Geographic Variation for the Composition of Parrotfish in the South China Sea

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Abstract

Based on the key ecological processes of parrotfish in coral reefs, we compiled species presence-absence data across 51 sites in the South China Sea to identify the distribution and composition of parrotfish and explore the relationship between species distribution and environmental factors, and 50 species (the Pacific: 57 species) of parrotfish were record. Nansha islands had the highest abundance with 41 parrotfish species. Nestedness analysis indicated parrotfish community had statistically significant nested patterns in the South China Sea and Nansha islands was the topmost site of nested matrix rank. Scleractinian coral species richness and Log(reef area) both had a significant effect on sites nested matrix rank ($P < 0.05$), which supports habitat nestedness hypothesis in the South China Sea. Scrapers were the most important functional group composition while the browser had a greater contribution on species nested matrix rank. Linear regression model showed parrotfish species richness increased with increasing longitude, scleractinian coral species richness and reef area. Variations in the parrotfish species richness in longitude was related to distance from the biodiversity hotspot in the Indo-Australian Archipelago. Parrotfish was mainly distributed in the range of 26-29℃, which was almost the same as the optimum temperature for coral growth. Nansha islands should be as biodiversity conservation priority areas, which could provide important reference significance for conservation efforts of parrotfish in degraded coral reefs habitats, especially in the context of increasing natural variability and anthropogenic disturbance.

Introduction

Parrotfish are recognized as a distinct family, the Scaridae, closely related to the Labridae(Sabetian 2010; Bonaldo et al. 2014). They are protogynous hermaphrodites, undergoing a sex change from female to the terminal male phase(Choat and Robertson 1975), and tending to have different colours and habits among each phase (juvenile, female, male)(Siebeck 2018). At present, 100 recognized parrotfish species belonging to 10 genera (*Bolbometopon* (1 spp.), *Calotomus* (5 spp.), *Cetoscarus* (2 spp.), *Chlorurus* (18 spp.), *Cryptotomus* (1 spp.), *Hipposcarus* (2 spp.), *Leptoscarus* (1 spp.), *Nicholsina* (3 spp.), *Scarus* (52 spp.) and *Sparisoma* (15 spp.)) in two subfamilies (Scarinae and Sparisomatinae) have been described worldwide(Kulbicki et al. 2018). Genera *Sparisoma* and *Cryptotomus* are restricted to the Atlantic, *Nicholsina* is found in both the Atlantic and Eastern Pacific, five genera are unique to the Indo-Pacific (*Bolbometopon*, *Cetoscarus*, *Calotomus*, *Hipposcarus*, and *Chlorurus*), and the genus *Scarus* is found in all oceans(Kulbicki et al. 2018). Although the geographic distributions of most parrotfish were known(Bonaldo et al. 2014), why some regions can accommodate an extraordinary diversity and how to protect them remains a hot-button question(Comeros-Raynal et al. 2012).

Parrotfish are a unique and conspicuous component of the reef fish faunas both for their abundance and ecological function on the reef. Sufficient numbers are needed for them to play a significant ecological role(Fox and Bellwood 2008). Parrotfish have been estimated that parrotfsh are up to 72% of the total biomass of herbivorous fish assemblages in the Red Sea; 40-60% on the Great Barrier Reef and about 54-98% in the Caribbean(Williamsá and Polunin 2001; Fox and Bellwood 2007; Afeworki et al. 2013). Parrotfish are also important fishery targets, especially in developing nations(Cinner and Mcclanahan 2006;

Edwards et al. 2014). For example, parrotfish account for the largest proportion of fish biomass (36.8%) caught from coral reef in Polynesia(Pratchett et al. 2011). In terms of ecological function, parrotfish are considered herbivores. One of the most powerful demonstrations of the functional importance of parrotfish (and other herbivorous reef fish) is the large-scale fish exclusion experiment conducted by Hughes et al(Hughes et al. 2007), which showed that the removal of herbivores after mass coral bleaching severely eroded the reef's ability to recover and regenerate. They can help to mediate the competition between corals and macroalgae and enhancing the resilience of coral reef ecosystems following anthropogenic or natural disturbance(Adam et al. 2015). By exerting top-down control on algal communities in a cropped state can provide more space resources for corals and promote the attachment and recruitment of coral larvae, whcih is a vital ecological process(Bellwood et al. 2012; Thurber et al. 2012; Adam et al. 2015; Roos et al. 2016). Compared to other herbivorous fish, parrotfish have specialized feeding morphology that can remove the calcareous surface layers of the reef as they graze and get nutritional resources that are largely unavailable to other fishes. Coupled with abundance, their unique interactions (i.e., grazing, erosion, coral predation, production, reworking and transport of sediments) makes parrotfish an integral part of coral reefs(Bonaldo et al. 2014).

