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Global evaluation of shark sanctuaries

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ABSTRACT

Due to well-documented declines in many shark populations there is increasing pressure to implement new management and rebuilding strategies at the national and international scale. Since 2009, fifteen coastal countries in the Atlantic, Indian and Pacific Oceans have opted to ban commercial shark fishing altogether, and have laws that prohibit the possession, trade or sale of sharks and shark products. These 'shark sanctuaries' collectively cover > 3% of the world's oceans, a similar coverage as all currently established marine protected areas combined. Despite their prominence, and an intense scientific debate about their usefulness, the condition of shark sanctuaries has not yet been empirically evaluated. Here, we report results from a global diver survey used to set baselines of shark populations, human use patterns, public awareness and threats in all 15 shark sanctuaries, and contrasted with observations from 23 non-sanctuary countries. Specific results varied by country, but there were some general trends: i) shark sanctuaries showed less pronounced shark population declines, fewer observations of sharks being sold on markets, and lower overall fishing threats compared to non-shark sanctuaries, ii) bycatch, ghost gear, marine debris and habitat destruction are significant threats that are often not addressed by sanctuary regulations and need to be resolved in other ways, and iii) participants in sanctuaries were more optimistic about the survival of shark populations in local waters, but also highlighted the need for further conservation efforts. These results suggest that shark sanctuaries, as seen through the lens of local experts, may be a helpful conservation tool but likely not sufficient in isolation. There is an urgent need for higher-resolution data on shark abundance, incidental catch, and markets to direct priority conservation needs and optimize the conservation benefits of existing and future shark sanctuaries.

1. Introduction

Around the world, targeted fisheries and bycatch have reduced numerous shark populations to a fraction of their unfished abundance (Dulvy et al., 2014, 2008; Oliver et al., 2015), and rendered nearly one third of species vulnerable to extinction (Dulvy et al., 2014). Despite growing awareness and concern, shark mortality rates may still exceed reproductive rates in many regions (Worm et al., 2013). In addition, the threats of illegal, unreported and unregulated fishing (IUU) represent significant regional management challenges (Agnew et al., 2009; Clarke et al., 2006; Worm et al., 2013).

Recognizing these threats to sharks, as well as the growing value of non-extractive uses (Cisneros-Montemayor et al., 2013; Gallagher and Hammerschlag, 2011), has led some coastal countries to implement laws that ban shark fishing within their entire economic exclusive zones (EEZ) and prohibit the possession, sale, or trade of sharks or shark parts, with some limited exceptions for local consumption (Ward-Paige, 2017). At the time of writing, fifteen countries had declared their EEZ as so-called shark sanctuaries. The primary goals (where stated) are to protect and, where necessary, recover shark populations nationwide by reducing fishing mortality to near zero, and to eliminate the local contribution to the global supply chain of shark products (Ward-Paige, 2017).

With the first national shark sanctuary being declared in 2009 by Palau, and 14 other countries following suit, the total area covered by shark sanctuaries now exceeds 3% of the world's oceans (Ward-Paige, 2017) – similar to the total coverage of marine protected areas worldwide (Lubchenco and Grorud-Colvert, 2015). The majority of this coverage is in Oceania, followed by the Caribbean and the Indian Ocean (Maldives) (Fig. 1). A summary of existing shark sanctuary regulations (Ward-Paige, 2017) shows that countries that have implemented shark sanctuaries are diverse in terms of socio-economic factors, but marine tourism is an important industry for most; sharks are explicitly defined by only six countries, while some also include rays under full protection details of protective measures vary among countries where, for example, it may be "illegal to catch, keep in captivity, trade, or harm any

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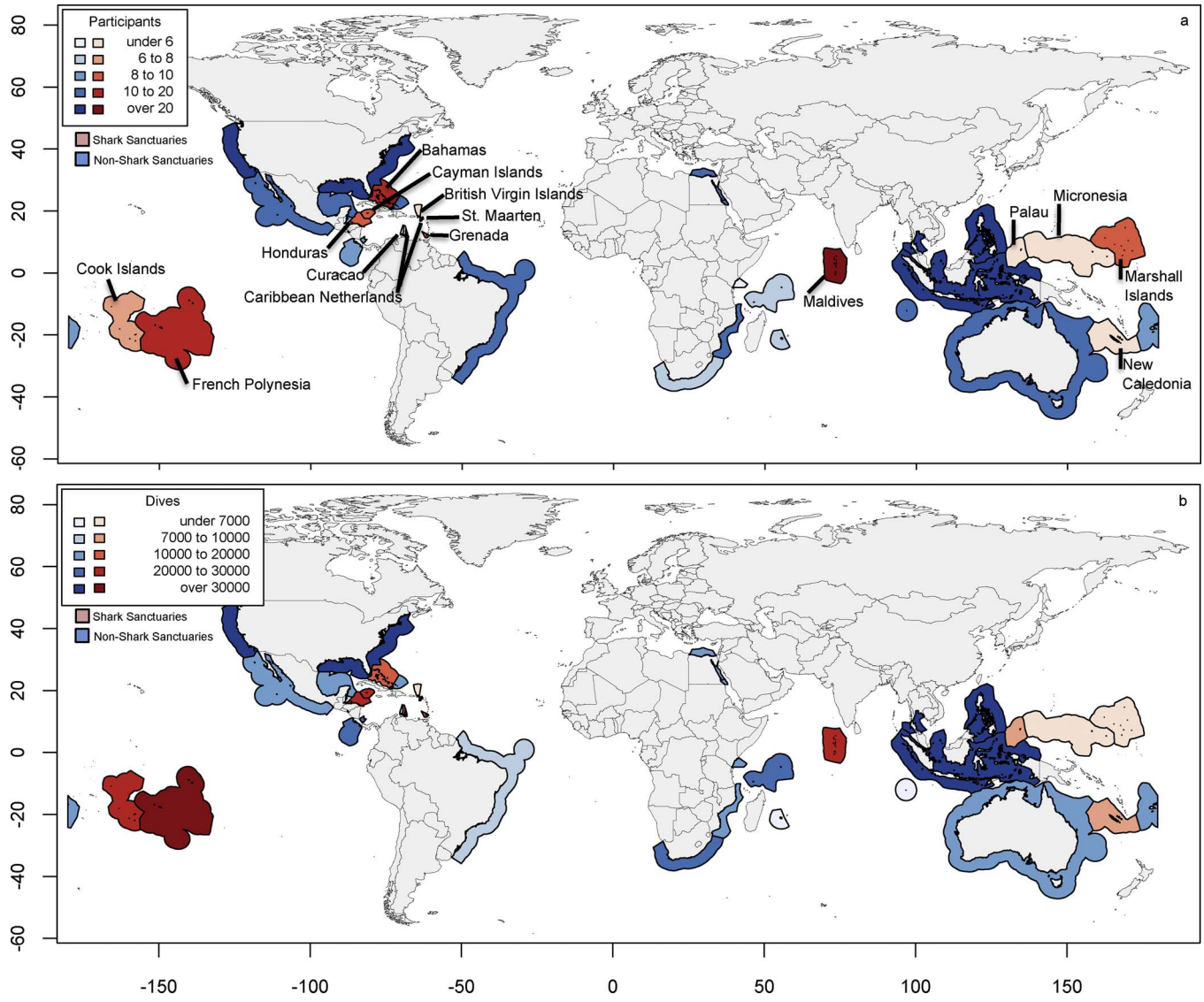

