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Red Sea fish market assessments indicate high species diversity and potential overexploitation

Claire T. Shellem [a,*], Joanne I. Ellis [a,b], Darren J. Coker [a], Michael L. Berumen [a]

[a] Red Sea Research Center, Division of Biological and Environmental Science and Engineering, King Abdullah University of Science and Technology, Thuwal 23955, Saudi Arabia

[b] School of Biological Sciences, Waikato University, Tauranga 3110, New Zealand

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ABSTRACT

In many parts of the world, particularly remote and underdeveloped regions, reports of fisheries catch, effort, and landing data are limited. In order to implement effective fishing regulations to protect natural stocks, understanding fishing pressure, key target species, catch composition, and value of each species is vital. In regions where published data is limited, and the sampling of numerous small boats and landing sites is not feasible, fish market surveys represent an opportunity to obtain key fisheries data. This study therefore aims to obtain species-specific prices and market composition for fish landed in the central Red Sea by surveying local fish markets. We conducted 11 surveys at two major Red Sea fish markets to ascertain key fisheries metrics using market data as a proxy for catch data. Results indicate that a high proportion of the market composition is generated by 46 species from six family-level groups, Serranidae, Labridae, scarine labrids, Carangidae, Lethrinidae, and Lutjanidae, contributing to 87 % of the total market biomass. Species-specific values ranged from 4.50 USD/kg to 26.44 USD/kg, with market surveys highlighting the economic value of three local serranid species: *Plectropomus pessuliferus marisrubri*, *Plectropomus areolatus* and *Variola louti*, all valued at more than 25 USD/kg, and a labrid: *Cheilinus undulatus*, valued at 26.44 USD/kg. The Serranidae family represents 47 % of the total biomass and 55 % of the potential revenue in the market, while also indicating potentially overfished reefs due to the high occurrence of smaller species and undersized individuals of higher priced serranid species. Many of the high-valued serranids were below the size at sexual maturity. Target species exhibited small body size and decreasing abundance, potentially indicating a "shrinking baseline" scenario occurring in the Saudi Arabian artisanal coral reef fishery. These results indicate that introducing effective fisheries legislation and management is necessary for the longevity and sustainability of the reef-based fishery in the Saudi Arabian Red Sea. Implementing catch quotas, size limits, and seasonal restrictions are potential mechanisms that could be used to facilitate positive change within this vulnerable fishery.

1. Introduction

Overfishing is one of the greatest threats to our world's oceans, illustrated by the collapse of numerous fisheries in recent decades. The situation is becoming dire as legislation fails to keep up with declining fish stocks (Pauly et al., 2002; Myers and Worm, 2003). While advancements in technology are often touted as the main culprit of historical overfishing epidemics, a more recent key issue is the shortage of fishing regulation and oversight in many areas of the world. One of the greatest challenges to fisheries management is the lack of accurate species-specific information, including landing composition, catch, effort, and local economic contributions (Watson et al., 2004; Vasconcellos and Cochrane, 2005; Sethi et al., 2010). Unfortunately, these limitations are often compounded by a poor biological (e.g., life-history) understanding of key species (Hilborn et al., 2003). Particularly at smaller, local scales in underdeveloped or isolated areas, landing and biological data is often limited or nonexistent (Pauly and Palomares, 2005; Vasconcellos and Cochrane, 2005). However, such information is fundamental to accurately and effectively manage fisheries to ensure their longevity and sustainability.

In total, marine fisheries contribute 100 billion USD annually to global trade (McClanahan et al., 2015). Worldwide, 260 million people

* Corresponding author.
E-mail address: claire.t.shellem@gmail.com (C.T. Shellem).

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are employed through marine fisheries, 22 million of whom work in small-scale fisheries (Teh and Sumaila, 2013). These small-scale fisheries supply up to 50 % of the fisheries export worldwide (McClanahan et al., 2015), yet they are among the world's most vulnerable fisheries (Allison et al., 2009). Since the 1950s, there has been an unprecedented increase in commercial fishing effort, which has led to the depletion of natural populations around the globe (Pauly et al., 2002). Unfortunately, in recent decades, habitat degradation has begun to exacerbate the effects of overfishing, particularly on coral reefs (Pratchett et al., 2008; Rogers et al., 2014, 2017).

The Red Sea is home to expansive coral reef habitats which support tens of thousands of artisanal fishers. Saudi Arabia is the largest country bordering the Red Sea and covers the majority of the eastern Red Sea basin. Despite minimal large-scale commercial fishing in the region (which in other areas is often responsible for fisheries collapses), Saudi Arabia is not exempt from the global overfishing epidemic. The lack of compliance with fishing regulations is an issue prevalent in numerous tropical fisheries worldwide (PERSGA, 2006; Bailey and Sumaila, 2015; Katikiro and Mahenge, 2016). Tesfamichael and Pauly (2015) assert that lack of enforcement and compliance with current regulations has compromised the sustainability of the artisanal fishery in Saudi Arabia. It is estimated that Saudi Arabian reefs have exposed to overfishing since the early 1990s (Jin et al., 2012; Tesfamichael and Pauly, 2015). A recent assessment has shown that similar reefs on the western side of the Red Sea possess both larger individuals and a higher presence of top carnivores than the eastern side (Kattan et al., 2017). This discrepancy is likely the result of heavier fishing pressure on the eastern coast of the Red Sea. Small-scale artisanal fishers are responsible for nearly 70 % of the wild seafood supply in the Saudi Arabian Red Sea, with most of the artisanal fishing effort directed on or around coral reefs (MOA Report, 2006; Jin et al., 2012). Fishers primarily use handlines, which account for 76 % of their total landing, as well as gillnets and traps, which account for the majority of remaining landings (MOA Report, 2006; Jin et al., 2012). The primary targets of artisanal fishers, which remove up to 40,000 tons annually from the Red Sea, are top carnivores, including sharks and serranids, notably the highly prized "nagil" (*Plectropomus pessuliferus marisrubri*) (Myers et al., 2007; Tesfamichael and Pauly, 2015). Unfortunately, species-specific catch data is limited for this region, yet paramount to sustainably managing this coral reef fishery.

