Distribution and diversity of fish species exposed to artisanal fishery along the Sudanese Red Sea coast.

By: Erik Olsen^{1*}, Bjørn Erik Axelsen¹, Even Moland^{1,2}, Anne Christine Utne-Palm¹,
Elamin Mohammed Elamin³, Motassim Ali Mukhtar³, Adel Mohamed Saleh⁴,
Sheikheldin Mohamed Elamin⁴, Mohamed Abdelhameed Iragi⁵, Said Gumaa Fadul
Gumaa⁵

Affiliations:

- 1) Institute of Marine Research, P.O. Box 1870 Nordnes, N-5817 Bergen,
Norway
- 2) Department of Natural Sciences, University of Agder, P.O. Box 422, N-4604
Kristiansand, Norway
- 3) Red Sea Fisheries Research Station, P.O. Box 730, Port Sudan, Red Sea State,
Sudan
- 4) Faculty of Marine Science and Fisheries, Red Sea State University, P.O. Box
24, Port Sudan, Red Sea State, Sudan
- 5) Marine Fisheries Administration, Port Sudan, Red Sea State, Sudan

*) corresponding author, e-mail: eriko@hi.no

25 **Key-words:** Sudan, coral reef, Red Sea, trap, handline, gillnet, CPUE, data-limited,
26 fisheries

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28

29 **Abstract**

30 The semi-enclosed Red Sea harbours one of the longest coral-reef ecosystems on the
31 planet. The ≈ 850 km section of the western shore, comprising the coastline of the
32 Red Sea State of the Republic of Sudan, has however been sparsely studied. Sudan's
33 coral reef fishery provides livelihoods to fishers and business opportunities by means
34 of local and regional trade, however, the knowledge level of the state of the natural
35 resources and the impacts of fisheries are poorly known. Here we report the results
36 from the first three comprehensive fisheries research surveys spanning the entire
37 Sudanese coast in 2012-13, representing a new baseline for the western coast fisheries
38 resources. The surveys covered the entire coast from inshore down to about 150 m
39 bottom depth using a combination of baited traps, gillnets and handlines to sample the
40 various reef habitats and fish assemblages. The results demonstrate a uniform
41 latitudinal species distribution with peak catch per unit effort rates in and around the
42 Dungonab Bay area in the north and the outer Suakin archipelago in the south.
43 Functional diversity (Rao's Q index) was found to be highest in and around the
44 Dungonab Bay area, thus coming through as a regional hot-spot of biodiversity. The
45 results form a baseline for future research and monitoring, thus representing key input
46 for an ecosystem approach to management of Sudan's coastal artisanal fisheries.

47

1 Introduction

With its semi-enclosed location between the African continent and the Arabian peninsula the waters of the Red Sea are warmer and more saline than many other marine tropical ecosystems [1]. The Red Sea is host to a uniquely rich marine biodiversity and high prevalence of endemic species [2,3,4]. While the northern reef areas of Egypt and the Gulf of Aqaba/ Eilat have been extensively investigated [1,5], the Red Sea proper is generally poorly studied, and only rudimentary studies from decades back have focused on commercial fisheries [6]. The research published on the Red Sea ecosystem is dwarfed by that of the Great Barrier Reef and, in particular, the Caribbean [1], despite equal scientific relevance. The sparseness of information about the fisheries and the state of the resources harvested severely limits the authorities' ability to sustainably manage the sector in an effective and directed manner [1].

Institutional capacities in the region are limited and official landings data are sparse and essentially unreliable. Tesfamichael and Pauly [6] reconstructed the catch statistics from all Red Sea countries using a combination of unpublished data and interviews with managers, stakeholders and fishers around the Red Sea. They found that the reconstructed catches were $1.5 \times$ larger than the official FAO statistics with artisanal fisheries dominating, accounting for 49% of the total catch from 1950 – 2010 [6]. These estimates, however, also rely on several assumptions and are too rather uncertain, and management and enforcement of the fisheries in the region are essentially based on a highly data-poor knowledge base (Sudan, Eritrea, Yemen) [6].

The Republic of the Sudan's Red Sea State include 853 km of the 2250 km African (western) Red Sea shore (Figure 1). Although there are large latitudinal gradients in environmental conditions with salinity increasing to the north and temperature

73 increasing towards the south [6,7], the biological community changes little from north
 74 to south [8]. Most studies from the region are over 50 years old and have primarily
 75 focused on single reef study sites such as the Costeau Conshelf habitation experiment
 76 at Sha'ab Rumi in 1963 [9]. More recently, the Dungonab Bay area north of Port
 77 Sudan was studied and deemed to be of global significance and has subsequently been
 78 included in the UNESCO list of world heritage sites since 2016 along with the
 79 Sanganeb atoll as the “Dungonab Bay – Mukkawar Island Marine National Park” and
 80 the “Sanganeb Marine National Park” [4]. Historically, specimen collectors and early
 81 natural scientists have described the marine fauna [1,10,11], but thus far there have
 82 been no large-scale studies systematically covering the coastal fish assemblages (but
 83 see Kattan et al. [7]).

84

85 The 2008 Equipe Costeau expedition was the most comprehensive study to date, but
 86 has limited value in terms of describing the marine fishery resources as it only
 87 covered a small part of the coast, focusing on local biodiversity rather than abundance
 88 [4,12]. Their teams applied underwater visual census (UVC) methodology to survey
 89 the reef fish assemblages and collect benthic data [12]. Kattan et al. [8] carried out
 90 comparative UVC surveys of Sudanese and Saudi reefs and found the Sudanese reefs,
 91 especially those furthest offshore and to the south, to be in pristine conditions, with
 92 biomass levels approaching those observed at remote Pacific islands and atolls.
 93 However, the Kattan et al. [8] study did not cover the northernmost section of the
 94 Sudanese coast, nor the near shore coastal reef areas.

