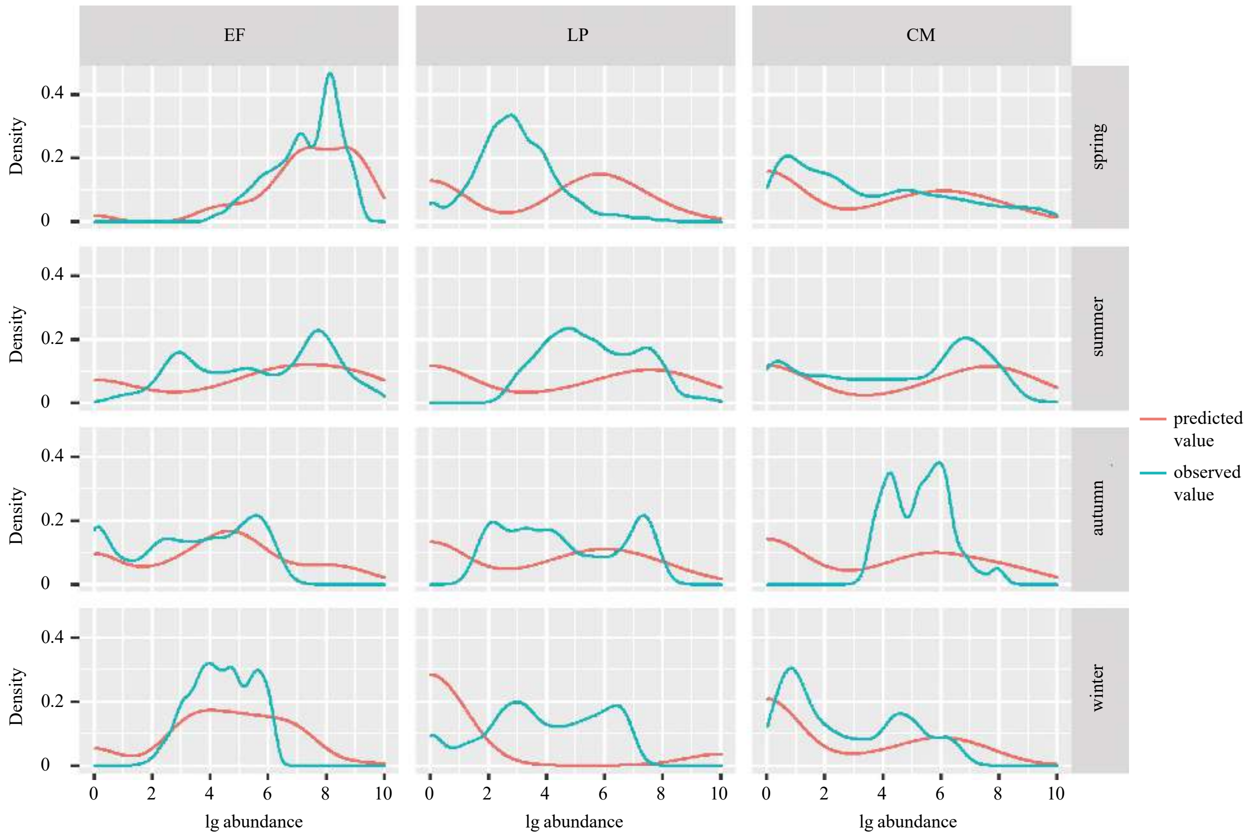

Fig. 5. The probability density distribution of the observed (fixed station sampling design) and simulated abundance index of the selected fish species.

3.4 *REE and RB*

The REE and RB values for two sampling designs showed that fixed-station sampling design had higher precision but lower accuracy than simple random sampling design in estimating abundance indices of selected fish species (Fig. 7). The REE values of abundance index estimates of each species from fixed-station sampling were relatively high but with low variance compared with simple random sampling in four seasons.