Due to the use of thousands of small boats and dozens of scattered landing sites, catch and landing data for coastal fisheries such as the artisanal fishery in Saudi Arabia can be challenging to document. Inaccurate catch and landing data leads to difficulty in monitoring fisheries (Chang, 2014). Many such coastal fisheries sell the majority of their catches in local fish markets, therefore surveying markets can provide insight into the landing and catch compositions of fisheries (Rhodes and Tupper, 2007; Chang, 2014). Fish market surveys can help provide important baseline fisheries data, including species composition, size, abundance, price, and seasonality to local managers and resource users (Rhodes and Tupper, 2007; To and Sadovy de Mitcheson, 2009; Sumaila et al., 2011; Bos and Gumanao, 2012; Chang, 2014). Popular markets that sell local fresh fish are ideal candidates for conducting market surveys (Bos and Gumanao, 2012).

Here we conducted surveys at fish markets in Saudi Arabia to ascertain specific baseline information on the coral reef fishery in the central Red Sea. From 11 market surveys, we identified the composition of catch being landed in this region. For each fish, we recorded the total length (TL) and market price to calculate species-specific prices per kilogram (kg) to better understand which species are of the most value, and therefore likely targeted by fishers. In addition, we ascertained if any species were being harvested at unsustainable levels through the comparison of mean and maximum sizes to known sizes at maturity and maximum lengths. Obtaining these fisheries-relevant values will be necessary in order to establish effective fishing regulations, without which it is likely that several species will continue to be removed from the Saudi Arabian Red Sea at unsustainable rates.

2. Materials and methods

Data was collected from two fish markets in Saudi Arabia, the Thuwal fish market, a small-scale traditional market, and the Jeddah fish market, the largest on the Red Sea coast. It is estimated that over 90 % of the Saudi Arabian population consume fish as a weekly part of their diet, with 60 % of this purchased from local fish markets (Burger et al., 2014). As a result, there are numerous regional fish markets within the kingdom. The largest market is in the coastal city of Jeddah, supported by its proximity to the sea and large population (pop. ~4 million). Along the Saudi coast, smaller fish markets selling locally caught fresh fish daily are common, including the Thuwal fish market. Therefore, sampling the Jeddah and Thuwal fish markets provides insights into both large- and small-scale markets within the region and captures a more comprehensive economic assessment of artisanal fisheries in Saudi Arabia. The Thuwal fish market sells only locally caught reef species. The Jeddah market primarily sells locally caught species but also some farmed (non-reef) and imported species. Based on the species present, quantity of individuals and packaging at each stall, we were able to determine if the fish were locally caught reef fish; additionally, many of the imported species are not reef associated or do not naturally occur in the Red Sea. Generally, vendors selling locally caught fish will display a variety of local reef species over ice (Fig. 1). If vendors displayed only one species in high quantity, or their goods were displayed in Styrofoam shipping boxes, we ascertained that those goods were not likely locally caught and did not include them in our surveys. Only locally caught reef fish were surveyed and included in our analyses. With the exception of fish that are kept and consumed by local fishers themselves, nearly all of the harvest is transported overnight fresh to local markets. Salting and freezing fish are not common practices in this region (pers. comm.). As surveyors were non-Arabic speakers, occasionally the language barrier prohibited data collection from some vendors, however this occurred fewer than five times and is unlikely to affect overall survey results. While bargaining does occur in this region, for the purposes of this study, we were interested in standard prices and not the more variable bargained price (which can be influenced by time of day and number of fish being purchased). Due to the congruency between quoted prices and those posted on placards, we do not believe there to be much discrepancy between our prices and the actual market value. While species-specific valuation data was collected from both the Jeddah and Thuwal markets, the species composition of the fish market was assessed only in the larger Jeddah fish market.

2.1. Species composition assessment

Three visits were made to the Jeddah fish market to sample the composition of species present, in order to better understand which species are being substantially targeted and removed from Red Sea reefs. Over the period of one hour, two or three surveyors identified, counted and measured the total length of each locally caught fish being sold. At the Jeddah market, we identified the 15–20 stalls that regularly sell exclusively locally caught reef associated fish species (not farmed or imported species), and resurveyed these during each visit. Generally, the vendors at the fish market are not fishers themselves. The fish are sold wholesale at auction around 05:00−06:00, where vendors purchase them to sell in the retail stalls. Surveys were conducted in the morning between the hours of 09:00 and 12:00. This period is when the majority of fish are displayed and sold in the retail stalls, and maximizes the likelihood of recording a representative fish market composition assessment. We surveyed the retail prices only as auctions are restricted to vendors and fish are not always sold singularly (i.e., it is common for multiple fish to be strung together and auctioned as a set). Additionally, only fish that were on display at the time of the visit were sampled; any fish that were in coolers or freezers were not sampled. Species composition assessments were conducted during the months of July and August. While seasonality can be an important aspect for some fish

Fig. 1. Examples of fish market displays from two Red Sea locations in Saudi Arabia. a. A stall at the Thuwal fish market displaying several locally caught herbivorous species. b. A stall at the Thuwal fish market displaying several serranid and scarine species. c. A stall at the Jeddah fish market offering a diversity of species and posted placards displaying prices (Saudi Arabian Riyals (SAR)/kg).

market studies, it falls beyond the scope of our assessment. After each market visit, using the total number of fish sampled and the quantity for each family, relative abundances in the fish market were calculated. All comparisons were made using percentages of the total sample (Table 1). Percentages by count, biomass, and revenue were calculated for each of the key targeted families (Serranidae, Carangidae, Lutjanidae, Lethrinidae, Labridae, Scarinae). We acknowledge that scarine labrids (parrotfish, formerly Scaridae) are not an accepted taxonomic family (Westneat and Alfaro, 2005), but in Saudi Arabia, parrotfish are a commercially distinct group (e.g., Jin et al., 2012) and carry cultural significance (e.g., Gladstone, 1996). Thus, we distinguish the subfamily Scarinae among the other families reported herein (and implicitly refer to Labridae as all non-scarine labrids, i.e., the non-parrotfish wrasses).