95

96 Several development aid organizations as well as the Red Sea State government have
 97 pointed to development in the marine fisheries sector as one possible route to

98 increased revenue, food production and employment in coastal communities.
 99 However, an appropriate understanding of the fisheries and its resource base, that can
 100 provide guidelines for sustainable harvesting practices and restrictions, is essential in
 101 order for such development to be ecologically and economically sustainable in the
 102 long term [13].
 103
 104 The data-poor situation as that of the Red Sea State coral reef fishery offers limited
 105 opportunity to draw inference regarding the status and evolution of the fishery, the
 106 resource base and the sustainability [14]. Despite management efforts in coral reef
 107 fisheries worldwide, 55 % of island-based coral reef fish communities are fished in an
 108 unsustainable manner [15], and a review of artisanal coral reef fishery research found
 109 that nearly 90 % of the studies listed overfishing as a concern [16]. Several strategies
 110 have the potential to improve management outcomes, such as strengthening
 111 governance, developing a more nuanced understanding of the interaction between
 112 fishing, alternative livelihoods and human well-being, and explicitly linking gear
 113 selectivity to ecosystem effects [17]. A recent study has raised concern that the roving
 114 coral grouper *Plectropomus pessuliferus marisrubri* and the squaretail coral grouper
 115 *P. areolatus* (Arabic names ‘Najil’ and ‘Silimani’, respectively), both highly valued
 116 target species in the hook-and-line fisheries, are already in an overfished state [18], a
 117 situation documented on the eastern, Saudi Arabian, side of the Red Sea [8,19].

118

119 **BOX – Sudan’s coral reef fisheries**

120 The marine fisheries sector in Sudan is comparatively small with annual catches
 121 reported at 5700 tons according to the official FAO statistics [21,22], while according
 122 to the catch reconstruction of Sudanese fisheries [23] the annual catch for 2010 was

2000 tonnes, predominantly from artisanal handline- and gillnet fisheries on and along the fringes of coral reefs operating from many small landing sites and villages along the coast. The management of the artisanal fishery is divided into seven management areas (Figure 1). Tesfamichael and Elawad [23] attributed the discrepancies between the official catch statistics and the reconstructed catches to misreporting on the side of the Sudanese fisheries authorities.

The artisanal fishing fleet currently consists of approximately 2000 fishers operating about 1000 vessels that are mostly in the range of 6-10 m of length, many equipped with 30–40 horsepower outboard engines (Marine Fisheries Administration, unpublished data). Most of these vessels target fin-fish (particularly the high-priced groupers) and have facilities for storage of ice and catch. With a crew of typically 2-5 fishers these vessels operate throughout the near- and offshore reef systems and archipelagos for several days up to two weeks per fishing trip. The most common fishing gear is handline, but mono- and multifilament gillnets are also prevalent in some areas. Some of the larger vessels bring small flat-bottom dories to reach into lagoons and onto reef flats to deploy gillnets (barrier nets) for capturing roving herbivores (parrotfish, surgeonfish) that are chased into the nets by fishers using snorkelling gear.

Sudan is the Red Sea country that utilizes its marine resources to the least degree [8] and compared to other countries bordering the main part of the Red Sea, Sudan has the lowest catch per km of coastline [6], governing some speculation that there may be room for expanding fisheries yields.

148 **1.1 Aims**

149 The project “Surveys of renewable marine resources in the Red Sea State” was
 150 implemented in the period from 2012 to 2013 [24] with the main aim to provide a
 151 baseline study of the available fish resources along the entire coast. Three monitoring
 152 surveys using different fishing methods were carried out, at two at different periods of
 153 the year, and in two subsequent years. Because institutional and technical capacity in
 154 Sudan was limited the projected opted to employ survey and monitoring methods that
 155 required as little technology and resources as possible while still gathering quality
 156 data. This approach thus excluded diver-based methods like UVC that requires
 157 extensive training, expensive equipment and costly maintenance of equipment.

158
 159 During each survey, conventional fishing methods such as gillnets and handlines were
 160 operated in conjunction with baited traps to sample the proportion of fish assemblages
 161 vulnerable to these fishing gear types, thus enabling comparison of the efficiencies of
 162 various fishing methods for monitoring fish assemblages in coral reef areas. The
 163 project also provided training opportunities for local scientists, managers and students
 164 in fisheries research and monitoring methods.

165
 166 Here, we report on the catch rates, species densities and functional diversity from trap,
 167 gillnet and handline catches obtained during three surveys conducted in November
 168 2012, May 2013 and November 2013 covering all seven management regions of the
 169 Sudanese coast (Figure 1). Here we document a baseline of the fisheries resources
 170 along the coast of Sudan and provide updated information on biodiversity hot spots,
 171 distribution and indices of relative abundance. The results provide valuable basic
 172 biological information on several Red Sea fish species that are currently unavailable

173 in the public domain (FishBase) [24], and are relevant with regards to the ecological
174 understanding of fish communities in the Red Sea

175 **2 Material and Methods**

176 The sampling scheme was stratified according to the seven established fisheries
177 management areas (Figure 1). The Sudanese coastal shelf is narrow, especially in the
178 north, before it drops off into the deep waters of the central Red Sea. Extensive
179 fringing near-shore coral reefs extend over much of the shelf area complicating both
180 navigation and anchoring, effectively restricting surveying to well-established sea-
181 ways during daytime, consequently producing a somewhat patchy sampling design
182 (Figure 2).

183

184 The surveys covered the coast from Egypt in the north to the border with Eritrea in the
185 south. Two vessels were used: the M/S ‘Don Questo’ (32 m LOA), a previously
186 British oceanographic research vessel currently equipped for liveaboard diving, was
187 used as base for measurement and sampling of the catch, accommodation and meals,
188 and a sheltered fiberglass vessel (10 m LOA) with an inboard engine was used to
189 deploy and retrieve traps and for oceanographic measurements.