Fig. 1. Diver observation effort by country. Effort in number of participants (a) and number of dives (b) in shark sanctuaries (red) and non-shark sanctuaries (blue). Note: Since the time of writing, Curaçao and Grenada appear to have delayed implementing shark sanctuary laws, and Kirbati has moved to implement shark sanctuary laws. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the animals", but the possession of imported sharks or shark parts is not explicitly prohibited; however, bycatch, an important source of shark mortality (Oliver et al., 2015; Worm et al., 2013), is treated fairly consistent across all regulations where all caught sharks are required to be returned to sea regardless of being dead or alive (See additional information and details of shark sanctuary legislation in Ward-Paige, 2017).

Sanctuaries that aim to protect all shark species of all age classes, should, in theory, promote population protection and recovery. However, the success of a sanctuary in rebuilding shark populations may be complicated by the catch of sharks that travel outside of the sanctuaries, by illegal catch or bycatch inside the sanctuary (Chapman et al., 2013; Davidson, 2012), and by other threats such as marine debris, or the degradation of essential habitat like nurseries. The effectiveness of shark sanctuaries has also been questioned more generally, as they may divert attention from other conservation and fishery management efforts, and because insufficient enforcement could enable further overexploitation (Davidson, 2012; Dulvy, 2013).

Despite these possible barriers, the recent momentum towards implementing shark sanctuaries suggests public and governmental support for this conservation strategy, and hence, a need to evaluate their effectiveness. Yet, for most shark sanctuaries there is a lack of baseline data that can be used to evaluate the success of the sanctuary in protecting and rebuilding shark populations. Compounding this is the fact that a complete ban on catch and bycatch removes the possibility of fisheries-dependent data collection and monitoring. Therefore, acquiring a fisheries-independent snapshot of shark population status, trends, and human use patterns inside sanctuaries is an important first step in assessing the potential value of shark sanctuaries for conservation.

The thousands of resource users, who regularly explore the marine environment making qualitative observations on a daily basis, present an opportunity for comprehensive data collection (Nadon et al., 2012; Topelko and Dearden, 2005; Ward-Paige and Lotze, 2011). With very few exceptions, the majority of these observations remain undocumented and unused. However, when observations are collated and standardized, they can be used to define important biological trends and human use patterns; this has been shown repeatedly in particular for recreational divers (Nadon et al., 2012; Topelko and Dearden, 2005; Ward-Paige et al., 2013, 2010a,b; Ward-Paige and Lotze, 2011). Here we report results from a diver-based 'Global Marine Conservation Assessment' survey, via the eOceans.org platform, that was conducted in

countries declared as shark sanctuaries since 2009, as well as 23 non-sanctuary EEZs, to determine if (1) sharks are detected by divers frequently enough to establish contemporary baselines of shark populations and their threats, (2) to describe human use patterns for sharks inside and outside of shark sanctuaries, (3) to quantify the level of knowledge and support regarding shark sanctuaries.

2. Methods

2.1. Data collection

Building on a model employed in previous work on manta rays, where divers around the world were queried about manta rays observed on dives, being harvested, and sold in markets (Ward-Paige et al., 2013), a standardized questionnaire was developed as part of a larger marine citizen science initiative, eOceans (www.eoceans.org). Before release, the questionnaire was first tested by 15 divers in different regions, who were then queried for more details to ensure the questions were clear and responses were relevant. Then, the survey was delivered to ocean explorers (divers, fishers, surfers, etc.) around the world. All coastal countries were targeted, with shark sanctuaries considered a priority. The goal was to obtain as many responses as possible from each country. The questionnaire covered three main topics (Table 1): Part A, collected demographic information on the area surveyed, level of diver experience, and general observations of shark-related tourism, markets, and fisheries; Part B, detailed observations on the number of sharks observed underwater; Part C, queried observer awareness of local conservation and management measures (Table 1). Because some shark species are difficult to identify, three techniques were used to improve reporting and detection of errors: i) a global species list was provided for selection, ii) an "unknown species" selection was provided to avoid guessing, and iii) follow-up queries were made with individuals reporting outliers. The questionnaire was disseminated by direct emails to colleagues, dive shops and divers using the contact list of previous participants of eOceans projects (e.g., eManta), social media (Twitter and Facebook), posted on online community boards (ScubaBoard), and via other organizations with large numbers of interested followers (e.g., Mission Blue, X-ray magazine, see Acknowledgements below). Some on-the-ground volunteers also took physical copies of the questionnaire to experts in Indonesia, the Philippines and Thailand. The survey opened November 2015 and closed August 2016. Participants who started but did not complete the questionnaire (n = 98) were queried directly about missing answers. All that responded stated that either their internet connection had broken down or they felt they were not experienced enough to contribute; 21 subsequently filled out the questionnaire in its entirety.

2.2. Data treatment and analysis

All surveys with at least parts A and B (Table 1) completed were retained. Surveys were carefully quality-checked for inconsistencies and obvious data entry errors, such as through verification of reported species versus known distributions, inconsistencies between the number of sites visited and the number of sites with sharks (the later should be lower), or for errors in the amount of effort given the timeline diving (e.g., number of dives is possible given the timeline). As such, one record was excluded because the participant submitted for two areas simultaneously (the Mesoamerican Reef and the Red Sea). One record was removed because it featured several species that are not known to occur in the area. In four cases the species needed to be corrected (e.g., two "blacktip" were "blacktip reef", and two "nurse" were "tawny nurse"). All shark sanctuary countries were included for analyses, regardless of effort, and non-shark sanctuary countries with low effort (i.e., < 5 expert surveys) were excluded (i.e., 94 surveys from 48 countries or regions). Because the majority (95%) of participants reported scuba diving as their primary or secondary ocean activity, non-scuba divers (n = 34) were excluded to standardize observation platforms. The final dataset had 438 records from 38 countries or country-ocean regions (note that data were reported by ocean for countries that had coasts on two different oceans, i.e. USA, Mexico, Thailand and Australia, and the Caribbean Netherlands includes Bonaire, St Eustatius and Saba.).

Observations are influenced by a diver's experience in terms of number of dives and number of years diving (Ward-Paige and Lotze, 2011). These two metrics were, therefore, used as a proxy for experience and observers were separated into three categories: 'experts' had > 200 dives and > 3 years living in the country, 'intermediates' had either > 3 years or > 200 dives in the country; and 'novices'

Table 1
Survey questions.