2.2. Size distributions

Total length (TL cm) was measured to the nearest centimeter for each fish counted and identified during surveys in the Jeddah market. Using the lengths recorded for each individual, a mass for each fish was calculated using known length-weight relationships and the formula: $W = a \times L^b$, where W represents the weight in grams, L represents total length in centimeters and a and b are species-specific constants obtained from FishBase (Friedlander and DeMartini, 2002; Froese and Pauly, 2016). Using the aforementioned mass values, we calculated percentages by biomass of the six groups.

2.3. Determination of price per kilogram

Between February and August 2019, surveys were conducted at two local fish markets to calculate species-specific price estimations. Two surveys were conducted at the Thuwal fish market and nine surveys at the Jeddah fish market. Vendors were asked for the price per kilogram for each specific fish; if the vendor gave a price for the whole fish (as was often the case) the total length of the fish was measured so that a weight could be calculated using the above biomass formula or, when possible, fish were weighed so that we could determine a price per kilogram. All prices were quoted in Saudi Arabian Riyals (SAR); we present here values converted into United States Dollar (USD) using the fixed exchange rate of 1 SAR = 0.27 USD. Prices were collected at the species level when possible, however some prices were ultimately averaged due to limited species-specific samples. For example, the price of *Lutjanus ehrenbergii* was only sampled once, therefore that price was averaged with other similar species, such as *Lutjanus kasmira*, to generate an average price for all similar small lutjanid species. Furthermore, vendors rarely discriminate at the species level, particularly among lower value species, and instead group similar valued species together. When the prices were posted on placards, vendors were not interviewed and displayed prices were collected to eliminate surveyor bias (Fig. 1). However, most of our calculated prices revealed relatively low variance, so this is unlikely a concern. No differences were noted between prices at the two markets, so we used combined data from all market visits. After the valuation data was compiled from the 11 visits to the fish markets, family level or species-specific prices were assigned to each fish depending on the number of individuals sampled, the similarity of that species to others in its family and whether or not the vendors differentiated between the species (see Appendix A for further details). Lastly, using the estimated biomass and the quoted prices, we calculated economic values for each family based on the market composition surveys from the Jeddah fish market (section 2.1). Price and value data are used to generate relative comparisons among species and groups of species. Thus, it was not necessary to scale our estimations spatially or temporally (e.g., to the entire fish market, for the entire coast, or to an annual amount).

3. Results

3.1. Jeddah fish market composition

A total of 3036 fish from 70 different species were recorded during the three trips to the Jeddah fish market. The Serranidae family was the most abundant (1085 individuals, 36 % of the total). A total of 39 *Plectropomus pessuliferus marisrubri* were sampled and 52 *P. areolatus* individuals were sampled in the Jeddah market (Table 1). *Variola louti* was among the most abundant serranids, with a total of 75 individuals sampled. The second most abundant family was Lethrinidae, of which 700 individuals accounted for 23 % of the total individuals in the market

Table 1
Species composition at the Jeddah fish market, Saudi Arabia. Data collected from surveys of a subset of the retail stalls in the market (15-20 per survey). Abundance represents the total number of individuals encountered during three visits to the market. Biomass (kg) represents the total biomass of that species in the market combined over the three visits. Proportion of occurrence was calculated by dividing the total number of that species by the total number of individuals sampled (3036 individuals). Families are ordered alphabetically and species are arranged alphabetically within each family. The top 32 (of 70) species are listed here.

Species	Family	Proportion of Occurrence	Abundance	Biomass (kg)
Acanthurus gahhm	Acanthuridae	0.7 %	21	4.52
Carangoides bajad	Carangidae	3.5 %	107	26.5
Caranx melampygus	Carangidae	0.9 %	26	15.07
Chanos chanos	Chanidae	0.8 %	24	16.91
Plectorhinchus gaterinus	Haemulidae	1.4 %	43	29.7
Cheilinus abudjubbe	Labridae	0.5 %	16	15.639
Cheilinus undulatus	Labridae	0.4 %	12	152.79
Gymnocranius grandoculis	Lethrinidae	1.1 %	34	106.2
Lethrinus harak	Lethrinidae	2.5 %	75	28.68
Lethrinus mahsena	Lethrinidae	9.6 %	292	233.52
Lethrinus microdon	Lethrinidae	2.8 %	84	89.27
Lethrinus xanthochilus	Lethrinidae	2.7 %	83	46.79
Lutjanus kasmira	Lutjanidae	1.1 %	33	12.74
Cetoscarus bicolor	Scarinae	0.5 %	15	18.31
Chlorurus sordidus	Scarinae	0.7 %	22	37.76
Hipposcarus harid	Scarinae	1.4 %	44	31.33
Scarus ferrugineus	Scarinae	3.4 %	103	122.53
Scarus ghobban	Scarinae	0.9 %	28	40.87
Grammatorycnos bilineatus	Scombridae	0.5 %	16	43.4
Cephalopholis oligosticta	Serranidae	0.9 %	26	24.61
Cephalopholis sexmaculata	Serranidae	0.7 %	21	7.99
Cephalopholis sonnerati	Serranidae	3.8 %	115	102.36
Epinephelus areolatus	Serranidae	10.6 %	322	238.14
Epinephelus chlorostigma	Serranidae	5.9 %	178	174.93
Epinephelus malabaricus	Serranidae	2.4 %	72	374.08
Epinephelus stoliczkae	Serranidae	0.4 %	13	10.82
Epinephelus summana	Serranidae	1.6 %	50	43.82
Plectropomus areolatus	Serranidae	1.7 %	52	88.89
Plectropomus pessuliferus marisrubri	Serranidae	1.3 %	39	165.51
Variola louti	Serranidae	2.5 %	75	53.34
Siganus rivulatus	Siganidae	3.0 %	90	15.7
Siganus stellatus	Siganidae	0.7 %	20	8.37