190

191 The same locations were sampled on each cruise in the northern and central regions to
192 ensure comparability between surveys, producing similar geographical coverages
193 there (Figure 2). In the southernmost part of the study, however, challenging weather
194 conditions restricted the degree of coverage and in November 2013 the survey had to
195 be cut short due to technical delays. The reef at Habily Lory was only sampled in May
196 2013, while the reef location at Abu Marina was not sampled in November 2013

197

198 **2.1 Fishing gear**

199 In addition to the fishing gear used conventionally by Sudanese fishers (handlines and
200 gillnets), an alternative approach using collapsible baited fish traps was employed to
201 obtain samples from the coral reefs with minimum damage to coral colonies and to
202 target species with low catchability using the artisanal handline method.

203

204 Baited traps – The main fishing gear used were collapsible fishing traps baited with
205 sardines. The traps measured $150 \times 180 \times 80$ cm and were constructed from steel
206 frames with plastic coated square steel mesh with approximately 50 mm bar length.
207 The number of traps deployed at each reef area ranged from 5 to 14, depending on the
208 site-specific geography (topography and reef length) and weather conditions (wind
209 strength and wave heights) at the time when traps were deployed. The traps were
210 deployed at a mean depth of 21.5 m, but depth varied from 5 – 145 m between areas
211 and surveys (Figure 3). Mean set depth never exceeded 50 m, but deeper traps were
212 set in all areas except area 5 in November 2012, with the deepest traps set at 142 m in
213 area 1 in Nov. 2012 and at 145 m in area 2 in May 2013 (Table 1, Figure 3). Area 5
214 had the shallowest distribution of trap set depths (and for May 2013 and Nov. 2013
215 the shallowest mean trap set depth), consistent with this area being inshore of the
216 outermost reefs hence having a shallower average topography than the other
217 management areas. When using traps fish were caught alive and in good conditions,
218 thus any sharks, moray eels or other red-listed species were immediately released
219 upon retrieval of the gear. Whenever caught, species ID and approximate length was
220 noted prior to their release.

221

222

223 Gillnets – Pelagic gillnets were deployed at dusk and hauled at dawn, recording the
 224 exact time of setting and hauling. The nets were inspected hourly to release any
 225 sharks or turtles caught inadvertently, after the species, approximate length and catch
 226 position had been recorded. Turtles, however, were not identified or recorded in the
 227 data. Two types of pelagic gillnets were used at each site: two multi-monofilament
 228 gillnets of 28.0 m length and 10.5 m height with 89 mm mesh size (stretched), and
 229 one multifilament gillnet of 40.0 m length and 10.5 m height with 76 mm mesh size.
 230 The gillnets were anchored to the bottom at one end, with a float attached at both
 231 ends, and smaller floats running along the float line to ensure that it floated at the
 232 surface. Nets were deployed in channels between reefs, or in open waters inshore or
 233 off-shore of the reefs. At some particular shallow stations, the gillnets reached from
 234 the surface to the bottom.

235

236 Handlines – On some locations, during daytime, simple monofilament handlines with
 237 a single hook (size 5 – 6) and lead sinker were fitted with fresh bait (sardines) and
 238 fished by 2-3 fishermen. The fishermen were told to fish for a standard period of two
 239 hours and record the time they started and stopped fishing. However, this information
 240 was not well communicated, and for most locations the fishermen returned the next
 241 day with the catch but lacking records of how long they had been fishing. Therefore the
 242 actual duration of the fishing trials was uncertain and resulting catches could thus
 243 only be used for composition of the catch by gear type rather than catch rates as
 244 anticipated.

245

246 In total 760 stations were sampled during the three surveys (Table 1). The number of
247 gear units deployed increased during the second and third survey because the
248 participants had gained experience and worked more efficiently. Traps were the most
249 common gear with 674 sets. However, 25 % (220 traps) were empty when hauled,
250 compared to only 5 % of gillnet hauls being empty. Use of gillnets increased from 34
251 in the first survey to 137 in the November 2013 survey, while the use of handlines and
252 traps remained more constant (see Table 1).

253

254

255 **2.2 Biological measurements**

256 Upon gear retrieval fish caught were removed and placed in numbered plastic boxes
257 on the deck of the vessel where they asphyxiated, as is the normal practice in fisheries
258 operations throughout history as well as in modern fisheries research surveys. This is,
259 however, seldom specified in articles describing fisheries research surveys (see [26-
260 28] for examples).

261

262 The length-weight relationship for sharks and moray eels, which were released
263 immediately after capture, was estimated from published length-weight relationships
264 [25]. All other species caught were brought to the ‘Don Questo’ where they were
265 identified to species, and their total lengths and total wet weights were recorded.

266

267

268 **2.3 Calculation of catch-per-unit-effort**

269 Assuming that the catch coefficient remains constant, the catch-per-unit-effort
270 (CPUE) is proportional to abundance [6], although with caveats regarding
271 hyperstability (CPUE remains stable while abundance is declining) and

hyperdepletion (CPUE declines more than the actual decline in abundance) [29]. To facilitate relative comparisons between surveys and gear, CPUE for each species group were standardized as kg fish caught per hour of fishing.

The catch data contained many stations with no catch resulting in CPUE data being non-normal, and rather zero-inflated. Variabilities in CPUE's between areas, surveys and by depth were therefore evaluated using a zero-adjusted GAM model with depth, area, survey and gear as dependent factors, calculated using the "GAMLSS" package in R. Two models, including or excluding gear as a factor, were evaluated. As the AIC were comparable (-1080 and -1082) we chose to use the model including gear as a factor as this would yield information on the potential effect of gear on CPUE.

2.4 Species diversity and functional diversity

Species caught were classified according to the species traits of Stuart-Smith et al [30]: trophic group (carnivores, herbivores, corallivores, invertivores, planktivores), trophic level, maximum length, place in water column, diel activity, habitat and gregariousness. Following the methods of Stuart-Smith et al. [30], we evaluated species density and functional diversity to delineate biodiversity of the catchable component of coastal fishes along the Sudanese coast. Estimation of biodiversity measures were done using the catch data from traps only as neither the gillnets nor handlines covered all management areas during all surveys (see Table 1).