Despite their importance to reef ecosystems, parrotfish has still failed to ward off the threat of artificial factors(Bellwood et al. 2012; Choat et al. 2012; Heenan et al. 2016). Over-exploitation and habitat degradation were considered to be important man-made reasons for the decline of reef fish stocks(Hawkins and Roberts 2004; Hamilton et al. 2017; Suciyono et al. 2019). For example, *Bolbometopon muricatum* and *Scarus guacamaia* were classified by the International Union for Conservation of Nature (IUCN) as "vulnerable" (VU) and "near threatened" (NT), respectively. Overfishing can lead to significant declines in fish populations and a tendency to miniaturize individuals, which is detrimental to parrotfish's ecological functions(Hawkins and Roberts 2004; Bellwood et al. 2012). Habitat complexity also plays a key role in reef fish community construction, with reduced complexity leading to a decrease in reef fish richness and diversity(Bellwood et al. 2006; Emslie et al. 2014; Hoey et al. 2016; Hoey et al. 2016). It could lead to local extinction in extreme circumstances(Emslie et al. 2014). And a full understanding of parrotfish composition and distribution patterns and the formation and driving factors of species diversity are necessary and essential steps, if we want to effectively protect parrotfish resources and coral reef (Hoey et al. 2016). The geographical distribution pattern of species diversity is one of the main topics in biogeography(Losos and Ricklefs 2009). Biogeographers believed that the distribution pattern of species richness at a large regional scale can be determined by a variety of factors, such as available habitat, latitude and longitude, temperature, connectivity, evolutionary history, dispersal and colonization capacity, etc(Bellwood and Hughes 2001; Mora et al. 2003; Mcclanahan et al. 2011; Parravicini et al. 2013). There are two main gradients in the global distributions of coral reef fish. The first major distribution gradient is the distance from the center of biodiversity, represented by the Indo-Australian Islands, commonly known as the Coral Triangle(Allen 2008). The second major distribution gradient is the latitudinal gradient, where a decline in species diversity is a common feature of many biota(Choat 1991). Based on most work on the distribution characteristics of parrotfish diversity(Choat et al. 2012; Parravicini et al. 2013; Taylor et al. 2015; Kulbicki et al. 2018), we selected the influencing factors that were relevant and easy to collect data to study the distribution characteristics of parrotfish in the South China Sea.

The South China Sea lies in the tropical zone of the western Pacific Ocean bordered by nine coastal states, with a surface area of 3.5 million square kilometers(Wang et al. 2012). It is one of the world's richest marine biodiversity hotspots, with abundant and diverse marine resources. Existing research reports indicate that a preliminary assessment of the South China Sea biological diversity contains more than 8,600 species of plants and animals(Ng and Tan 2000). Fish alone contribute 3,365 species(Randall and Lim 2000). At the same time, the South China Sea is an important transfer station for reef fishes to spread from the coral triangle to high latitude in China(Gao et al. 2014). The resources of the South China Sea where fish is the major protein source for coastal communities, and where contribute to the economic livelihood of neighboring countries(Nguyễn 2004). However, the progress of science technology, the increase of human demands and growing coastal populations have significantly increased the pressure on reef fish stocks(Cinner and Mcclanahan 2006).

Due to the unique importance of parrotfish in reef systems and the lack of research in the South China Sea, investigating the species composition of parrotfish and their relationship with environmental factors in various regions can explore the spatial distribution characteristics and the most suitable living environment for parrotfish. The purpose of this article is a) to investigate parrotfish species composition and spatial distribution patterns in the South China Sea; b) to explore the relationship between parrotfish species richness and environmental factors.

Materials

Study sites. The South China Sea(Randall and Lim 2000) is a semi-enclosed sea that is part of the Pacific Ocean (bordered by Brunei Darussalam, Cambodia, China, Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam and contains numerous small islands(Nguyễn 2004).To obtain a comprehensive dataset about the distribution patterns of parrotfish in the South China Sea, we collected data from 51 sites, including Tioman island in Malaysia, Natuna islands and Anambas islands, Redang island, Nansha islands, Taiping island, Subi reef, Zhongye island, Brunei Darussalam, El Nido in Philippines, the Vietnam coastal areas (including Con Dao, An Thoi, Cu Lao Cau bay, Nha trang, etc), Cambodia, Koh Tao in Thailand, Xisha islands, Qilianyu, Hainan island, Dongsha islands, Weizhou island, Daya bay, Minjiang river estuary, Jiulong river estuary, Pearl river estuary, Hongkong, Taiwan islands (subdivided into the southern, northern, eastern and western of Taiwan), Kenting National Park, Lanyu, Green island, Ryukyu and South Penghu National Park. All sites were between 99.84 °E and 121.73 °E, and between 2.78 °N and 26.06 °N.