Part A: Demographics. Tell us about your experience.
1. Email address.
2. Country and ocean where you have the most ocean-related experience.
3. Year you started diving/snorkeling in this area? (e.g., 1996)
4. Most recent year diving/snorkeling in this area? (e.g., 2016)
5. Total number of dives/snorkels in this area?
6. Number of regularly dived/snorkeled sites in this area?
7. Have you ever spearfished in this area? Yes/No
8. Have you ever chummed, berleyed, or otherwise baited wildlife, including
9. In this area, in addition to scuba diving, what other ocean activities have you regularly participated in?
10. Are you aware of any tourism for sharks in this area? Yes/No
11. Have you personally observed anyone catching sharks (by accident or on purpose) in this area? Yes/No
12. In this area, have you personally observed any sharks or shark parts being sold, traded, or in markets – including the whole body or parts (e.g., skin, jaws, head, fins, teeth – including as a meal in restaurants, in aquariums, in grocery stores, etc.)? Yes/No

Part B: Your Observations
1. What species have you seen alive in the wild in this area?
2. Of all the sites you visited regularly in this area, how many sites ever had sharks present at any time?
3. Have you personally come across a site in this are that you would consider a shark nursery*? Yes/No *Nursery is an area where newborn or young sharks regularly occur in high numbers.
4. Thinking back to your first year(s) in this area, have you personally observed a change in the maximum school size of any sharks you have seen? Unchanged/Increased/Decreased
5. Thinking back to your first year(s) in this area, have you personally observed a change in the maximum school size of any sharks you have seen? Unchanged/Increased/Decreased

Part C: Conservation & Management
1. In this area, are you aware of any restrictions on catching, fishing, or interacting with sharks? Select all that apply: Best practice guidelines (codes of conduct), such as maintaining minimum distances when viewing sharks, maximum number of boats/divers in an area, etc.; Shark Sanctuary; Shark finning rules (e.g., ratio rule, fins attached, fins naturally attached); Species restrictions; Maximum allowable quotas; Trade or export bans

If selected 'Shark Sanctuary' above, then these questions were asked:
   a) How large is the Shark Sanctuary? Entire national waters (Exclusive Economic Zone – EEZ)/Part of the national waters – zone or area of EEZ/I don't know
   b) In your opinion, why was the Sanctuary initiated? I don't know/No real threat/Threat was imminent, but there was no existing threat/To reduce existing threats to sharks
   c) What were the main threats? No threats/Commercial fishing/Recreational fishing/Habitat destruction
   d) In your opinion, since gaining Sanctuary status in this area, have any of the following changed? Tourist interest in sharks; Targeted shark fishing; General fishing; Local community interest in sharks. Unchanged/Increased/Decreased
   e) In your opinion, since gaining Shark Sanctuary status, has there been compliance to the rules? I don't know/Yes/No
   f) In your opinion, since gaining Sanctuary status, has there been ENFORCEMENT of the rules? I don't know/Yes/No
2. In your experience in this area, how relevant are the following threats for sharks? Sea-level rise; Sea-water warming; Ocean acidification; Marine garbage and microplastics; Discarded fishing gear (ghost gear); Tourism influenced behaviour and diet changes; Targeted shark fishing (commercial, recreational, artisanal); Bycatch (accidental) of sharks in fishing (commercial, recreational, artisanal). Very low threat/Low threat/Threat/Important threat

had < 3 years and < 200 dives in the country. Shark abundance proxies, quantified as the maximum number of each species observed at any one time, was collected in bins (e.g. 6–10) and converted to a minimum estimate (e.g. 6–10 was coded as 6). For species richness calculations, species identities were summed, except where no species ID (i.e., unknown species) was given and richness was set to one.

Summary analyses were done by averaging data at the country level and only using the observations of those with the appropriate experience level for the question being addressed: Only experts' observations were used for shark population data, expert and intermediate observers were used for describing human uses and threats, and all levels of experience contributed to our exploration of awareness of conservation and management measures. Diverging stacked barplots (done in R using the Likert package: (Bryer and Speerschneider, 2015)), which show the spread of positive and negative responses centred on the neutral value, were used to describe patterns in the Likert-type scale questions presented to participants to rank various marine threats in their country (Part C). In comparing shark sanctuaries to non-sanctuaries, chi-squared tests were used to test for differences among categorical variables (tourism, catching, markets, spearfishing, chumming, and further conservation needs) and *t*-tests were used to test for significant differences ($p < 0.05$) for numerical variables (diversity, number of sharks, number of sites with sharks, nurseries, change in maximum school size and change in the number of sites with sharks). Because "lifetime" reports were collected – covering the observations across the range of a diver's' experience in the area – there is a possibility that shifted baselines would impact the 'change' metrics (i.e., changes in shark abundance or number of sites with sharks). Regression analyses, however, showed that out of 64 tests only one (New Caledonia) had a significant trend between the number of years in the area and the change in maximum school size (see Appendix A1). Maps were generated in R using the Maritime Boundaries Geodatabase (Flanders Marine Institute, 2016). Since the majority of countries that are now sanctuaries had little or no data on shark fisheries in the past, here, we use reconstructed shark and total catch by EEZ obtained from the Sea Around Us Project database (Pauly and Zeller, 2015), which are estimates based on the combination of reported catches and alternative information sources on missing data, as proxies to evaluate past fishing threats (1950–2010) by country.

3. Results

3.1. Survey data overview

Through our extensive global survey, 438 divers from 38 countries contributed observations based on a total of 667,033 individual dives (Table 2; Fig. 1; see additional comments from participants in Appendix A2). On average, each person regularly visited 32 sites, for a total of 13,602 regularly surveyed sites worldwide. Observations date back as far as 1954, or 62 years, with a mean of 12 years spent diving in their respective country.

Across the 15 shark sanctuaries, 158 divers completed the questionnaire for a total of 254,547 dives on 5241 sites (Table 2; Fig. 1). The mean time spent in the respective country was 12 years, for a combined experience of 1699 years, with observations going back as far as 1954 (in Bonaire). For the 23 non-shark sanctuary countries 280 divers contributed ~412,486 dives from 8361 regularly visited sites. Records went back as far as 1964 (in Aruba), with a mean of 12 years experience and a combined experience of 4720 years. Observations in all countries extended before the first shark sanctuary implementation in 2009 (Palau; Table 2), providing a comprehensive timeframe that includes the implementation of this regulatory strategy.

Within shark sanctuaries, the majority (63%) of participants fell into the 'expert diver' category, while 22% and 15% were intermediate and novice, respectively. Spearfishing rates were generally low (Table 2), with only 33% stating that they had participated in spearfishing, and involvement in this activity ranged from < 10% in Micronesia and the Maldives, to over 50% in St. Maarten, New Caledonia, French Polynesia and the British Virgin Islands. Many reported only "lionfish spearfishing" in Caribbean countries, while others stated that an "emerging threat to sharks is spearfishing" (Aruba, 500 dives, since 2010). Chumming (baiting, berleying, provisioning) to attract sharks was even less common at 23% overall, but higher incidence of chumming (> 50%) was reported in French Polynesia and the Bahamas.