Species densities were calculated as the number of species caught at each station area per hour of fishing, and averaged by management area,. Variability in species density

296 between stations was evaluated using a zero-adjusted GAM model with depth, area
297 and survey as dependent factors, and calculated using the “GAMLSS” package in R.
298

299 The Rao’s Q functional group richness index was calculated using the ‘dbFD’
300 function in the ‘FD’ package in R using all species occurring in three or more traps
301 aggregated across all surveys applying ‘lingoes’ correction to achieve an Euclidian
302 species by species distance matrix. Dimensionality was limited to 10 PCoA axes to
303 avoid integer overload during calculations. The quality of the reduced vector space
304 representation of the traits, R^2 , was 0.42 with 10 PCoA axes, using all traits. To
305 evaluate the contribution of individual trait on the functional diversity the model was
306 rerun seven times excluding one trait at a time. As the R^2 was lower for all models
307 excluding a trait, except when excluding maximum length, when R^2 increased to
308 0.468, an increase of 0.047, the model excluding maximum length was adopted. This
309 observed increase in R^2 when excluding maximum length was likely caused by the
310 large spread in maximum length across the species caught, with few catches of
311 species with a maximum length > 200cm (mostly sharks, morays and large
312 Scombridea).

313
314

315 **2.5 Data management, statistical and GIS analysis**

316 All data from the surveys were entered into a NAN-SIS [31] database. The tropic
317 group of species in our samples was added to the catch data from a list of traits of
318 coral reef fish from [30], amended with information from FishBase [25] for the Red
319 Sea species not covered in the original species traits list. Detailed information on the
320 position, depth, date, and time, for all fishing stations and all three gear-types as well
321 as species-specific catch information was recorded in the data files (station.csv and

catch.csv) deposited on GitHub (<https://github.com/erikjsolsen/Sudan>). All plotting and statistical analysis was carried out using the R Statistical software package version 3.5.2 (Eggshell Igloo) [32]. The scripts used for all plots and analyses are also made available on GitHub.

3 Results

3.1 Catch composition by gear

The catch composition of the three fishing gears was markedly different (Figure 4, A), with the gillnets being the only gear catching species in the Chirocentridae family. Trap catches were dominated by Serranidae, Lutjanidae, Lethrinidae and ‘other species’. Gillnets were the most efficient gear towards Carangidae and Scombridae but caught relatively few Lutjanidae and Lethrinidae species that made up the majority of the handline and trap catches. Serranidae were rare in the handline catches, except in May 2013, contrasting the prevalence of larger bodied serranid groupers in the artisanal handline fishery. In terms of trophic groups (Figure 4, B), carnivores dominated the gillnet catches and was the most important trophic group in the trap catches. Invertivores constituted the second largest catch of the traps, while planktivores were the second largest catch of the gillnets. Hand-lines only caught carnivores and invertivores, of which the former dominated the catches.

3.2 Cath per unit effort (CPUE)

347 3.2.1 Effect of gear, survey, area and depth on CPUE.

348 Catch rates between management areas showed large variabilities (Figure 5).
 349 Evaluating the combined effects of gears, depth, management area and survey on the
 350 biomass CPUE in a zero-adjusted Gamma GAM model (AIC: 307, df:14,– see SI
 351 Table 1 for a full summary of model analysis) showed that all gear types, survey
 352 (November 2013), and area (areas 1, 5, 6 and 7) had a significant effect, while depth
 353 did not have a significant effect on catch rates. Area 2 had the highest recorded CPUE
 354 in all three surveys, while area 3 had the highest average CPUE in Nov. 2012, area 6
 355 in May 2013 and area 6 in Nov. 2013 (Table 2). Relative difference in catches of the
 356 different family groups varied between the surveys (see Figure 4).

357

358

359 3.2.2 Trophic group composition of catches for traps

360 The trap catches (Figure 6) were dominated by the carnivores in all areas during all
 361 surveys, except during the Nov. 2012 survey for area 3 where the invertivores had
 362 higher CPUE. Corallivores were only caught during the Nov. 2012 survey in areas 2
 363 and 6, while herbivores were caught in all surveys, with the highest catch rates in area
 364 2 and 6. Invertivores had the second highest catch rates, present in all surveys, but
 365 with highest CPUE in the Nov. 2012 and May 2013 surveys. Planktivores were
 366 caught at very low CPUE in area 7 during the Nov. 2012 survey, but in May 2013
 367 they were also caught (at low CPUE rates) in areas 2, 3, and 5 (but not in area 7),
 368 while in Nov. 2013 they had the second highest catch rate in area 2 (after the
 369 carnivores) and were also caught in areas 5 and 6.

370

371 3.2.3 CPUE of trophic groups by depth for traps

372 Carnivores and invertivores were caught in traps at 0-100 m depth in all management
373 areas (with some few carnivores caught even deeper, with the highest CPUE, kg/hrs,
374 shallower than 50 m depth (Figure 7). Herbivores had a more restricted range, with no
375 catches made deeper than 65 m bottom depth. There were only two catches of
376 corallivores, the threadfin butterflyfish *Chaetodon auriga*, one in area 2 at 55 m depth
377 and the other in area 6 at 17 m bottom depth. Planktivores were generally caught near
378 the surface, shallower than 25 m, except for one catch of *Paracaesio sordius*
379 (Lutjanidae) in area 7 at 66 m bottom depth(Figure 7).

380

381 3.2.4 Trophic level of trap catches

382 The mean trophic level in the catches was 3.84, with averages per area and survey
383 ranging from 3.20 (area 3, Nov. 2013 survey) to 3.97 (area 3, May 2013 survey)
384 (Figure 8), although when averaged across surveys the range in trophic level
385 narrowed to 3.76 in area 6 to 3.83 in area 1 (Table 2). Trophic level per area and
386 survey was dependent on balance in occurrence between trophic groups as the
387 carnivores have a higher trophic level than the invertivores, the two most common
388 trophic groups in the trap catches.