Data collection. Collecting information on the composition and distribution of parrotfish in the South China Sea was through published works, regional checklists, monographs on specific families, scientific reports, and databases to obtain species records of parrotfish (i.e., presence/absence data). In addition, unpublished data from our team were used only in the compilation of species records for Xisha islands and Qilianyu. In the search process of scientific reports, key words were mainly reef fish, parrotfish, distribution, South China Sea and the place names mentioned above. It also searched by country or region in the Fishbase and through the Taiwan fish database (http://fishdb.sinica.edu.tw), from which mainly inquired information about the distribution of parrotfish in Taiwan islands and its surrounding islands. The full data set and detailed list of synonyms were available as a supplementary see Fishbase (https://fishbase.cn/summary/FamilySummary.php?ID=364).

According to jaw morphology, foraging activity and extent of substratum excavation, parrotfish were commonly classified into three main functional groups: browsers, scrapers and excavators(Bonaldo et al. 2014; Kulbicki et al. 2018). The parrotfish of genus *Hipposcarus* and genus *Scarus* almost belong to the scrapers; genus *Calotomus* and genus *Leptoscarus* almost belong to the browsers; genus *Bolbometopon*, genus *Cetoscarus* and genus *Chlorurus* almost belong to the excavators, respectively(Bellwood and Choat 1990; Ong and Holland 2010).

The environmental factors in this article include geographical location (i.e., latitude and longitude), scleractinian coral species richness, reef area, and sea surface temperature. First of all, latitude and longitude were mostly from wikipedia (http://en.wikipedia.org/). We also consolidated species records of scleractinian coral and reef area from literature, reports and books. Extensive search was conducted using key words such as coral reefs, reef-building corals, marine reserves, area and place names of various research sites in the retrieval process. At the same time, using Reefbase (http://www.reefbase.org/main.aspx) was used to supplement. But reef area of some sites (such as Green island, Lanyu, Hongkong) were unable to access via online data. The sea surface temperature were mainly obtained through the following websites: National Oceanic and Atmospheric Administration (http://www.noaa.gov/), Weather-stats (https://weather-stats.com/seamap), World sea water temperatures (https://seatemperature.info/).

Nestedness analysis. Based on the collected parrotfish data, a nested model was used to explore the distribution pattern of parrotfish in the South China Sea. Because nestedness is not a stable universal structure, it is closely related to the study object (such as category, island habitat type, matrix size, etc.) (Chen and Wang 2004). Firstly, sites with the paucity of published data or not conform to islands habitat types were removed from our analysis, such as eastern Taiwan, southern Taiwan, northern Taiwan, Cambodia, Brunei Darussalam, etc. Finally, 24 sites were eventually selected for nestedness analysis. The same sites were true for the following analysis. At first, a binary code “1/0” was used to show presence/absence of species at various sites. The temperature of the matrix is the disorder degree of the matrix system, which can reflect the deviation degree of the analyzed matrix from the completely nested matrix(Zhang et al. 2008). The lower temperature of the matrix, the higher nestedness degree of the matrix. Thus T ranges from 0 for a completely nested matrix to 100 for one that is completely disordered(Boecklen 1997; Wright et al. 1998). Species nestedness is currently calculated with the nestedness temperature T. We based on the calculation of matrix temperature (matrix temperature) of BINMATNEST (binary matrix nestedness temperature calculator) software to quantify nestedness. "BINMATNEST" will arrange input matrix to maximal packing that the occurrence of speices are as much as possible in the top left corner of the matrix, and calculate the nestedness temperature. At the same time, the null model of the software will randomly generate 1,000 matrices for the significance test of the input matrix. BINMATNEST creates three null models to test the significance of the results, among which null modal 3 has been proved to effectively control the influence of passive sampling(Moore and Swihart 2007; Rodríguez-Gironés and Santamaría 2010). The sequence of sites was calculated by BINMATNEST and the rank of species was sort according to occurrence frequency, maximum body length and morphological characteristics (the ratio of body length and body depth from Fishbase), which were called species nested matrix rank. First of all, in order of occurrence frequency, the species with high frequency was ordered from the top, when the occurrence frequency of species were the same, the maximum body length was used for further ranking, with larger maximum body length first. When the maximum body length was still the same, the species with the largest ratio was priority ordering according to the ratio of body length and body depth. The information of maximum body length and the ratio of body length and body depth were both obtained from Fishbase.

Statistical analyses. Paired sample t-test was used to test whether there was a significant difference in the number of the three functional groups in each site. The effect of environment factors (latitude, longitude, sea surface temperature, Scleractinian coral species richness, reef area) and species life-history traits on forming a nested pattern were evaluated by Spearman's rank correlation analysis(Schouten et al. 2007; Li et al. 2013). which was conducted between the nested matrix rank of site and environment factors as well as nested matrix rank of species and the maximum body length. According to the nested matrix rank of sites, we divided all sites into two groups and used independent samples t-test to compare whether there was a significant difference between the means values (scraper, excavator, browser, scraper/total, excavator/total, browser/total) of the two groups.