and 16 % of the total biomass. Following lethrinids, Scarinae were the next most abundant group: 421 individuals resulting in 14 % of the total count and 16 % of the total biomass. There were 189 Carangidae and 171 Lutjanidae individuals recorded, each making up ~6% of the total abundance at the fish market. Carangids account for 6% of the total individuals and 4% of the biomass. Lutjanids represent 6% of the individuals and 9% of the biomass. Only 62 labrids were counted, comprising 2% of the total individuals and 5% of the total biomass. The most valuable species at the market was the labrid *Cheilinus undulatus,* however only 12 individuals were sampled. The remaining 408 individuals, which included surgeonfish, unicornfish, spadefish, barracuda and others, were grouped together and cumulatively represent the remaining 13 % of individuals, and 4% of the total biomass.

3.2. Size distributions

Species ranged in size from a few centimeters to over 100 cm TL, however the majority of individuals were below 40 cm TL (Fig. 3). The size classes of serranids in the market ranged from 15 cm to over 100 cm, with the most abundant size class being 25−35 cm. The average market size of *P. pessuliferus marisrubri* is 59.7 cm, well below the maximum size for that species of 120 cm (Froese and Pauly, 2016), and slightly below 62 cm, the size at sexual maturity, with only 33 % of individuals in the market larger than the size at maturity (DesRosiers, 2011; Fig. 2). The same trend was present in the two next most highly valued serranid species: *P. areolatus* and *V. louti*, with average total lengths in the market of 37.9 cm and 44.3 cm respectively. *Plectropomus areolatus* reaches sexual maturity at 41 cm (DesRosiers, 2011), and has a maximum size of 80 cm (Froese and Pauly, 2016), yet the average size in the Jeddah fish market was merely 37.9 cm. *Variola louti* reaches sexual maturity at 47.6 cm, and has a maximum size of 83 cm (Froese and Pauly, 2016). Notably, the higher valued species are more often caught below the size at sexual maturity than lower valued species (Fig. 2). Two scarine species, *Cetoscarus bicolor* and *Scarus ferrugineus*, did not follow the same pattern and most individuals in the market were above the assumed size of maturation. *Cetoscarus bicolor* reaches sexual maturity at 32.3 cm (fork length) in Micronesia (Taylor and Choat, 2014, although the *Cetoscarus* species in the Pacific Ocean is generally now regarded as *Cetoscarus ocellatus* and *C. bicolor* is now regarded as endemic to the Red Sea, DiBattista et al., 2016). The average size in the Jeddah market was much larger at 44.3 cm, only slightly smaller than the maximum known size for that species of 50 cm (Froese and Pauly, 2016). In the Red Sea, it is estimated *Scarus ferrugineus* males reach maturity at 26.2 cm (Abdel-Aziz et al., 2012) which is below the average size of 31.6 cm recorded for this species in the market.

3.3. Fish market prices

Prices at the fish market ranged from 4.50 USD/kg to 26.44 USD/kg. The most expensive species were *Cheilinus undulatus* and *Plectropomus pessuliferus marisrubri*, and the lowest valued fish were small lutjanids and siganids, including *Lutjanus kasmira* and *Siganus rivulatus*. *Plectropomus pessuliferus marisrubri* and *C. undulatus* are worth 26.43 ± 1.2 USD/kg and 26.44 ± 3.5 USD/kg respectively (Table 2). *Plectropomus areolatus* and *Variola louti* are also highly valued species priced at 25.92 ± 2.5 USD/kg and 25.20 ± 1.4 USD/kg, respectively. Most other serranids all fall under the local name "hammour" and are sold indiscriminately from each other for 11.18 ± 0.7 USD/kg. The higher valued serranid species (*Plectropomus* spp. and *V. louti*) are found in the market at lower abundances than lesser valued species (*Epinephelus* spp. and *Cephalopholis* spp.; Fig. 3). *Carangoides bajad* is worth 12.06 ± 1.4 USD/kg. Due to the similar appearances of many scarine species, they are rarely distinguished at the species level in the market; most scarine are collectively referred to as "harid" and sold for 10.38 ± 0.7 USD/kg. *Cetoscarus bicolor* is the only scarine assigned a species-specific price; they sell at 14.40 ± 1.5 USD/kg. This species is easily identifiable and is often larger than other scarine species in this region (Table 2). Many smaller fish, including small lutjanids, acanthurids, ephippids and holocentrids are sold together, for 5.40 ± 0.7 USD/kg.

Of the total potential revenue from the Jeddah fish market, 55 % comes from serranids, 14 % from Scarinae species and 11 % from lethrinids. Although few labrids were encountered, they account for 10 % of the potential revenue. Lutjanids represent 5% of the potential revenue and carangids are responsible for 3% of the potential revenue. All other species account for only 2% of the potential revenue (Fig. 4).