389

390 3.2.5 Other functional traits of the trap catches: placement in the water column, 391 gregariousness and diel activity

392 The majority of the trap catches were of species classified as demersal, which were
393 caught in all areas and during all surveys. These were dominating the catches except
394 in area 3 during survey 2 where benthic species were most common (Figure 9).
395 During the November 2013 survey there was no station with catches other than
396 demersal fish, while both benthic and pelagic species were caught in the other two

surveys, benthic fish being the second most common group after the demersals. The most dominant family groups of demersals were the Lutjanidae (mainly *Lutjanus bohar* and *L. gibbus*) and Lethrinidae (mainly *Lethrinus lentjan* and *L. mahsena*), while the benthic group was dominated by the moray eel *Gymnothorax javanicus*. Carangidae (most common species being *Carangoides bajad*) and Scombridae (most common species *Scomberoides lysan*) were the two most common families in the “Non-site attached pelagic” group.

Day-active fish dominated the catches in all areas and surveys. Night active fish were hardly caught during the November 2013 survey, but were prevalent in the November 2012 survey particularly in area 3 (SI Figure 1).

Solitary fish (gregarious level 1) were the most common in the trap catches, except in areas 6 and 7 during the May and November 2013 surveys and in area 4 during the November 2012 survey where species of gregarious level 2 were most abundant. Species of gregarious level 3 were caught in the November 2012 and May 2013, and only in areas 2, 3, 5 and 7, but not at all during the November 2013 survey (SI Figure 2).

3.3 Species density

The highest number of species was observed in area 2 (36), followed by area 3, 6 and 7 (25 in each). Species density (number of species per hour of fishing - soak time of traps) ranged from 0.008 (areas 1, 2 and 6) to 0.019 (area 4) (Table 2). Area 4 had the highest species density across all surveys, while the area with the lowest species density varied by survey: area 1 in November 2012, area 7 in May 2013, and area 2

423 in November 2013 (Figure 10). The variability and relative difference in rank of
 424 species diversity per area was confirmed by the zero-adjusted GAM model (AIC: -
 425 4161, df: 12), where all surveys were significant factors in the model. In addition, area
 426 1, 2, 3 and 4 were also significant factors affecting species density, while the non-
 427 significant factors were depth, and areas 5, 6 and 7 (see SI Table 2 for details).

428

429

430 **3.4 Functional diversity**

431 The Rao's Q functional group richness index estimated using the functional diversity
 432 model excluding the 'max length' trait was highest (0.102) in area 2 and lowest
 433 (0.050) in area 6 (Table 2). The second-highest Rao's Q index was found in area 5
 434 (0.085). This was similar to the Rao's Q index calculated from the model including all
 435 traits were area 2 had the highest and area 6 the lowest Rao's Q index.

436

437 **4 Discussion**

438 The three surveys conducted in 2012 and 2013 constitute the first baseline monitoring
 439 of harvested fish along the Sudanese Red Sea coast. The first survey in November
 440 2012 was essentially a pilot survey testing the efficiencies, and performance of
 441 various fishing gear in this region. There were significant statistical differences in
 442 both catch rates, species diversity and functional diversity between the three surveys,
 443 with the November 2013 survey being most limited, both in terms of sampling
 444 intensity and geographic coverage in the southern region (Table 1) and sampling
 445 density in area 3 compared to the previous two surveys (Figure 2).

446

447 Our sampling aimed at covering representative reefs along the entire coast at varied
 448 depths. As the species composition of coral reefs is known to be depth-stratified we
 449 intended to use gillnets to sample the surface layer, and traps and handlines to sample
 450 from the surface to 200 m. However, sampling was effectively limited by bottom
 451 conditions, e.g., ledges, and avoiding entanglement in corals. This proved challenging
 452 as the seaward side of the reefs typically had steep drop-offs to depths, often
 453 exceeding 200 m, while the areas between reefs or towards shore typically had depths
 454 of less than 100 m. Consequently, few traps were set at depths deeper than 75 m
 455 (Figure 3). Nevertheless, we achieved a reasonably comparable coverage of depths in
 456 all management areas, except for in area 5 (all surveys) and area 4 (Nov. 2012 survey)
 457 (Figure 3), thus avoiding biasing our analysis of catch rates and species diversity by
 458 differences in depth. This is further confirmed by the GAM models of CPUE and
 459 species density (S1 Table 2) where depth was not found to have a significant effect on
 460 neither CPUE nor species density.

461

462 The present analysis took a practical fisheries approach on catch per unit effort,
 463 species densities and functional diversity, focussing on the differences between the
 464 seven fisheries management areas rather than biogeographic approaches evaluating
 465 effects of distance to shore used in studies of Saudi Arabian reefs [7,20].

466

467 Our results confirmed the presence of species already known to inhabit the Sudanese
 468 coast, although the methods used inevitably selected catchable fish above certain sizes
 469 and particular species due to the selective properties of the fishing gear, i.e. mesh
 470 selectivity (escapement, gilling, entanglement), hooks (minimum and maximum target
 471 sizes) and bait (species- and size dependent preferences and behaviour). With trap

stations constituting 89% of our stations across all three surveys, it was unsurprising that the major trophic group caught were carnivores (Figure 6) as these were the species most likely to be attracted to bait. Our trap-based method was thus sub-optimal to survey herbivorous fish species such as parrotfish and most surgeonfish, and fish closely associated with coral reef habitats were most likely considerably underestimated in the catches. For such species, underwater visual census (UVC) methods, or baited remote under-water video (BRUVs) remain the only current alternatives, albeit outside the scope of this study. However, for certain vagile species such as snappers (Lutjanidae), emperors (Lethrinidae) and Scombridae the use of baited traps proved appropriate, filling a gap where handlines and gillnets were proven inefficient (see Figure 4).