We applied a basic linear models to data from all sites to quantify the relationship between species richness and environmental factors, parrotfish species richness was taken as dependent variables, and environmental factors (scleractinian coral species richness, reef area, sea surface temperature, latitude and longitude) were taken as independent variables.

Principal Component Analysis (PCA) is a powerful techniques of multivariate statistical methods and can replace dataset with a smaller set of independent principal components. First, KMO and Spherical Bartlett tests were performed to analyze the data for the suitability of principal component analysis (PCA)(Zhu et al. 2015). And PCA technique was used to reveal the important component responsible for the distribution characteristics of parrotfish(ALabdeh et al. 2020).

The above data calculation and analyses were performed in IBM SPSS Statistics 26 software. In all analyses involving significance tests, we followed the common view that $P < 0.05$ means statistically significant differences, $P < 0.01$ means strongly significant differences and $P > 0.05$ means non-significant differences.

R was used to draw the map of study region and the distribution diagram of parrotfish species richness. Origin 2018 was used to perform linear regressions or nonlinear fitting of parrotfish species richness with respect to environment factors.

Results

Species composition. A total of 50 species across 7 genera were recorded at 51 sites in the South China Sea (see Tab S1). Genus *Scarus*, *Chlorurus* and *Calotomus* have 28, 13 and 3 species of parrotfish respectively. Followed by genus *Cetoscarus* and *Hipposcarus*, there were both 2 species of parrotfish.

Genus *Bolbometopon* and *Leptoscarus* both had only 1 species of parrotfish. Distribution characteristics of parrotfish species richness in the South China Sea was shown in Fig. 1. Parrotfish species richness were abundant in Nansha islands, Taiwan islands and Nha Trang. Among them, Nansha islands had the highest number of parrotfish with 41 species, followed by Taiwan islands with 38 species, and the two sites had 31 species in common. Co To in Vietnam and Minjiang River Estuary in China both had the lowest abundance, with only 2 species of parrotfish. The coastal sits had relatively few parrotfish species richness, such as Koh Tao, Redang island and Con Dao, while Nha trang had more abundant parrotfish species richness (33 species). In Taiwan islands, the southern region had the most abundant species of parrotfish, with 36 species. Compared with the whole Taiwan islands, Southern Taiwan was lacking of *Scarus scaber* and *Scarus ferrugineus*, among which *Scarus scaber* was recorded in the northwest of Taiwan, while *Scarus ferrugineus* was recorded in Penghu islands. *Scarus ghobban* are the most widely distributed species, with 47 sites, followed by Chlorurus sordidus (38 sites) and *Scarus niger* (37 sites).*Chlorurus perspicillatus*, *Chlorurus strongylocephalus*, *Chlorurus troschelii* and *Hipposcarus harid* all were found in a single site.

Composition of functional groups. Three functional groups of parrotfish (30 scrapers, 4 browsers and 16 excavators) were found in the South China Sea (see Tab S1). Scrapers were the most extensive distribution and browsers were the most restricted (Table 1). In addition, paired sample t-test showed that there was a significant difference in the number of scrapers and excavators (t_{50}= 11.500, P =0.00 < 0.01) as well as excavators and browsers (t_{50}= 9.46, P =0.00 < 0.01).

Table 1
Composition of functional groups of parrotfish in each region

Site	Scrapers	Excavators	Browsers	Site	Scrapers	Excavators	Browsers
Nansha islands	26	12	3	Nui Chua	16	4	0
Xisha islands	20	7	4	Hon Cau	12	3	0
Dongsha islands	16	5	3	Phu Quy	12	3	0
Subi reef	3	3	1	Con Dao	16	5	0
Qilianyu	18	6	1	Phu Quoc	12	4	0
Taiping island	12	6	0	Nam Du	4	1	0
Hainan island	16	5	3	Tho Chu	13	0	0
Hong kong	11	5	2	Cu Lao Cau Bay	6	1	0
Daya Bay	2	1	0	Zhongye island	10	2	1
Weizhou island	3	1	0	El Nido	8	3	0
Kenting National Park	19	7	3	Natuna islands	12	8	0
Green island	18	6	3	Anambas islands	9	6	0
Lanyu	12	6	2	Timon island	11	6	0
Ryukyu	10	3	3	Redang island	10	4	0
South Penghu National Park	15	5	1	Koh Tao	8	1	0
Co To	1	1	0	Pearl River Estuary	7	2	2
Bach Long Vi	2	2	0	Minjiang River Estuary	1	0	1

Site	Scrapers	Excavators	Browsers	Site	Scrapers	Excavators	Browsers
Con Co	6	3	0	Jiulong River Estuary	3	1	1
Hai Van-Son Cha	8	3	0	Taiwan	24	10	4
Da Nang	7	1	0	Eastern Taiwan	11	5	1
Cu Lao Cham	16	5	0	Southern Taiwan	22	10	4
Ly Son	12	3	0	Western Taiwan	4	3	0
Binh Dinh	10	2	0	Northern Taiwan	13	2	2
Phu Yen	6	1	0	Brunei Darussalam	1	3	1
Van Phong	13	5	0	Cambodia	3	0	0
Nha Trang	21	9	3				

“0”represents that the functional group was not collected and it did not mean that the functional group did not exist; Zhongye Island and El Nido both had 2 undefined species and South Penghu National Park had 1 undefined species in published book or literature.