4. Discussion

The importance of economics in explaining the overexploitation of fisheries resources is well established (Iudicello et al., 1999; Pascoe,

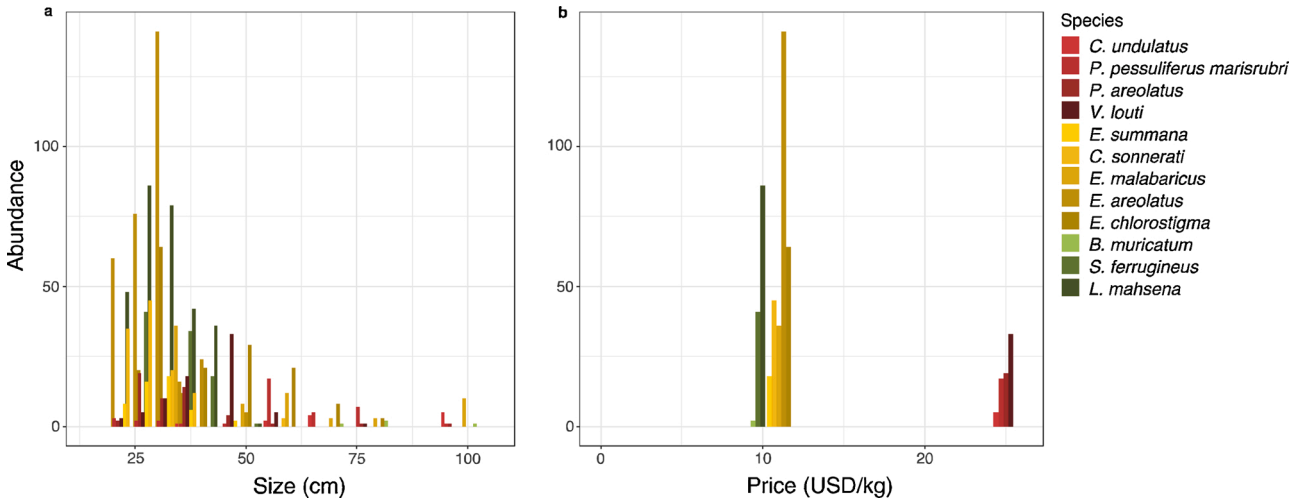

Fig. 3. Barplots depicting relative abundances of 12 species by size and price. Species contributing the greatest to the market revenue in fish markets surveyed on the Saudi Arabian Red Sea coast were selected. Species are indicated by the color of each bar. Red hues indicate species that are above 20 USD/kg, yellow hues indicate species between 10 and 20 USD/kg, green hues indicate species worth less than 10 USD/kg. a). The abundance (total number of individuals encountered during all market visits) of each species within various size classes (<10, 10-14, 15-19, 20-24, 25-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80-99, >100 cm). Although the maximum length encountered was >100 cm, the majority of the fish are between 20 and 30 cm TL. b). The distribution of abundance by price per kilogram (specific prices are listed in Table 2). The most valuable species, shown in red, are found in lower abundance than lower valued species shown in green and yellow.

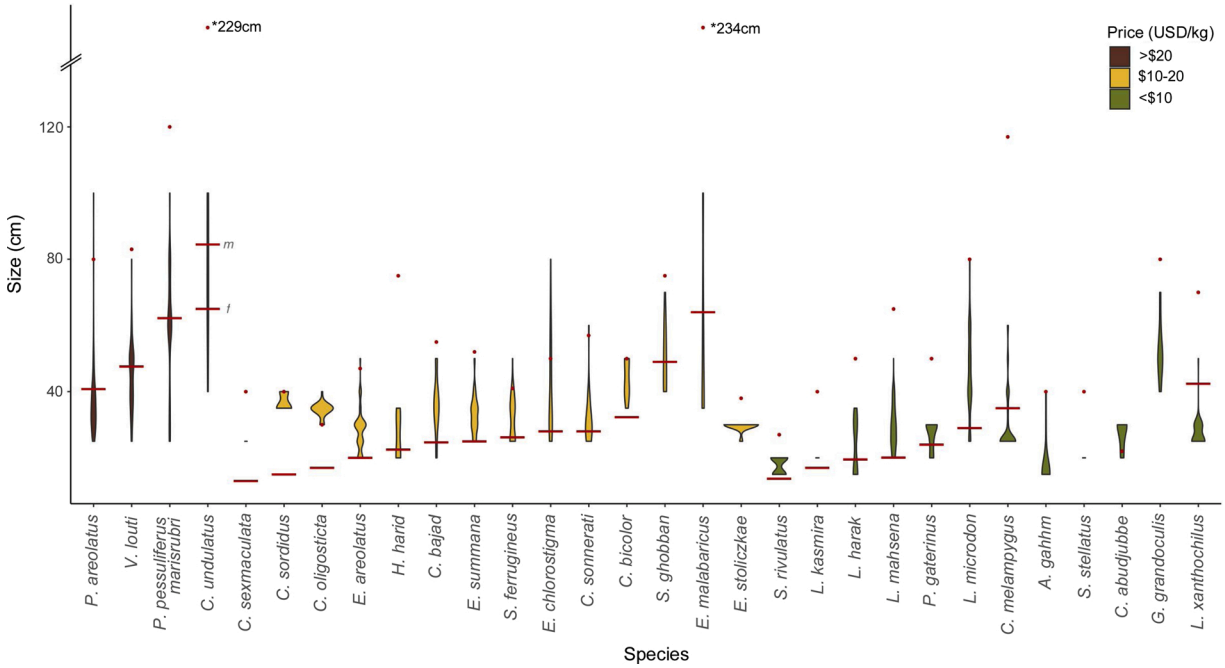

Fig. 2. Violin plot displaying size (TL (cm)) distributions of the 30 most abundant species in the Jeddah fish market. Wider widths indicate higher abundances of individuals in that size class. Red fill represents species priced over 20 USD/kg, yellow indicates species with prices between 10 and 20 USD/kg, green indicates species with prices below 10 USD/kg. The small points depicted here (such as C. sexmaculata) indicate that there is no variance among sizes of that species. Red horizontal lines indicate the published size at sexual maturity of each species. Cheilinus undulatus shows two red lines, one for males (m) and one for females (f). If there is no horizontal red line, the sexual maturity for that species is unknown. The red dot above each species indicates its published maximum size. Sample sizes can be seen in the abundance column of Table 1.