The differences in catch composition compared to the artisanal fishery that targets reef-dwelling species like groupers was apparent [23], with snappers (Lutjanidae) dominating the trap catches (Figure 4). This illustrates a potential for development of fisheries targeting the snappers, emperors and other species roaming between reefs by changing the current artisanal fishery to other gear types like traps and fishing locations. Similarly, our gillnet catches caught a markedly different species composition than handline and traps, that were more similar (Figure 4). For Serranidae, Scombridae, Lutjanidae and Lethrinidae, the differences between gillnet, traps and handlines were particularly apparent. Serranidae, the family containing the most sought-after target species in the artisanal fishery, was only somewhat prevalent in handline catches from the May 2013 survey (Figure 4). This coincides with the spawning season of the commercially important *Plectropomus* spp. [18, 34], and related species. That the presence of Serranidae in handline catches is almost

exclusive to this survey is likely due to increased vulnerability to harvesting in the time of spawning and -aggregation. Some species of Scombridae were only caught by gillnet which was also the most efficient gear for capturing carangids. Some Lutjanidae (e.g. *Lutjanus bohar*) were, however, caught on both gillnets, traps as well as handlines. This is to be expected given that gillnets mostly fished the upper part of the water column, while traps and handlines fished at or near the bottom, the two gears thus targeting different habitats. Similarly, from a trophic perspective this makes sense as planktivorous fish typically are pelagic, as is seen from our trap catches where planktivores were only caught in traps set shallower than 65m bottom depth (Figure 7), although it was initially surprising that planktivores were indeed caught in baited traps. The multi-gear approach was indeed chosen precisely for this reason – to sample and investigate different depth habitats of the same reef ecosystem.

509

510 **4.1 Catch-per-unit-effort**

CPUE varied significantly by gear, area and survey, but not by depth (Table 2, and S1 Table 1). The depth ranges of our stations fished were limited, with most traps set shallower than 50 m bottom depth, which probably explains why depth was not a significant factor in the model. Gillnet CPUE was higher than that of traps in all areas, and higher in the northernmost areas (1 and 2) compared to the southernmost areas (6 and 7), also with a higher standard deviation (0.482 vs 0.033). This indicated a possible higher abundance of pelagic fish along the northern part of the coast, compared to the south.

519

Our findings of the lowest trap CPUE in the Port Sudan and Suakin areas (4 and 5) are similar to Klaus et al. [12] who also found the lowest fish abundance in the Suakin

522 area. The Dungonab area (2) had the highest CPUE for traps in addition to the highest
523 diversity of trophic groups in the catches (Figure 6) and the highest functional
524 diversity (Rao's Q index - see Table 2), indicating that this is the most productive
525 region north of Port Sudan. It is also the area to the north with the widest shelf and
526 largest shallow-water region, also bordering on the very shallow Dungonab Bay with
527 relatively higher salinity [24]. The Dungonab Bay is a designated marine protected
528 area covering most of management area 2, granting access to local fishers only,
529 probably reducing fishing pressure in this area. However, several previously known
530 spawning aggregations for *Plectropomus* spp. in this area are considered lost due to
531 fishing [34]. Area 3, just south of Dungonab bay, had the second-highest trap CPUE
532 (0.136) and functional diversity (Rao's Q = 0.074) pointing to a possible ecological
533 linkage of fish communities between these two areas.

534 The two southernmost areas had higher trap CPUE than the Suakin and Port Sudan
535 areas (4 and 5), although lower than in the northernmost areas, corroborating Kattan
536 et al. [8] who found a positive relationship between top predator biomass and distance
537 to the nearest port. Kattan et al. [8] hypothesized that fishing pressure diminishes with
538 distance to port as fishermen prefer close and more near-shore reefs over more distant
539 off-shore reef areas. However, these results are not consistent, exemplified by the
540 high CPUE estimated for Dungonab (area 2). This may, however, be explained by the
541 higher level of protection and management in this area compared to other inshore
542 areas. Nevertheless, our results, taken together with the results of Klaus et al. [12]
543 and Kattan et al. [8], do indicate that the local artisanal fisheries have impacts on local
544 fish stocks.

545

In contrast to Klaus et al. [12], who noted the absence of large snappers, groupers and emperors in the UVCs conducted, the present surveys found these species in abundance (although large individuals were relatively rare). This can be explained by the more extensive geographic coverage, the greater depth of the sampling gear compared to UVC depths, and larger number of sampling stations in our study than in the Klaus et al. [12] study. It can also be explained by the difference in catchability of fishing gear compared to the UVC survey employed by Klaus et al. [12]. Snappers and emperors, and to a lesser degree groupers, showed a roving behaviour between reefs when observed during dives and snorkelling, often keeping a distance from divers (personal observations), similar to what Colton and Swearer [35] observed for mobile predators, possibly making them less available in UVC transect paths. These species were, however, attracted to baited traps, explaining their common occurrence in catches in the present study.

559

4.2 Species density and functional diversity

There were differences in species densities between the seven management areas (Table 2). The highest densities was found in area 4 (Port Sudan), which also was significantly different from all other areas. The species density results are thus in contrast with Kattan et al.'s [8] findings of relatively higher biodiversity in remote areas of the coast. Our present analysis was limited by the low number of stations in several areas and surveys, in particular area 4. When evaluating the functional diversity, a different picture emerges. Area 2 had the highest Rao's Q value of all the areas (0.102), while area 4 had a lower Rao's Q of 0.063 in the model excluding the maximum length trait. If maximum length was included in the model area 4 had the lowest Rao's Q value of all areas. Functional diversity (Rao's Q) was calculated

571 using CPUE as the abundance data, thereby weighing the species occurrence not just
572 on hours fishing, but also by the catch weight, contrasting species densities where the
573 species occurrence were weighted only by the fishing time. Since the CPUE in area 2
574 on average was higher than in area 4, except during the November 2013 survey
575 (Figure 5), this is the most likely explanation of the discrepancies between the species
576 densities and functional diversity. Stuart-Smith et al [30] argues that since the
577 ecological effects of a species generally are proportional to its abundance, abundance-
578 weighted functional diversity (e.g. Rao's Q) more accurately reflects the functional
579 structure of a community than diversity metrics based on simple counts or species
580 inventories. We therefore placed higher emphasis on the Rao's Q indices in the
581 present analysis than on species density. The higher Rao's Q in the Dunognab area
582 (area 2) and the low Rao's Q in area 4 indicate that the protected Dungonab bay area
583 has a higher functional biodiversity than the Port Sudan area (area 4) which is the
584 most heavily impacted by human activities along the Sudanese coast.