Nestedness of parrotfish assemblages. The maximally ranked species-habitat nested matrix of parrotfish was showed in see Tab S2. The results showed that the distribution of parrotfish presented nested structure in the South China Sea (P<0.001,T=13.21℃). The top three in the site nested rank were Nansha islands, Nha Trang and Xisha islands. And the topmost island (Nansha islands) was judged to be the most hospitable island (see Tab S3). Similarly, the topmost species (*Scarus ghobban*) was most common and prevalent, which makes it the most resistant to extinction or most prone to colonization (see Tab S4).

Spearman rank correlation analysis was conducted between the nested matrix rank of sites and environment factors, and also between the nested matrix rank of species and maximum body length. The results showed that scleractinian coral species richness, longitude, and log(Reef area) all had significant effect on site nested matrix rank ($P < 0.05$). Latitude and sea surface temperature maximum both had no significant effect on site nested matrix rank, and maximum body length reflecting swimming ability also had no significant effect on species nested matrix rank. ($P > 0.05$) (Table 2).

Table 2
Spearman rank correlations of influences on nestedness for parrotfish assemblages on 41 sites in the South China Sea

	Nested rank for species		Nested rank for sites	
	r	*P*	*r*	*P*
Maximum body length (mm)	-0.024	0.869		
Longitude (°)			-0.371*	0.020
Latitude (°)			-0.070	0.673
Scleractinian coral species richness			-0.569**	0.001
Log(Reef area) (km^2)			-0.453*	0.034
Sea surface temperature (°C)			-0.117	0.498

* means the correlation is significant at the level of 0.05 (2-sided), ** means the correlation is significant at the level of 0.01 (2-sided).

The distribution characteristics of functional groups. To compare whether functional group composition differs between islands with higher species richness and those with lower species richness, we divided the 41 study sites into two groups in order. Group 1 was the site nested rank 1-20 and group 2 was the site 21-41 (see Tab S5). The Independent sample t-test showed that three functional groups and the ratio of browser to total species of parrotfish were significantly different between group 1 and group 2, while the scraper/total species of parrotfish and excavator/total species of parrotfish were not significant difference. For more details please see Table 3. Compared with scraper and excavator, browser had a greater contribution on the nested matrix rank of site and was an important reason for the difference.

Table 3
Independent samples t-test based on nested matrix rank.

	t	Sig. (2-sided)
Scraper	6.817	0.000
Browser	4.346	0.000
Excavator	7.142	0.000
Scraper/Total species of parrotfish	-1.609	0.120
Browser/Total species of parrotfish	3.407	0.002
Excavator/Total species of parrotfish	0.475	0.640

$P < 0.05$ means significant differences (2-sided); $P > 0.05$ means no statistically significant (2-sided).

Patterns of parrotfish species richness. Linear regression results showed that longitude, scleractinian coral species richness and reef area could explain the variation of parrotfish species richness to a certain extent

($P < 0.05$, Fig. 2a, c, d). Parrotfish species richness increased with increasing longitude In terms of coral reefs, Parrotfish species richness also increased with the increase of scleractinian coral species and reef area, and the fitting degree of the curve was relatively high, being R^2 =0.44 and R^2 =0.34, respectively. Parrotfish species richness decreased with the increase of latitude (R_1^2 =0.04, $P = 0.253 > 0.05$, R_2^2 =0.01, P =0.848 > 0.05, Fig. 2b), but this trend was not significant, as was the trend in temperature (R^2 =0.01, $P = 0.619 > 0.05$, Fig. 2e). The figure shows that parrotfish were mainly distributed in the range of 26-29°C in the South China Sea

We found that the Kaiser-Meyer-Olkin measure of sampling adequacy (KMO) was 0.542 < 0.6, but the Bartlett's spherical test was $P < 0.05$, which could indicate that the factors were suitable for further factor analysis. According to the principle of eigenvalue ≥ 1, the results showed that the 5 factors (longitude, latitude, sea surface temperature, scleractinian coral species richness and reef area) were consolidated into 2 principal components (Table 4). The cumulative variance contribution value of two components accounted for 70.379%. According to the composition matrix, the first principal component was taken to represent geographical location (i.e., latitude and longitude) and sea surface temperature, while the second principal component was mainly related to biological factors, such as scleractinian coral species richness (Table 5).