3.2. Shark sanctuaries

3.2.1. Shark abundance and diversity

Shark populations were described using the responses of only the 99 expert divers' within shark sanctuaries, whose combined experience was > 253,000 dives on 4330 regularly dived sites. The average observed shark species richness was 12 species, with a low of 6 in the Caribbean Netherlands and a high of 20 in Palau (Table 3). Relative abundance, a sum of the maximum number of each species observed at one time, was an average of ~40 sharks, with lowest abundances recorded in the Caribbean Netherlands (n = 9) and the Cayman Islands (n = 8), and largest in French Polynesia (n = 97), Palau (n = 88) and the Maldives (n = 87). Shark nurseries were observed in most countries, except Curaçao and the Marshall Islands, and were reported by 100% of respondents in Palau, Micronesia and the Maldives. Examples of nursery observations included "mangrove habitat has been an observed nursery for 25 years for juvenile lemon sharks" (Bahamas, 200 dives, since 2013) and "nursery for lemon sharks and grey reefs" (French Polynesia, 3200 dives, since 2005) and "blacktips commonly use lagoons as nurseries" (Maldives, 10,000 dives, since 1988).

Observed changes to the maximum school size and number of sites with sharks were mostly unchanged (−0.01 and 0.12, respectively), but varied by country (Table 3). Some participants declared that the "shark population is too minimal" (Bonaire, 3000 dives, since 1998). Others said it was complicated, where sharks are "unchanged in North Pass, but there are less in South Pass" (French Polynesia, 1000 dives, since 2009). Many participants did not notice changes in the number of sites where sharks were present, where they saw that declines occurred "not in number of sites but in species present" (Marshall Islands, 500 dives, since 2002). Decreases were reported in the Bahamas, Cook Islands, Marshall Islands and the Maldives. Increases were reported in the British Virgin Islands, St. Maarten, Palau, Honduras and Micronesia.

3.2.2. Human uses

Shark-based tourism was reported by half the expert and intermediate participants (Table 4), which varied by country. Shark tourism was considered to be minimal in the Cayman Islands, Cook Islands, Curaçao and Grenada, where "people do not come expecting to see sharks but do like to see one" (Bonaire, 4000 dives, since 1993). Shark-based tourism was high in other countries where there is a "significant shark diving component of diving tourism" (Palau, 2000 dives, since 1997) and it is "extremely valuable" (Maldives, 2000 dives, since 1983), with some running "a shark diving business" (Bahamas, 6000 dives, since 2007).

Sharks caught in fisheries or sold in local markets were observed by about half of all expert and intermediate participants in shark sanctuaries (Table 4). Lowest shark catch observations were in the British Virgin Islands, Cayman Islands, the Cook Islands, Caribbean Netherlands and French Polynesia (~30–45%), while the lowest market observations occurred in Micronesia, French Polynesia, and the Caribbean Netherlands. The highest catch observations occurred in the Bahamas, Curaçao, Grenada, Maldives, and St. Maarten (> 60%), and the highest market observations occurred in Cayman, Curaçao, Maldives, New Caledonia and St. Maarten (Table 4). Some participants provided detailed recollections of a single experience, such as "hammerhead caught by a fisherman about a year ago" (British Virgin Islands, 2000 dives, since 2010), while others made more general comments like "jaws,

Table 2
Observation base in shark sanctuary and other countries. Shark sanctuaries include all participants and non-shark sanctuaries include countries where > 5 expert and intermediate participants contributed. EEZ area from Pauly and Zeller (2015).

Country	Shark sanctuary	EEZ area (km^2)	Participants (#)	Dives (total)	Sites (total)	Sites (mean)	Start year	Years (mean)	Spearfishing (%)	Chumming (%)
Bahamas	2011	628,026	16	14,250	169	11	1978	7	44	69
British Virgin Islands	2014	80,111	3	2800	90	30	2008	5	100	0
Cayman Islands	2016	119,134	9	27,300	670	74	1986	14	33	11
Cook Islands	2012	1,960,027	7	25,300	120	17	1996	13	29	14
Curacao	2016	30,427	4	10,920	75	19	1996	11	25	0
Caribbean Netherlands	2015	24,866	35	48,962	922	26	1954	14	20	6
French Polynesia	2012	4,771,088	11	34,200	181	17	1990	13	55	55
Grenada	2016	26,133	8	12,510	144	18	1999	9	25	0
Honduras	2011	218,804	10	25,011	471	47	1996	10	30	40
Maldives	2010	916,011	25	25,742	594	24	1983	6	8	8
Marshall Islands	2011	1,992,022	9	5370	128	14	1994	12	11	33
Micronesia	2015	2,992,415	5	3323	208	42	1981	16	0	20
New Caledonia	2013	1,422,596	6	8324	1278	213	1970	17	50	33
Palau	2009	604,253	8	7535	154	19	1983	7	13	13
St. Maarten	2016	1066	2	3000	37	19	1995	20	50	50
Total shark sanctuaries		**15,786,979**	**158**	**254,547**	**5241**	**39**	**1954**	**12**	**33**	**23**
Aruba	No	25,199	7	8872	155	22	1964	24	57	29
Australia – Indian Ocean	No	6,369,268	5	1990	58	12	1990	12	20	0
Australia – Pacific Ocean	No		12	12,630	171	14	1980	13	17	33
Belize	No	36,182	8	5245	206	26	2000	7	86	14
Brazil	No	2,400,918	10	7850	430	43	1984	15	22	33
Cocos (Keeling) Islands	No	467,229	10	6885	180	18	1990	11	0	0
Costa Rica – Pacific Ocean	No	572,131	9	23,815	125	14	1991	13	11	11
Egypt	No	260,404	10	11,685	280	28	1989	12	0	0
Fiji	No	1,281,703	9	14,200	1110	123	1997	6	11	67
Indonesia	No	6,024,450	60	71,061	2809	47	1995	8	3	3
Kenya	No	162,794	5	11,150	100	20	1976	21	20	0
Mexico – Atlantic Ocean	No	829,311	5	14,040	90	18	2002	11	60	0
Mexico – Pacific Ocean	No	2,444,238	5	3452	70	14	1995	12	40	0
Mozambique	No	571,452	11	11,920	146	13	2000	7	9	18
Philippines	No	2,263,816	20	74,870	741	37	1978	17	5	0
Reunion	No	315,071	6	710	27	5	2000	8	0	0
Seychelles	No	1,331,964	6	20,762	109	18	1993	10	0	0
South Africa – Indian Ocean	No	1,065,941	7	29,200	85	12	1988	20	14	86
Thailand – Indian Ocean	No	118,714	30	28,409	494	17	1985	9	3	7
Thailand – Pacific Ocean	No	187,064	5	6600	69	14	1999	8	0	20
Turks and Caicos	No	153,533	13	14,696	388	30	1984	13	38	15
US – Atlantic Ocean	No	926,067	20	30,620	472	24	1968	17	33	20
US – Pacific Ocean	No	821,679	7	1824	46	7	1996	10	17	33
Total non-shark sanctuaries		**28,629,128**	**280**	**412,486**	**8361**	**25**	**1964**	**12**	**20**	**17**
Total overall		**44,416,107**	**438**	**667,033**	**13,602**	**32**	**1954**	**12**	**53**	**40**