2006; Kompas et al., 2010). More specifically, the species that fishers target, the methods used and the level of exploitation are often influenced by the economic benefits received. Identifying which species garner the highest revenues is a key factor in understanding which species are being targeted and provides insight into methods to mitigate overharvesting. Furthermore, the composition of species in the market allows us to infer which fish and what degree individuals are being harvested from local reefs. Surveys of local Red Sea fish markets emphasize the economic importance of six groups, notably Serranidae and Scarinae, and highlight the need for effective monitoring and legislation to promote the longevity of this reef-based fishery. Visits to the Jeddah fish market revealed that 98 % of the potential revenue is generated from species belonging to six families: Serranidae, Carangidae, Lutjanidae, Lethrinidae, Labridae, and Scarinae; therefore, only 2 % of the potential revenue is yielded from species outside those six groups. The most valuable species in local markets are *Cheilinus*

Table 2
The average price per kilogram ± SE (USD/kg), average size ± SE (cm), maximum size (cm) for the species (Froese and Pauly, 2016), and percent of the revenue potential of key fisheries species sampled at central Red Sea fish markets (Thuwal and Jeddah, Saudi Arabia). Mean prices and sizes are presented with standard error from the mean. Prices denoted with '*' indicate a species-specific price, where all others are averaged to the family level. The 32 most abundant species are listed here in order of price. Unfortunately, no prices were sampled for the species Chanos chanos.

Species	Family	Price (USD/kg)	Mean Size (cm)	Max. Size (cm)	Percent of Revenue
Cheilinus undulatus	Labridae	$26.44 ± 3.5 *	78.3 ± 5.3	229	7.48%
Plectropomus pessuliferus marisrubri	Serranidae	$26.43 ± 1.2 *	59.6 ± 2.8	120	11.47 %
Plectropomus areolatus	Serranidae	$25.92 ± 2.5 *	37.9 ± 17.8	80	4.74%
Variola louti	Serranidae	$25.20 ± 1.4 *	44.3 ± 1.1	83	7.14 %
Epinephelus summana	Serranidae	$14.58 ± 2.0 *	33.0 ± 8.0	52	1.27%
Cetoscarus bicolor	Scarinae	$14.40 ± 1.5 *	44.3 ± 1.1	50	1.20%
Carangoides bajad	Carangidae	$12.06 ± 1.4 *	36.0 ± 8.0	55	0.84%
Epinephelus areolatus	Serranidae	$11.18 ± 0.7	28.2 ± 0.3	47	4.94%
Epinephelus chlorostigma	Serranidae	$11.18 ± 0.7	40.4 ± 1.0	80	6.44%
Cephalopholis sonnerati	Serranidae	$11.18 ± 0.7	31.1 ± 6.2	57	2.31%
Epinephelus malabaricus	Serranidae	$11.18 ± 0.7	53.2 ± 2.6	234	9.00%
Cephalopholis oligosticta	Serranidae	$11.18 ± 0.7	34.4 ± 0.4	30	0.48%
Cephalopholis sexmaculata	Serranidae	$11.18 ± 0.7	25.0 ± 0.0	50	0.16 %
Epinephelus stoliczkae	Serranidae	$11.18 ± 0.7	29.6 ± 0.4	38	0.21%
Scarus ferrugineus	Scarinae	$10.38 ± 0.7	31.6 ± 0.6	41	2.29%
Hipposcarus harid	Scarinae	$10.38 ± 0.7	26.8 ± 1.0	75	0.57%
Scarus ghobban	Scarinae	$10.38 ± 0.7	50.0 ± 1.8	75	2.01%
Chlorurus sordidus	Scarinae	$10.38 ± 0.7	36.8 ± 0.5	40	0.68%
Grammatorycnos bilineatus	Scombridae	$9.74 ± 1.1	55.8 ± 1.4	100	0.25%
Caranx melampygus	Carangidae	$9.74 ± 1.1	28.8 ± 1.7	117	0.39%
Lethrinus mahsena	Lethrinidae	$8.10 ± 1.2	28.9 ± 0.4	65	3.29%
Lethrinus microdon	Lethrinidae	$8.10 ± 1.2	44.3 ± 1.4	80	2.94%
Lethrinus xanthochilus	Lethrinidae	$8.10 ± 1.2	27.2 ± 0.4	70	0.70 %
Lethrinus harak	Lethrinidae	$8.10 ± 1.2	35.0 ± 0.0	50	0.08%
Gymnocranius grandoculis	Lethrinidae	$8.10 ± 1.2	52.1 ± 1.4	80	0.92%
Siganus rivulatus	Siganidae	$7.09 ± 1.5	17.8 ± 0.3	27	1.90 %
Siganus stellatus	Siganidae	$7.09 ± 1.5	20.0 ± 0.0	40	0.10 %
Cheilinus abudjubbe	Labridae	$6.41 ± 0.6 *	27.2 ± 1.0	22	0.17%
Plectorhinchus gaterinus	Haemulidae	$5.60 ± 0.6	27 ± 0.6	50	0.27%
Lutjanus kasmira	Lutjanidae	$5.51 ± 0.7	20.0 ± 0.0	40	0.12%
Acanthurus gahhm	Acanthuridae	$4.50 ± 0.4 *	17.1 ± 1.3	40	0.04%
Chanos chanos	Chanidae	–	36.7 ± 1.6	180	–

undulatus, *Plectropomus pessuliferus marisrubri*, *Plectropomus areolatus* and *Variola louti*, one labrid and three serranids, all of which are worth over 25 USD/kg. Those four species, however, were found in relatively low abundances compared to lower valued species, with the bulk of the fish in the market, including all other serranid species and most scarine species, worth 8–12 USD/kg.