Table 4
Eigenvalues of environmental factors

	Initial Eigenvalues			**Extraction Sums of Squared Loadings**		
	Total	**% of Variance**	**Cumulative**	**Total**	**% of Variance**	**Cumulative**
1	2.18	43.597	43.597	2.18	43.597	43.597
2	1.339	26.783	70.379	1.339	26.783	70.379
3	0.995	19.902	90.282			
4	0.293	5.859	96.14			
5	0.193	3.86	100			

Table 5
Loadings of environmental factors

	1	**2**
Longitude (°)	0.743	0.522
Latitude (°)	0.918	-0.191
Scleractinian coral species richness	0.042	0.942
Log(Reef area)	-0.073	0.272
Sea surface temperature (°C)	-0.881	0.263

Discussion

We comprehensively summarized the parrotfish assemblage and distribution across the South China Sea, and showed that there were abundant species of parrotfish and significant variation in the composition of parrotfish in the South China Sea. Compared with the entire Pacific (57 species of parrotfish)(Kulbicki et al. 2018), it was inferred that South China Sea (50 species) was an important biogeographical regions and hub for the spread of parrotfish between the Indian and the Pacific. Additionally, biogeographical region were one of the primary predictors of reef fish species richness(Parravicini et al. 2014). This may be the reason why there were more species of parrotfish in the South China Sea. With regard to the composition of three functional groups, we found that scrapers and excavators were significantly greater than the browsers in the South China Sea. The spatial pattern manifested that the composition characteristics of parrotfish were consistent with the Indo-Pacific, i.e. Indo-Pacific reefs supports a higher diversity of scraping and excavating species and fewer browsing species(Bonaldo et al. 2014). Scrapers (17 spp.) were also particularly abundant compared to excavators (6 spp.) and browsers (1 spp.) on the Great Barrier Reef(Cheal et al. 2012).

Nestedness was a prevalent pattern of island community composition nowadays(Choat 1991; Ishihara and Tachihara 2011). The study also revealed that the composition of depauperate parrotfish assemblages represents a nested subset of the structure found in richer assemblages in the South China Sea, which supported the importance of nestedness for reef fish assemblages across the Indo-Pacific. Nestedness of faunal assemblages is a widespread phenomenon and potentially influenced by a variety of factors(Cook 1995; Fleishman et al. 2002; Bender et al. 2017; Wang et al. 2019). Scleractinian coral species richness and Log(reef area) was the most significant associated with nested matrix rank in our study, which could be habitat nestedness of parrotfish. Many scraping and excavating parrotfish have also been recorded to feed from the surface of live scleractinian corals(Bonaldo et al. 2014). And at the global scale, coral reef area was also regarded as the key variables in reef fish richness patterns across the Indo-Pacific(Parravicini et al. 2014). Larger reef area could provide more available resource such as food and shelter for fish, and more fish species were found in these reef. Browsering parrotfish feed mainly on macroalgae, however, limited space in coral reef was not conducive to the growth of macroalgae, which indirectly lead to insufficient food sources for browsering parrotfish(Bonaldo et al. 2014). We also showed that browser had declined significantly in relatively small reef area, and even did not exist in some sites, such as taiping island, tioman island and redang island. In addition, life-history traits, such as body size, were likely to affect the capacity of new colonizers to survive and establish reproductive populations(Luiz et al. 2013). Specific physiological limitation may fundamentally determine the distribution range of species and large body had the potential to expand their ranges(Davenport and Sayer 1993; Luiz et al. 2012). But the maximum body length reflecting the locomotion of fish had no significant correlation with nestedness, which was similar to the results of Kulbicki's study that geographical range was not related to maximum body size among parrotfish(Kulbicki et al. 2015). Therefore, when developing strategies to protect parrotfish resources and species diversity, we should give priority to islands or archipelagos with larger reef area and less human disturbance, such as Nansha islands and Xisha islands in the South China Sea.

In terms of spatial variation, we found that parrotfish species richness increased along longitude and the most abundant parrotfish species was in Nansha islands, which had something to do with the shorter distances to the Indo-Australian Archipelago marine biodiversity hotspots(Siqueira et al. 2021). This result supported the global first major distribution gradient of coral reef fish mentioned in the introdution. Species richness declines nearly uniformly with increasing distance from the mid-domain of the Indo-Pacific(Bellwood et al. 2012). In additon, Nansha islands had a large reef area and low degree of human disturbance, which could also be the main reasons for the higher parrotfish speceis richness. Latitudinally, the decline of diversity with latitude was a general feature of many biota and could be easily observed in coral reef fish(Choat 1991). Latitude also showed significant negative associations with species richness of four main herbivorous fish families combined (Acanthuridae, Kyphosidae, Pomacentridae, Scaridae) in the Atlantic Ocean(Floeter et al. 2005). But our result for the latitudinal distribution characteristics was not significant. It was worth noting that Taiwan island and its surrounding islands are relatively rich in parrotfish species. It could be influenced by the kuroshio (Taiwan warm current), which provided warmer seawater for the growth of coral reefs in the winter and expanded the boundaries of more warm-water species northward(Wu et al. 2015; Wang et al. 2020). All these pelagic-spawning species did not have larval dispersal restrictions(Floeter et al. 2001; Floeter et al. 2005). Parrotfish were no exception and it included a pelagic larval phase(Ishihara and Tachihara 2011). The stochastic forces of wind and currents which largely drived the passive dispersal of these larvae would be more likely to bringing a given larvae close enough to a potential home(Musburger 2012).