The random sampling design was unbiased with RB values distributing around zero. However, the fixed-station sampling

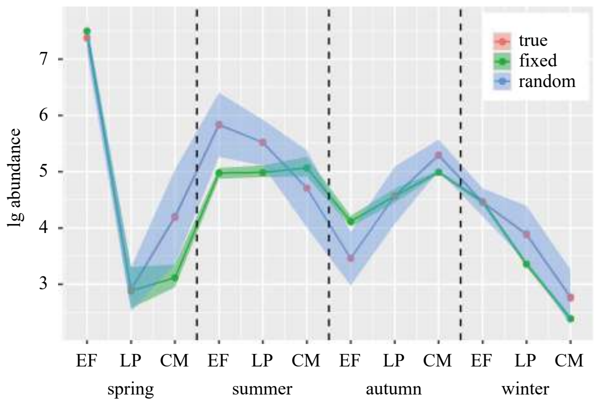

Fig. 6. Temporal trends of mean abundance indices calculated from two sampling designs and simulated true populations for three target species. The shaded areas represent 95% confidence intervals.

design was biased. Most of the RB values of abundance index estimates of the target species were significantly greater or less than zero in different seasons. The absolute RB values of simple random sampling were less than 0.6%, which were much less than those of fixed-station sampling design (Fig. 7). As for the abundance index of LP in autumn and abundance index of EF in winter for fixed-station sampling design, the RB values were around zero, and the REE values were small, which showed that fixed-station sampling design could have both higher precision and accuracy for LP in autumn and EF in winter.

The mean REE values of abundance index estimates over seasons were calculated from the 100 replications in the simulation study. The mean REE values showed increasing trends with coefficient of variation of the original survey data of abundance indices for target fish species in four seasons, which indicated that the effectiveness of sampling design was influenced by the variance of the original survey data. Fixed-station sampling design was influenced by variability of spatial distribution of abundance data more than simple random sampling design (Fig. 8).

4 Discussion

Fisheries scientists and managers require accurate information on fish communities to make effective management decisions (Quist et al., 2006), and they typically rely on standardized sampling data to make population inferences (Bonar et al., 2009). Fixed-station sampling design was widely used in fishery-independent surveys because of its characteristics of convenient sampling station setting (Questel et al., 2013; Kiraly et al., 2014; Li et al., 2015). The fishery monitoring program is designed to monitor seasonal changes and population distribution of multispecies. In this study, we selected three species with different spatial distribution patterns to evaluate the effectiveness of the fixed-station sampling design for monitoring different population abundance in a fishery-independent survey. It showed that fixed-station sampling design could detect the seasonal trend of mean abundance of multispecies with high precision but low accuracy.