The high prevalence and high prices for serranid species indicate a consumer preference for those fish, which implies that they are highly targeted and harvested from local Saudi Arabian reefs. Over one third of the fish sampled at the fish market were serranids, cumulatively making up 55 % of the potential revenue from the reef based fishery. Unfortunately, due to their slow growth rates and late sexual maturation, serranidaes are highly susceptible to overfishing (Rhodes and Tupper, 2007). *Plectropomus* spp. specifically are heavily targeted by reef fishers around the world and are particularly vulnerable to overharvesting (Frisch et al., 2016; Kadison et al., 2017). Internationally, *Plectropomus* spp. have been depleted through uncontrolled fishing which has led *P. areolatus* to be classified as vulnerable under the IUCN criteria (Sadovy de Mitcheson et al., 2013; Frisch et al., 2016). In this region, *Plectropomus pessuliferus marisrubri* is the most coveted species and it is likely that the values of *P. areolatus* and *V. louti* are elevated due to their resemblance to *P. pessuliferus marisrubri*, all of which are red, large bodied serranid species with light-colored dots. Worldwide, serranids are a heavily targeted and economically important fisheries species (Rhodes and Tupper, 2007; Bejarano Chavarro et al., 2014; Huliselan et al., 2017; Giglio et al., 2018). In recent decades, serranids found in fish markets have shifted from large bodied individuals to smaller, often sexually immature, individuals; the unsustainable practice of catching juveniles is occurring in many reef-based fisheries around the world (To and Sadovy de Mitcheson, 2009). Based on our size estimates, it is likely occurring in the Saudi Red Sea. One study from Hong Kong estimated that up to 80 % of the serranids found in markets are juveniles (To and Sadovy de Mitcheson, 2009). The estimated reproductive size for *P. pessuliferus marisrubri is* 62.2 cm and for *P. areolatus* is 40.6 cm (DesRosiers, 2011). Among the fish we surveyed at the Jeddah fish market, the average sizes of those species were 59.6 cm and 37.9 cm, respectively, with over 60 % of individuals of both species below the size at maturation indicating they are being caught as juveniles before they have the chance to reproduce. Additionally, the mean sizes for *P. pessuliferus marisrubri, P. areolatus,* and *V. louti* in the market are merely half of the maximum sizes for those species (Froese and Pauly, 2016). Furthermore, although those species are heavily targeted, smaller serranid species such as *Epinephelus areolatus*, *Epinephelus chlorostigma* and *Cephalopholis sonnerati* are far more abundant in the markets, in accord with Pauly's (1995) "shrinking baseline" hypothesis, whereby smaller individuals are found in the markets over time, ultimately undermining fishery sustainability (To and Sadovy de Mitcheson, 2009). It is possible that the larger-bodied species, such as *P. pessuliferus marisrubri* and *P. areolatus*, were overharvested in recent years, forcing fishers to catch smaller serranid species instead. There are presently no size restrictions in Saudi Arabia, yet size is an important determinant of price in fish markets (Thyresson et al., 2011), therefore smaller serranid individuals are far less valuable than larger bodied serranids. Despite the higher prevalence of smaller size classes within the family, serranids still represented over half of the potential revenue in the market.

We found evidence that the phenomenon of "fishing down the food web" may be occurring in the Red Sea (Pauly et al., 1998). Unfortunately, in this region, reliable historical, species-specific, catch information is extremely limited. However, because a better understanding of past fisheries allows for more effective assessment of current stocks, the use of anecdotal evidence is increasing in fisheries studies (Pauly, 1995). Lifelong Saudi Arabian fishers have highlighted that both the size and number of species, including *P. pessuliferus marisrubri* have decreased in recent decades (pers. comm.). Furthermore, it is likely that "fishing down marine food webs" is more severe and widespread than previously thought, especially in data-poor regions like the Red Sea (Pauly et al.,

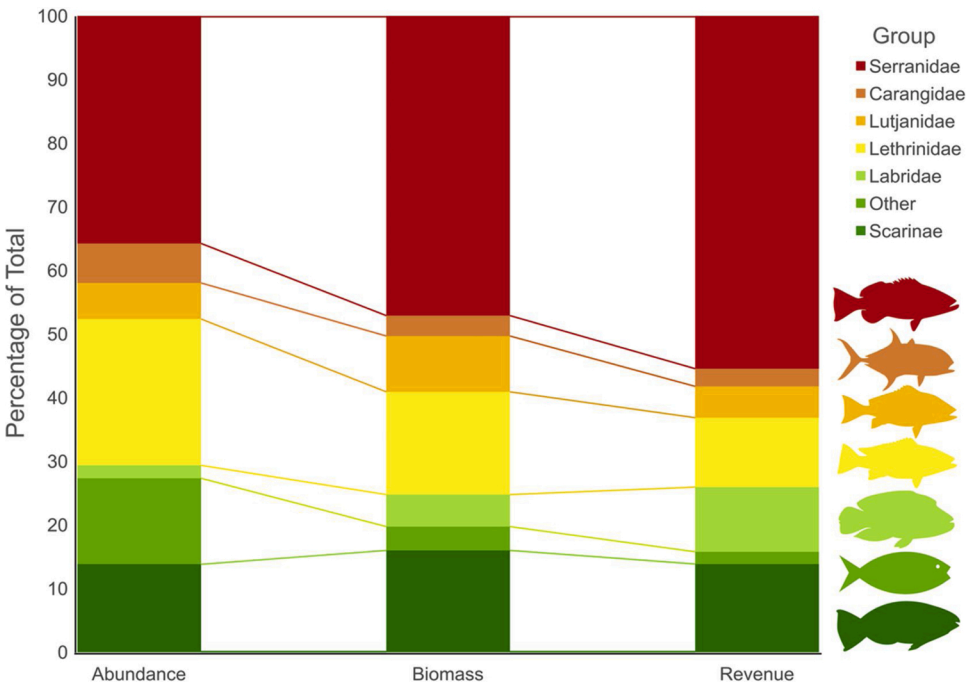

Fig. 4. The percentages of total abundance, biomass, and potential revenue generated by the Serranidae, Carangidae, Lutjanidae, Lethrinidae, Labridae, and Scarinae groups at the Jeddah fish market. Abundance represents the percentage that each group contributes to the total 3036 individuals sampled. Biomass represents the percentage of the total biomass of all 3036 individuals. Revenue denotes the percentage of the total potential revenue accumulated by each family/subfamily. Red/orange colors indicate carnivorous species and yellow/green colors indicate generally herbivorous and omnivorous species.