Sea surface temperatures, habitat size, isolation, and evolutionary history were also influenced the global distributions of parrotfish(Hoey et al. 2016). Our results showed that sites with more scleractinian coral species and larger reef areas helped support more parrotfish species. But when reef area reached a certain size, parrotfish species richness would not fluctuate greatly even as the reef continued to increase in size. For example, the reef area of Nansha islands (26, 059 km^2) was much larger than Philippines (11,852 km^2)„ but parrotfish species richness was about the same as Nansha islands, with a total of 40 species(Licuanan and Gomez 2000). This was in agreement with the findings of Parravicini et al(Parravicini et al. 2014), who implemented boosted regression trees to show that species richness did not eventually increase with coral reef area. Presumably other environment factors would have a more significant impact on parrotfish species richness when the reef was large enough, such as abundace of specific coral species(Johnson et al. 2011), habitat complexity(Ivan et al. 2012), interspecific competition(Kulbicki et al. 2018), mangroves and seagrass beds(Hamilton et al. 2017), etc. In other words not all parrotfish species would be represented on a given reef, with some species saturation at the highest regional diversity(Kulbicki et al. 2018). Studies have shown that sea surface temperature had a key indirect role on reef fish richness and had a direct effect on corals (Parravicini et al. 2014), Most of coral live in above 18 ℃, and the optimum growth temperature is between 25 ℃ and 29 ℃(Wang and Zhao). It could be seen that the temperature of parrotfish distribution basically overlapped with the optimum temperature for coral growth. The results also suggested that coral reef played a significant role in parrotfish distribution pattern. Therefore, for some sites with smaller reef area, particularly nearshore islands, if human activity continues to damage coral reef or no protective measures were taken, it was easy to accelerate the degradation of coral reef, which was not conducive to the survival of parrotfish and changed the distribution pattern of parrotfish community.

Declarations

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Author contributions CHLand TW designed and oversaw the research. QMQ and TW analyzed the data. QMQ , YL and TW drafted the manuscript. YL, TW and CHL edited and revised the manuscript. TW and CHL were considered joint corresponding author. All authors approved the final version of manuscript.

Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

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Figures

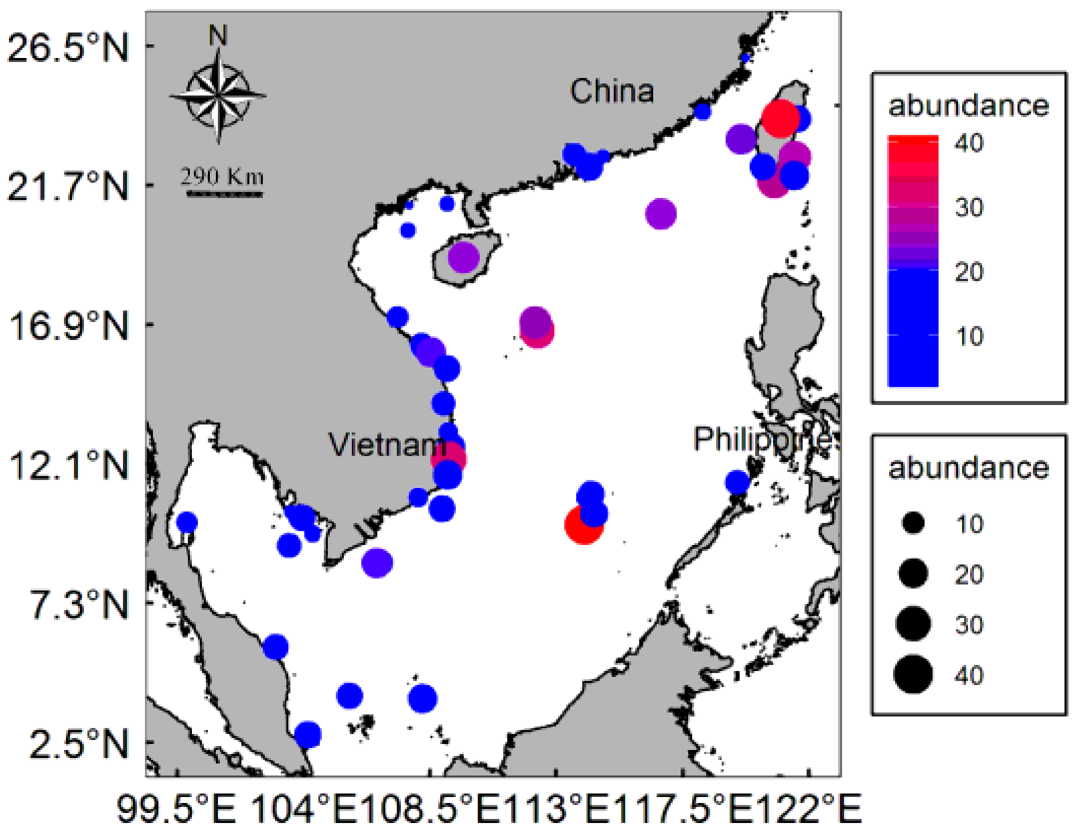

Figure 1

Distribution characteristics of parrotfish species richness in the South China Sea.