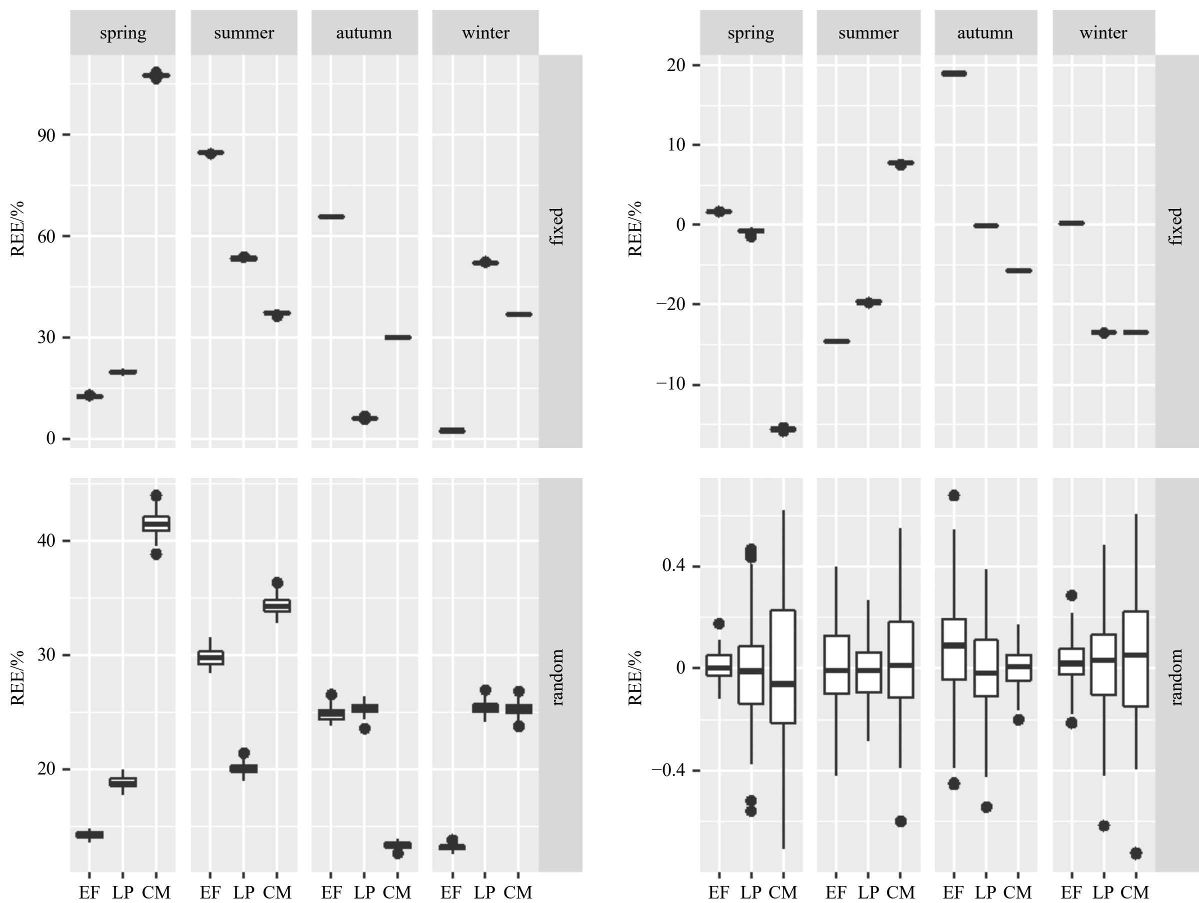

Fig. 7. REE and RB of abundance index estimates of three species for fixed-station sampling and random sampling designs in four seasons.

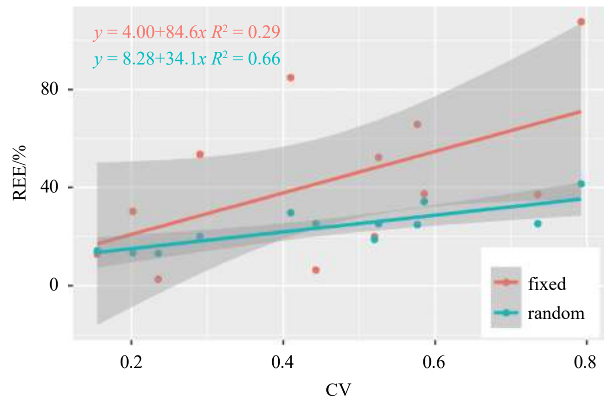

Fig. 8. The relationship between mean of REE and CV of abundance index of original survey data for all of the selected species in four seasons. The shaded areas represent 95% confidence intervals.

The fixed-station sampling design would underestimate or overestimate the population abundance for some fish species in some seasons, while the abundance index estimates of LP in autumn and EF in winter were unbiased with high precision. The comparison of calculated species mean abundance between fixed and random sample sites found that fixed sampling sites may be acceptable due to ease of sampling and accessibility when monitoring temporal changes instead of absolute estimation.