1998; Pauly and Palomares, 2005). Compounding this issue are the potential "bottom up" effects of habitat degradation on fish communities and the negative feedback of removing fish before they have reached sexual maturity (Pratchett et al., 2008; Robinson et al., 2019). Fortunately, the survey data for Scarinae species indicate that those populations may be harvested at sustainable levels in this region of the Red Sea, contrary to other regions worldwide (e.g., Mumby, 2016). Due to their prevalence in the markets, it is clear that scarines are being targeted by reef fishers, though they seem to be targeted less heavily than carnivorous species. The use of nets and traps, which are used to catch scarines, represent only 24 % of the artisanal fishing effort in this region (Jin et al., 2012). *Cetoscarus bicolor* is a Red Sea endemic and the only scarine with a species-specific price, seemingly more valuable than other scarines. Fortunately, most individuals observed had reached the size of sexual maturity and the average size was just 5–6 cm below the maximum known size of that species. It is important to note, however, that life history information (including maturation data) for this species has not yet been established in the Red Sea. Nonetheless, the relatively large size of individuals and frequent observation of terminal-phase males are promising indications for an endemic species with ecological and economic value. In addition, scarine species are functionally important, helping to maintain reef health through the control of benthic algae (Bellwood et al., 2004). The largest individuals found in the market and the most valuable were *Cheilinus undulatus*, which is valued at 26.44 USD/kg with an average size of 78.3 cm and a maximum size of >100 cm. A single individual can sell for more than 300 USD. However, of the 3036 individuals sampled at the market, only 12 were *Cheilinus undulatus*. It is likely that a low abundance of this valuable fish highlights its rarity, as ecological conditions are often reflected in fish markets (Pauly et al., 1998). The value of each species determines the investment fishers will undertake to catch it, therefore even in low abundances they will be heavily targeted (Pinnegar et al., 2002). Furthermore, the price will continue to increase as the species becomes scarce (Murawski and Serchuk, 1989; Pinnegar et al., 2002), which may be occurring with *Cheilinus undulatus* in the Saudi Arabian Red Sea.

5. Conclusions

Results from this study indicate that economic market surveys can be used to gather fisheries data in regions or in fisheries where landing data is inaccessible or incomplete. Surveys of local Red Sea fish markets yielded data in accord with other studies suggesting that Saudi Arabian reefs are overharvested (Jin et al., 2012; Spaet and Berumen, 2015; Kattan et al., 2017), particularly within the Serranidae family. These results however are not prevalent across all families; Scarinae species do not appear to express signs of severe overharvesting. While this study presents a preliminary assessment of Red Sea coastal fisheries, there is much more work to be done, namely achieving a better understanding of fishing effort. At present, the temporal and spatial patterns of the fishery are unclear. Ideally a future study can endeavor to collect this type of data (catch composition, volume, price etc.) regularly over multiple years to capture seasonal variation. Disentangling these questions will offer nuanced detail into this artisanal reef-based fishery and can help policy makers enact effective change toward sustaining these reef fish communities. Fisheries management, when used properly, can change the incentives and behavior of fishers. In many regions, marine protected areas (MPAs) have been used to promote recovery of endangered fish stocks (Emslie et al., 2015). However, the use of MPAs is not effective in all regions; for fisheries targeting highly mobile species, such as many serranids, implementing catch quotas, size limits, gear restrictions, and closed seasons can be effective in stimulating the recovery of overharvested populations (Hilborn et al., 2004; McGarvey et al., 2015). Implementation of similar efforts may represent a first step in the mitigation of overfishing on Saudi Arabian coral reefs supported by more robust fisheries stock assessments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Methods for determining species-specific or family level prices

Serranidae: Within the Serranidae family, *Plectropomus areolatus, Plectropomus pessuliferus marisrubri* and *Variola louti* were assigned species-specific prices. These three species were assigned species-specific prices for three reasons: i. they are identified at the species level by vendors and consumers, ii. due to their high abundance in the markets an accurate species specific average could be calculated, iii. their price dissimilarity from other Serranid species. Additionally, due to the large number of *Epinephelus summana* encountered, this species was also assigned a species-specific price. All other serranids were assigned family level prices.

Lutjanidae: Among the Lutjanidae family, *Lutjanus bohar* and *Macolor niger* were both assigned species-specific prices because their biology (size in particular) differs greatly from other common lutjanids in the market. For the remaining members of the Lutjanidae family, two mean prices were calculated, one for 'small lutjanids', which include *Lutjanus ehrenbergii* and *Lutjanus kasmira* and have a maximum size of 60 cm or smaller, and one for 'large lutjanids', which include *Lutjanus argentimaculatus* and *Lutjanus sebae*, and have a maximum size of over 60 cm.

Carangidae: Among the carangids, *Carangoides bajad* is the only species assigned a species-specific price due to its frequency in the markets. The prices for the rest of the Carangidae family (e.g. *C. melampygus* and *C. ignobilis*) were averaged.

Lethrinidae: Because there is very little discrimination among Lethrinidae species in the market, an average price was calculated for all lethrinid species.

Scarinae: Most scarids were assigned mean prices due to their biological similarities and lack of distinction at the fish market. However, *Cetoscarus bicolor* was assigned a species-specific price due to typically larger size, higher price, and distinctiveness from other members of the family.

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