Bold values show column totals.

teeth etc. in local shop for tourists" (Maldives, 2000 dives, since 2010, and 13 other participants made similar comments), or "boats from Honduras loaded with shark fins" (Cayman Islands, 5000 dives, since 1993). In some cases, catch observations were justified by "Fisherman who keep it for their family" (Grenada, 4000 dives, since 2009). Others suggested the catches were made by accident where "shark caught by accident on fishing boat gave to local restaurant and they made shark fin soup" (Cayman Islands, 2000 dives, since 2010). The highest catch rates, by far, occurred in Micronesia, Maldives, Marshall Islands and French Polynesia, whereas only the Maldives was similarly high in catches and observed catches.

Combining shark population information (richness and abundance) with observed human use patterns further demonstrates the variability associated with individual shark sanctuary countries (Fig. 2). Countries with relatively high richness and abundance in conjunction with relatively high tourism occurred in the Maldives, Palau and New Caledonia (black cross with red square in Fig. 2). No countries were found to have low richness or abundance and high shark-based tourism. The Maldives was the only country with high shark richness and abundance with high shark catch observations (black crosses with red squares), while Grenada was the only country with low shark richness and high shark catches (red crosses and squares). New Caledonia was the only country with high richness and abundance with high rates of observed sharks in markets (black cross with red square) and Curaçao was the only country with low shark abundance and high sharks market observations (red cross with red square).

Table 3
Shark abundance and species richness in shark sanctuaries. Change values are reported as means, where 0 = unchanged, −1 = decrease, 1 = increase and the value indicates the mean trend.

Country	Experts	Richness (max)	Richness (min)	Richness (mean)	Abundance (max)	Abundance (min)	Abundance (mean)	Nursery (%)	Percent of sites with sharks (mean)	Change in max. school size (mean)	Change in number of sites (mean)
Bahamas	6	11	3	9	89	10	51	67	80	−0.2	−0.3
British Virgin Islands	2	5	4	5	11	10	11	50	62	0.5	1.0
Cayman Islands	8	9	1	5	20	1	8	25	34	0.0	0.4
Cook Islands	7	8	1	4	70	1	32	14	15	−0.6	−0.3
Curaçao	3	12	3	7	66	3	25	0	14	0.0	0.3
Caribbean Netherlands	24	6	0	3	111	0	9	13	20	0.1	−0.1
French Polynesia	11	14	1	9	245	3	97	91	69	0.1	0.1
Grenada	5	9	1	3	23	3	11	20	28	−0.4	−0.2
Honduras	7	13	1	7	44	15	27	57	11	0.0	0.6
Maldives	7	17	6	11	163	24	87	100	88	−0.4	−0.4
Marshall Islands	6	11	4	8	71	11	35	0	43	−0.3	−0.3
Micronesia	4	16	4	8	69	24	37	100	15	0.5	0.0
New Caledonia	4	15	6	12	107	19	66	50	28	−0.5	−0.3
Palau	3	20	7	13	122	58	88	100	83	0.0	0.3
St. Maarten	2	8	3	6	16	10	13	50	33	1.0	1.0
Total	99	11.6	3	7.3	1227	192	40	49	42	−0.01	0.12

3.2.3. Conservation awareness

Public awareness of conservation strategies may, at least partially, influence its success. Across all levels of diving expertise (expert, intermediate, novice), and excluding the three countries that recently designated shark sanctuaries in 2016, 61% of participants called their area a 'shark sanctuary' (Table 5). This varied from < 50% in the British Virgin Islands, Dutch Caribbean, the Maldives and New Caledonia, to > 80% in the Cook Islands and Palau. Awareness of the shark sanctuary also varied by experience in each country, with 67% of expert, 63% of intermediate, and 46% of novice divers being aware of the shark sanctuary (Fig. 3). However, some participants did not select the 'Shark Sanctuary' option in the survey for these countries, but did select that "Species restrictions" or "Trade or export ban" are in place, commenting that "… it is not policed and [fishing] still occurs" (Bahamas, 758 dives, since 2011).

Of those participants that called their area a 'shark sanctuary', just over half the respondents were aware that it extended across the entire EEZ. This awareness was low in Micronesia, and high in Honduras, French Polynesia, Maldives, and the Cayman Islands (Table 5). Reasons for implementing the shark sanctuary and the threats aiming to be addressed by the shark sanctuary also varied by country (Figs. 4 and 5). 64% said the shark sanctuary was implemented to reduce existing threats, while others thought the threat was imminent, there was no real threat, or they did not know. The primary threats that the shark sanctuaries were thought to address were commercial shark fishing (68%), followed by recreational fishing (25%) and habitat destruction (8%; Fig. 5). Illegal fishing was mentioned by two participants, such as "shark jaws for sale by vendors even though illegal the municipality rarely enforces it" (Honduras, 2000 dives, since 2000) and "…Whether a law has been passed to ban shark finning/shark fishing local fishermen still illegally catch and sell shark to commercial tuna fishing boats" (Marshall Islands, 100 dives, since 2002).

Changes to shark tourism, shark fishing, general fishing and local interest in sharks with implementation of the shark sanctuary differed by country (Table 5). For shark-based tourism, there were no reported decreases, with only slight increases (0.10) in the British Virgin Islands, the Cook Islands, Micronesia and New Caledonia, and large increases (0.80) in the Bahamas, French Polynesia and Palau. Targeted shark fishing was reported to have declined in 10 of 15 countries. On the other hand, there was no consistent change in the overall intensity of fishing (ranging from −0.50 in New Caledonia to 0.50 in Micronesia). Local interest in sharks was thought to have increased overall, but varied with no increased interest in sharks in the Marshall Islands and Micronesia, and increased interest in Honduras, the Maldives and New

Table 4
Human use observations of shark-based tourism, shark catches, and sharks being sold in markets, made by expert and intermediate participants. Shark catch and total catch are reconstructed values from Sea Around Us (Pauly and Zeller, 2015) and are totals (1950–2010), and percent shark catch is the amount of shark that comprised the total catch.