585
586 The lack of clear gradients in species distribution or geographically unique species
587 indicates that the species caught in our sampling gear have fairly uniform distributions
588 along the Sudanese coast. This could be expected given the lack of species gradients
589 observed elsewhere in the Red Sea [3,7]. It is inevitable that the capture-based
590 methodologies employed to cover the entire coast during surveys has resulted in
591 missing locally rare or endemic species. There are other issues pertaining to gillnet
592 and trap fishing in coral reef areas that make them less desirable from a biodiversity
593 and fisheries conservation science perspective, such as ghost nets/traps, and bycatch
594 of illegal and/ or vulnerable species (e.g., sharks). Selective passive gears, like traps
595 can, however, be employed with less environmental impact or bycatch of threatened

596 elasmobranch species than pelagic gillnets or long-lines, while traps without bio-
597 degradable openings may cause ghost fishing if lost.
598
599 Klaus et al. [12] identified the 70 km coastal region between Port Sudan and Suakin
600 as being the most heavily affected by coastal and harbour developments and
601 contended the notion that this had affected the reefs in this area. This is further
602 corroborated by Kattan et al. [8], who found that biomass and species richness
603 decreased with distance from the main port of Port Sudan. However, distance to Port
604 Sudan is a misleading measure of the distance fishers have to travel to catch fish as
605 they operate out of numerous landing sites all along the coast. A better measure of
606 distance to fishing areas would be to measure the distance of the actual fishing trips
607 from the local landing sites. However, our results did show low species density and
608 functional diversity (Rao's Q), and a lack of herbivores and planktivores in the Port
609 Sudan management area and in the Arakia area just to the north, supporting the
610 hypothesis that increased urban development and proximity to population centres
611 have resulted in a mining out of catchable fish biomass and reduced the productivity
612 of reefs. In management area 3 and 4 the higher human populations and number of
613 fishermen based in these regions have likely increased fishing pressures more than in
614 other areas, thus representing two highly likely factors in explaining the low species
615 diversity and lower catch rates in these regions.

616

617

618

4.3 Recommendations

Whether traps are more appropriate than visual census methods, which may underestimate species that actively avoid divers doing the census [35, 36], or are reluctant to approach a baited camera rig during the relatively short recording time, remains to be properly tested for species typically targeted by Sudan's artisanal coral reef fishery. In a study comparing the relative efficiency of commercial fish traps and BRUVs in sampling tropical demersal fishes in Western Australia, Harvey et al. [37] found that BRUVs had greater statistical power to detect changes in abundance than an equivalent number of traps. Among five commercially important Indo-Pacific species (*Epinephelus bilobatus*, *Epinephelus multinotatus*, *Lethrinus punctulatus*, *Lutjanus russelli* and *Lutjanus sebae*) only emperor red snapper (*L. sebae*) was more efficiently sampled with commercial traps. However, a monitoring system based on traps requires lower skill levels and less infrastructure than UVC- and BRUV methodology, and most species will survive capture and subsequent release if a non-extractive approach to monitoring is desired. Traps also have their drawbacks in being bulky, requiring a winch to haul and will involve more sea time if soaked overnight. Evaluating such practical constraints is essential when planning and designing fish monitoring programs in least developed countries with poor institutional capacities and limited resources like Sudan. Still, our results show the merit of a multi-methods approach to monitoring in a complex coral reef ecosystem area like the Red Sea.

4.4 Conclusions

We here present the first baseline survey of the fisheries resources along the Sudanese Red Sea coast, providing novel insights into the distributions, catch rates, species densities and functional diversities of fish communities along the Sudanese coast,

644 supplementing the rather scant biogeographic information available on fish species in
645 this area

646

647 Our results demonstrate differences in CPUE, highlighting the Dungonab Bay area as
648 a hot spot. The methods used do, however, not provide a full census of all fish species
649 in the areas and the surveys did not cover all habitats. The methods presented should
650 therefore be further developed and complemented with visual census-based methods
651 to cover the full diversity, and include all functional groups. Such a complementary
652 approach may yield further improved assessment of the fish distribution, abundance
653 and species richness in the highly complex coral-reef environment of the Sudanese
654 coast.

655

656 The observed species densities, functional diversity and catch rates demonstrate clear
657 local (Figure 8) and seasonal variabilities (Figure 6), as well differences in CPUE
658 between management regions that can be hypothesised to be caused by varying
659 degrees of human impacts along the coast of Sudan. With an increasing human
660 population, increasing coastal development and a push to expand and increase
661 fisheries, sustainable and ecosystem-based management plans should be developed,
662 implemented and enforced to avoid overfishing, habitat destruction and the associated
663 negative socioeconomic impact on the poor and fragile fishing communities along the
664 coasts of the Red Sea. The present study provides a first baseline to use as foundation
665 for developing such plans.

666

667 **5 Acknowledgements**

668 We wish to acknowledge the support from the Sudanese partner institutions: The
669 Marine Fisheries Administration, The Fisheries Research Institute and the University
670 of the Red Sea State – Faculty of Marine Science. Asbjørn Aasen of the IMR is
671 thanked for designing and building the collapsible traps used in these surveys. The
672 scientific and technical crew on the ‘Don Questo’ are thanked for their dedicated
673 work with sample collection. Rick Stuart Smith is thanked for providing a table of
674 biological traits for coral reef fish species. Funding was provided by the Norwegian
675 Government through the Embassy in Khartoum, and the project was administrated by
676 UNIDO.