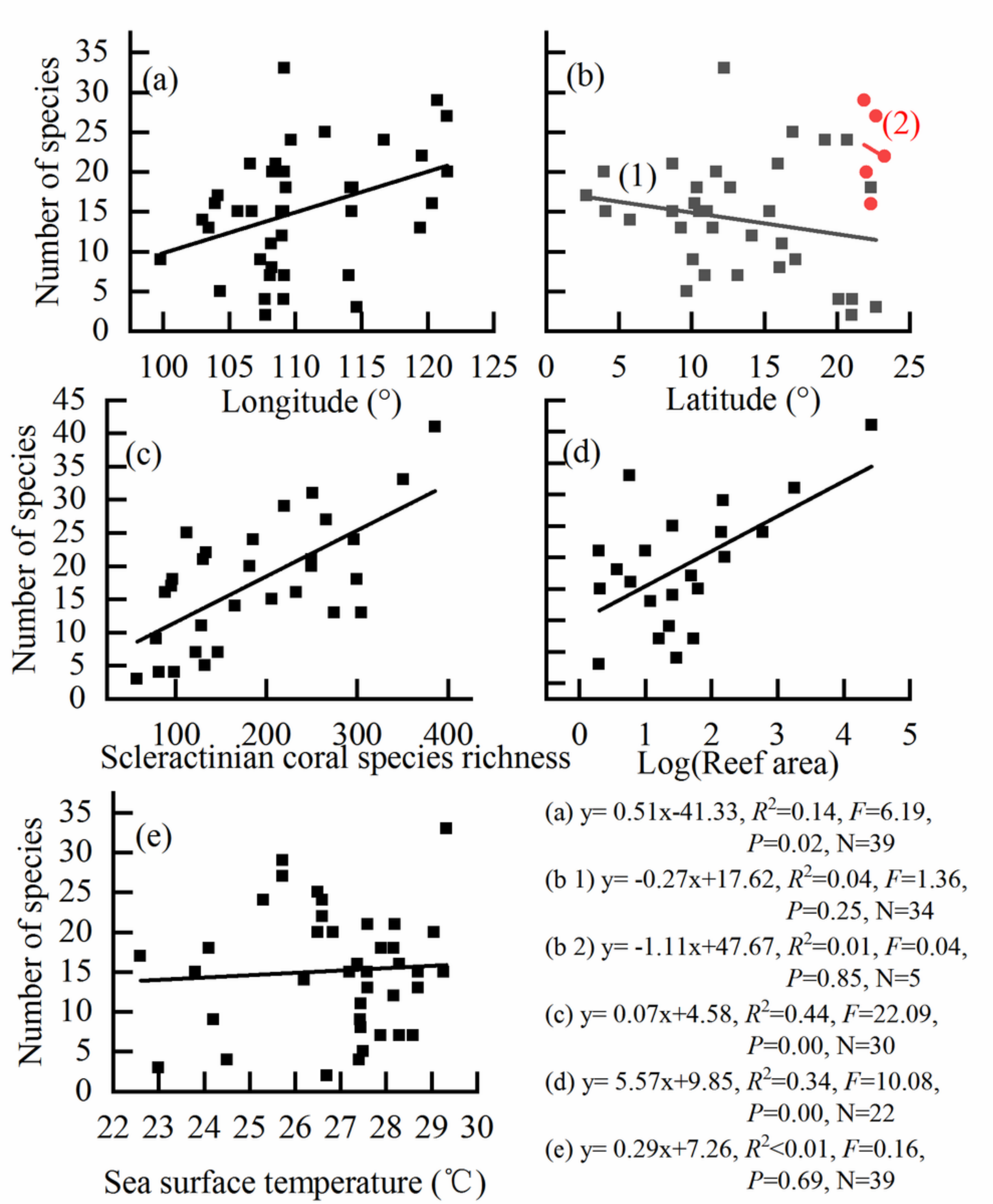

Figure 2

Relationship between parrotfish species richness and environmental factors.Each point represents the the parrotfish species richness at that location. Based on the results of the scatter plot, the anomaly (Nansha islands) was deleted in the fitting analysis of longitude, latitude and sea surface temperature.. Since Taiwan islands are affected by the Kuroshio, we separate the islands and reefs near Taiwan (2) from other sites (1) to construct a species - latitude curve.

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