Country	Records	Tourism (%)	Catching (%)	Markets (%)	Shark catch (tonnes)	Total catch (tonnes)	Percent shark catch
Bahamas	10	90	60	30	2134	1,022,266	0.21
British Virgin Islands	3	67	33	33	771	81,986	0.94
Cayman Islands	9	11	44	67	126	13,133	0.96
Cook Islands	7	0	29	29	3539	291,850	1.21
Curaçao	3	0	100	67	1971	116,094	1.70
Caribbean Netherlands	31	29	45	19	1375	122,718	1.12
French Polynesia	11	91	36	18	15,407	1,190,550	1.29
Grenada	8	13	63	50	3315	246,601	1.34
Honduras	8	100	50	25	3321	778,979	0.43
Maldives	20	80	65	60	198,537	6,623,412	3.00
Marshall Islands	9	33	56	11	247,957	1,792,276	13.83
Micronesia	4	50	50	0	373,130	9,416,309	3.96
New Caledonia	4	75	50	75	13,132	663,227	1.98
Palau	4	100	50	25	41,194	1,961,747	2.10
St. Maarten	2	100	100	100	1496	38,870	3.85
Total	133	56	55	41	907,406	24,360,017	2.53

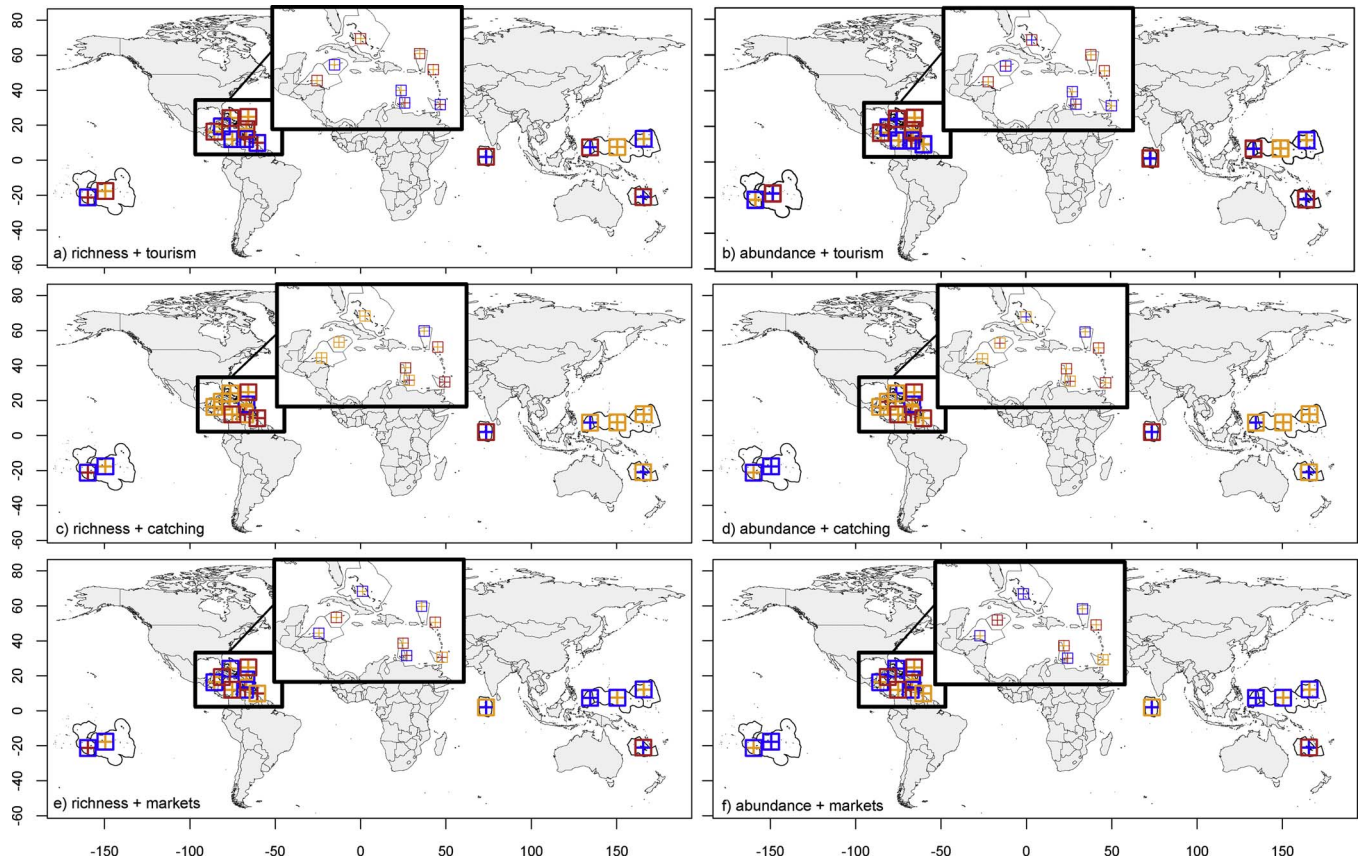

Fig. 2. Patterns in shark populations and human use within shark sanctuaries. Crosses depict richness (a,c,d) or abundance (b,c,e), where diversity is blue = > 10, orange = 5-10, red = < 5 species, and abundance is blue = > 50 orange = 10–50, red = < 10 individuals. Human uses are depicted by squares, tourism (a,b), catching (c,d) and markets (e,f), where blue = < 40%, orange = 40–60%, red = > 60%. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

Caledonia. Views on compliance and enforcement of the shark sanctuary laws were mixed, with the overall majority trend being positive (0.24 and 0.27; Table 5). In the Caribbean Netherlands and the Cook Islands, compliance and enforcement levels appeared relatively low, whereas both compliance and enforcement were considered to be high in French Polynesia. The Bahamas had mixed results, with high compliance and low enforcement values, whereas Palau and the Marshall Islands had low compliance and high enforcement values.

3.2.4. *Further conservation needs*

The majority of participants in most shark sanctuary countries, except Micronesia and French Polynesia, reported the need for further shark conservation (Table 5). Comments supporting this conclusion included, “sport fishing for sharks is still offered even though it is

Table 5
Shark sanctuary awareness across all participants in shark sanctuary countries. Included is the percent of participants that were aware of the shark sanctuary, the size of the shark sanctuary extending to the full economic exclusive zone (EEZ), and reported changes to tourism, shark fishing, general fishing, local community interest in sharks following shark sanctuary implementation, where positive values indicated increase and negative values indicate decrease, and percent believing there is (positive) and is not (negative) compliance, and enforcement.