If population attributes are estimated incorrectly, the results, and conclusions on which they are based, will be misleading and may impact unnecessarily on fishery resources if used in making management decisions. Seasonal variations in spatial distribution and different spatial distribution patterns of fish species all affected the effectiveness of survey designs in estimating abundance indices. Spatial distribution patterns of many commercial fish species have also changed due to the high-intensity fishing activity (Blanchard et al., 2008; Tang et al., 2011; VanDerWal et al., 2013; Xu et al., 2017). It would be improper even dangerous to make decisions for fishery management based on the biased data from fixed-station sampling design which overestimated or underestimated the abundance of target fish species in the long term run. For example, the concept of optimum yield at intermediate levels of fishing (the so called maximum sustainable yield) now is enshrined in legislation as a key objective of stock assessment, which is calculated based on fishery and fishery-independent survey data, including target species abundance and yield indices. If the fishery species were overfishing or even overfished, the misperception of stock status would accelerate the decline in abundance of fish populations. Therefore, it is necessary and important to make sure whether the fixed-station sampling design can provide unbiased estimation for a multi-species survey, especially when the survey data was the only information available for fishery management in the offshore waters. And the biased estimate must be calibrated cautiously before it can be used. Such as the underestimated EF mean abundance in summer (Fig. 6), it should be increased by nearly 20% and could be used in stock assessment.

The variability level in spatial distribution of fish population had large effect on statistical power of fixed-station sampling design in estimating abundance for target fish species. When spatial distribution variability level was low, fixed-station sampling design had high power to acquire the mean abundance of the true population with high precision and accuracy due to the advantage of continuity effect of fixed-station sampling (Questel et al., 2013; Kiraly et al., 2014). In this study, due to the relatively even distribution patterns for LP in autumn and EF in winter, fixed-station sampling design was superior to simple random sampling design in estimating the abundance indices of the two species. The high variability level of spatial distribution indicated that the fish distribution was heterogeneous or aggregated, and we might yield biased estimates based on fixed-station sampling design. EF mainly distributed in the deeper waters in summer, and the estimated abundance by fixed-station sampling design was about 20% lower than the mean abundance calculated based on the “true” value. On the contrary, simple random sampling design was unbiased in estimating fish population abundance. Because of the ability to get unbiased estimates but instability, simple random sampling design is commonly used as a null design for comparing the efficiency of different sampling schemes rather than as the optimal practical fishery-independent survey design (Pooler and Smith, 2005; Skibo et al., 2008).

OKI is widely used in mining, soil, environmental sciences, meteorological and medical research (Oliver and Webster, 1990; Pokhrel et al., 2013). The spatial distribution of fish species showed a certain spatial autocorrelation. So this method could be used to simulate target fish species population distribution over seasons. Though the accuracy of OKI varied depending on the original data structure, the kriging interpolated data could be regarded as the “true” values for abundance indices of fish populations in this simulation study. OKI might not have enough power to predict absolute values of species abundance, but it was sufficient for simulating the spatial patterns of fish abundance.

Fish species have various environmental preferences, showing obvious heterogeneity with water temperature and depth in different seasons in the offshore waters. The fixed-station sampling design is biased, misestimating the species population abundance. For a long-term fishery monitoring program which provides vital information for fishery management, a better sampling design is needed instead of the currently one. Stratified random sampling design would be a good option, which can overcome the characteristic of species stratified-distribution or patch distribution.

In summary, this study aimed to examine the performance of fixed-station sampling design compared with simple random station sampling design for multispecies survey in different seasons. Three fish species with different spatial distribution patterns were selected as target populations, and OKI method was applied to simulate the “true” population distribution. This simulation study suggested that the fixed-station sampling design had the power to detect the seasonal trends of species abundance. The effectiveness of fixed-station sampling design were different in different species distribution patterns. When the species had even distribution, fixed-station sampling design could get high quality data, but conversely, it might be biased. Evidently, the estimates based on the fixed-station sampling design must be calibrated cautiously while applying them for fisheries stock assessment and management.

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Supplementary information:

Fig. S1. Mapping abundance (log-transformed) distribution of small yellow croaker (LP) using spatial interpolation method based on survey data. The black dot was the original abundance (log-transformed) in each sampling station.

Fig. S2. Mapping abundance (log-transformed) distribution of whitespotted conger (CM) using spatial interpolation method based on survey data. The black dot was the original abundance (log-transformed) in each sampling station.

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