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787 **7 Tables**

788 Table 1 Number of gear deployed (fishing stations) in the seven management areas, total fishing time in each management area for each survey, and
 789 minimum, mean and maximum fishing depth for traps for each area and survey. Surveys were carried out in the coastal areas of Sudan in November 2012,
 790 May 2013 and November 2013

Survey	Mgmt. Area	Number of stations (gears set)			Hours fishing			Fishing Depth		
		Traps	Handlines	Gillnets	Traps	Handlines	Gillnets	Average	Maximum	Minimum
Nov. 2012	1	22	0	0	694	0	0	42	142	13
	2	54	3	3	722	78	62	41	71	0
	3	26	0	1	451	0	14	31	95	8
	4	5	0	0	77	0	0	23	54	10
	5	31	0	4	678	0	78	21	30	7
	6	36	0	1	850	0	38	32	88	0
	7	31	0	8	712	0	136	31	66	5
	Sum	205	3	17	4184	78	328			
	W.catch	109	3	12						
May 2013	1	29	0	1	420	0	24	31	70	5
	2	81	3	5	1102	378	222	27	145	5
	3	32	0	1	546	0	24	29	60	0
	4	13	0	10	160	0	138	30	67	9
	5	33	2	5	209	192	196	20	50	7
	6	45	1	2	642	156	78	35	88	9
	7	39	2	0	666	186	0	33	76	5
	Sum	272	8	24	3746	912	681			
	W.catch	141	8	16						
Nov. 2013	1	23	1	4	272	3	84	30	80	10
	2	57	2	6	500	111	156	38	80	7
	3	9	0	2	123	0	36	27	70	9
	4	16	2	4	151	5	143	33	68	12
	5	30	2	3	317	7	147	26	65	11
	6	40	4	2	444	32	72	40	89	6
	7	22	0	2	172	0	203	35	54	11
	Sum	197	11	23	1979	157	841			
	W.catch	62	9	23						

792
793
794 Table 2 Mean CPUE (kg per hours of fishing), mean trophic level and gregariousness
795 of traps and gillnets. Species density (no species in traps per hour of fishing) and the
796 functional group richness of trap catches (Rao's Q) for each of the seven management
797 areas along the Sudanese Red Sea Coast.

Mgmt. Area	CPUE (kg/hrs)		Trophic level		Gregariousness		Species Density (traps)	Rao's Q (traps)
	Traps	Gillnets	Traps	Gillnets	Traps	Gillnets		
1	0,12	1,64	3,83	3,93	1,51	2,41	1,07	0,051
2	0,15	1,18	3,82	3,89	1,48	2,26	2,20	0,079
3	0,14	0,31	3,84	4,14	1,55	2,50	1,44	0,074
4	0,06	0,70	3,77	4,28	1,36	2,11	0,71	0,048
5	0,08	0,73	3,80	3,85	1,63	2,18	1,12	0,073
6	0,14	0,27	3,76	3,93	1,53	2,29	1,39	0,048
7	0,10	0,68	3,83	3,61	1,57	1,90	1,45	0,064

798

799

800

801

802 **8 Figure legends**

803

804 Figure 1. The Republic of the Sudan Red Sea coast, with coral reef areas

805 (aquamarine) and the names and spatial extent of seven fisheries management areas

806 (black polygons) shown.

807

808 Figure 2. Map showing all survey stations sampled from 2012 – 2013 overlaid the

809 seven fisheries management areas. PZU: the city of Port Sudan.

810

811 Figure 3. Violin plots of the depths at which traps were set during the three surveys

812 (Nov. 2012, May 2013 and Nov. 2013) in each of the seven management areas (see.

813 Figure 1). The width of the violins are scaled to the relative number of traps set at

814 each depth. Horizontal line in each violin plot marks the mean depth.

815

816 Figure 4. Total catches (kg) for the three fishing gear types: Gillnet (GN), Handline

817 (HL) and Traps (TB), for each of the three surveys (Nov. 2012, May 2013 and Nov.

818 2013 split according to: (A) main fish families, and (B) trophic group

819

820

821 Figure 5. Violin plots of catch rates (kg per hour fishing) for traps in each of the seven

822 management areas and each of the three surveys. The width of the plots are scaled to

823 the relative frequencies of catches with that catch rate.

824

825

826 Figure 6. Cumulative catch rates (kg per hour of fishing) of carnivores (Carni),
827 corallivores (Coral.), herbivores (Herb.), invertivores (Invert.) and planktivorous
828 (Plankt.) fish, per trap for each management area and survey by the trophic groups:
829 carnivores, corallivores, herbivores, invertivores and planktivores.

830

831 Figure 7. Catch per unit effort (kg/hrs fishing) of carnivores (carni), corallivores
832 (Coral.), herbivores (Herb.), invertivores (Invert.) and planktivorous (Plankt.) fish,
833 versus depth for traps set during the three surveys (Nov. 2012, May 2013 and Nov.
834 2013) in each of the seven management areas (see. Figure 1).

835

836 Figure 8. Catch per unit effort (kg per hour of fishing) versus trophic level for traps by
837 each management area and survey, with the trophic groups: carnivores (Carni.),
838 corallivores (Coral.), herbivores (Herb.), invertivores (Invert.) and planktivores
839 (Plankt.) given different coloured symbols. Black vertical line shows the mean trophic
840 level of the trap catches in each respective area and survey panel-plot.

841

842 Figure 9 Cumulative catch rates (kg per hour of fishing) per trap for each management
843 area and survey by the species place in the water column: benthic, demersal, pelagic
844 non-site attached, and pelagic site attached

845

846 Figure 10 Average species densities for each of the seven management areas (number
847 of species in trap per hour of fishing), by the three surveys.

848

Survey 1: Nov. 2012

Survey 2: May 2013

Survey 3: Nov. 2013

A **B**

CPUE (kg/hrs fishing) / number of traps pr area

Place in water column

- benthic
- demersal
- pelagic non-site attached
- pelagic site attached