Country	Shark sanctuary (%)	Size (entire EEZ, %)	Tourism change	Shark fishing change	General fishing change	Local interest change	Compliance	Enforcement	Further conservation needs (%)
Bahamas	56	61	0.9	−0.75	0.13	0.50	0.63	−0.38	100
British Virgin Islands	33	0	0.0	−1.00	0.00	0.00	0.00	0.00	67
Cayman Islands[a]	11	100	0.0	0.00	0.00	0.00	−1.00	0.00	89
Cook Islands	86	75	0.0	−0.33	0.33	0.33	−0.33	−0.33	100
Curaçao[a]	0	0	NA	NA	NA	NA	NA	NA	100
Caribbean Netherlands	43	63	0.2	−0.27	−0.27	0.67	−0.20	−0.20	60
French Polynesia	55	83	0.8	−0.83	−0.17	0.33	0.83	0.83	40
Grenada[a]	0	0	NA	NA	NA	NA	NA	NA	100
Honduras	70	86	0.4	−0.57	0.14	0.71	0.00	0.14	86
Maldives	36	83	0.5	−0.88	0.13	0.75	0.38	−0.25	89
Marshall Islands	78	71	0.3	−0.86	−0.14	0.00	0.14	0.86	89
Micronesia	60	33	0.0	−0.50	0.50	0.00	0.50	0.00	33
New Caledonia	33	50	0.0	−0.50	−0.50	1.00	1.00	1.00	67
Palau	100	63	0.8	−0.67	−0.17	0.50	0.17	0.83	100
St. Maarten	100	75	1.0	−0.50	−0.50	1.00	1.00	1.00	100
Overall average	51	56	0	−0.59	−0.04	0.45	0.24	0.27	81

[a] Shark sanctuaries implemented during the assessment period, where the majority of participants contributed prior to designation.

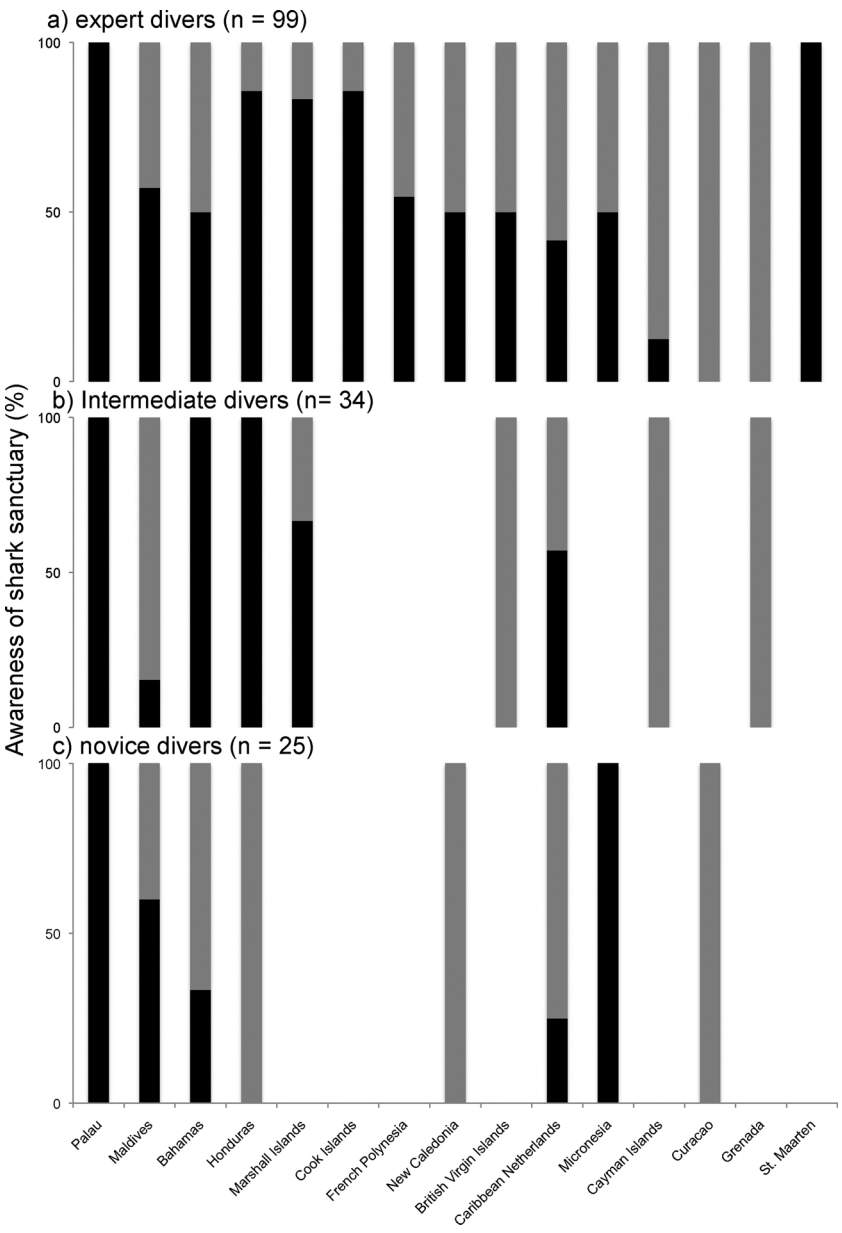

Fig. 3. Awareness of shark sanctuary regulation by experience level.

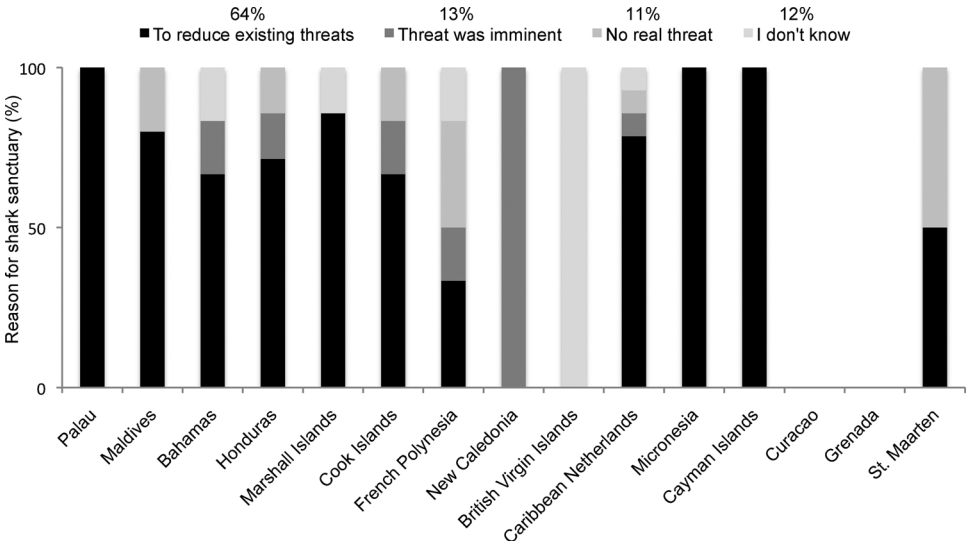

Fig. 4. Reasons for implementing a shark sanctuary.

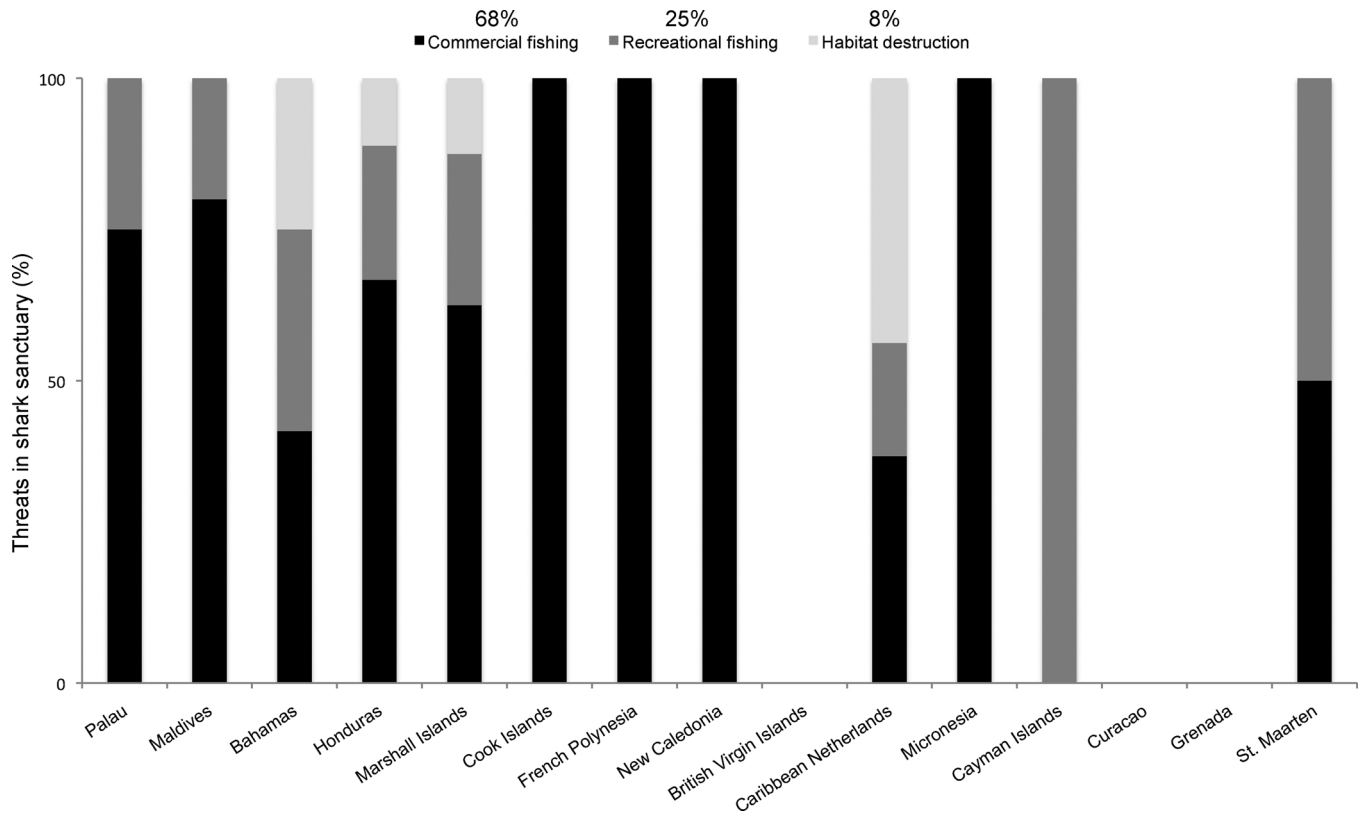

Fig. 5. Important threats prior to the implementation of shark sanctuaries.

illegal." (Bahamas, 500 dives, since 2004), "NPOA exists, population monitoring is underway, but enforcement of protection is likely needed in places" (Maldives, 10,000 dives, since 1988) and "there needs to be better enforcement and patrolling" (Honduras, 2000 dives, since 2000). Others called for "shark feeding bans" (French Polynesia, 2 participants) and the need for more "education" (4 of 4 comments in the Bahamas). Thirty-five participants said no further shark conservation was needed, because "There have never been a plethora of sharks especially in Grand Cayman" (Cayman Islands, 3000 dives, since 1996), or because there is a "National Marine Park" (Caribbean Netherlands, 1000 dives, since 2007). Others suggested the need for collaborative and ecosystem-based approaches, such as "Protection for crucial habitat (Bahamas, 2000 dives, since 2013), and "our 'protected sharks' do swim out of our marine park and can be caught in other islands" (St. Eustatius, 2000 dives, since 2009).

3.2.5. Ongoing threats

Shark sanctuary laws, with the few exceptions (i.e., for chumming and some gear limits), exclusively ban targeted shark fishing, but many other threats afflict marine ecosystems and shark populations. These threats vary at local and regional scales and some are currently a challenge to detect by observation alone (e.g., sea level rise, ocean warming, acidification). Overall concern for sharks across all measured threats was lowest (< 40% total weight) in French Polynesia, New Caledonia, Micronesia and Curaçao (Fig. 6). Those with the highest concern (≥70% total weight) were in Palau, the British Virgin Islands and Grenada. Concern for sharks based on each of the evaluated threats varied by country (Fig. 6), and no threats were consistently highlighted across all countries. Generally, sea level rise and tourism were considered the lowest threats, while marine debris and ghost gear were the highest threats. Many of the comments regarding direct threats to sharks dealt with attitudes, such as "Local fisherman will kill any shark that comes through" (Bonaire, 3500 dives, since 1998).

3.3. Shark sanctuaries compared to non-shark sanctuaries

3.3.1. Shark baselines

Assuming no double counting of sharks occurred across participants, a minimum of 12,323 sharks were observed across 79 species, with the species observed most commonly being whitetip reef shark (*Triaenodon obesus*), blacktip reef shark (*Carcharhinus melanopterus*), nurse shark (*Ginglymostoma cirratum*), and whale shark (*Rhincodon typus*) by 283, 265, 221 and 212 participants, respectively. The maximum number of species reported in any country was 20 (Table 6), with a mean richness across all countries of ~6 species and abundance of 35 sharks (maximum number observed at one time summed across all species). Summing across maximum school size of all species, the highest abundance was observed in South Africa, French Polynesia and the Philippines, all exceeding 200 sharks. On average, 39% of sites had sharks and 50% of countries had at least one observed shark nursery.

Observed shark species richness, abundance and site occupancy was similar (no significant differences; $p > 0.05$; Table 6) across shark sanctuaries as compared to non-shark sanctuaries. The only significant difference was in nursery occurrence (slightly higher in non-shark sanctuaries) and in the change in maximum school size – where non-shark sanctuaries reported more pronounced declines than their shark sanctuary counterparts. However, some claimed that they "haven't seen them enough to gauge" (Cayman Islands, 1400 dives, since 1996). This was particularly the case in countries where sharks had lower species richness, abundance and site occurrence. But others said that they see "less white-tips at several locations" (Costa Rica, 2450 dives, since 1998), with "decreases in all shark sightings" (Kenya, 4000 dives, since 1988) and that they have "dramatically decreased across all species" (Mozambique, 3000 dives, since 2000). Other observations were more nuanced, in that they are "seeing more large sharks and less small sharks close to shore" (Australia, 500 dives, since 2005).

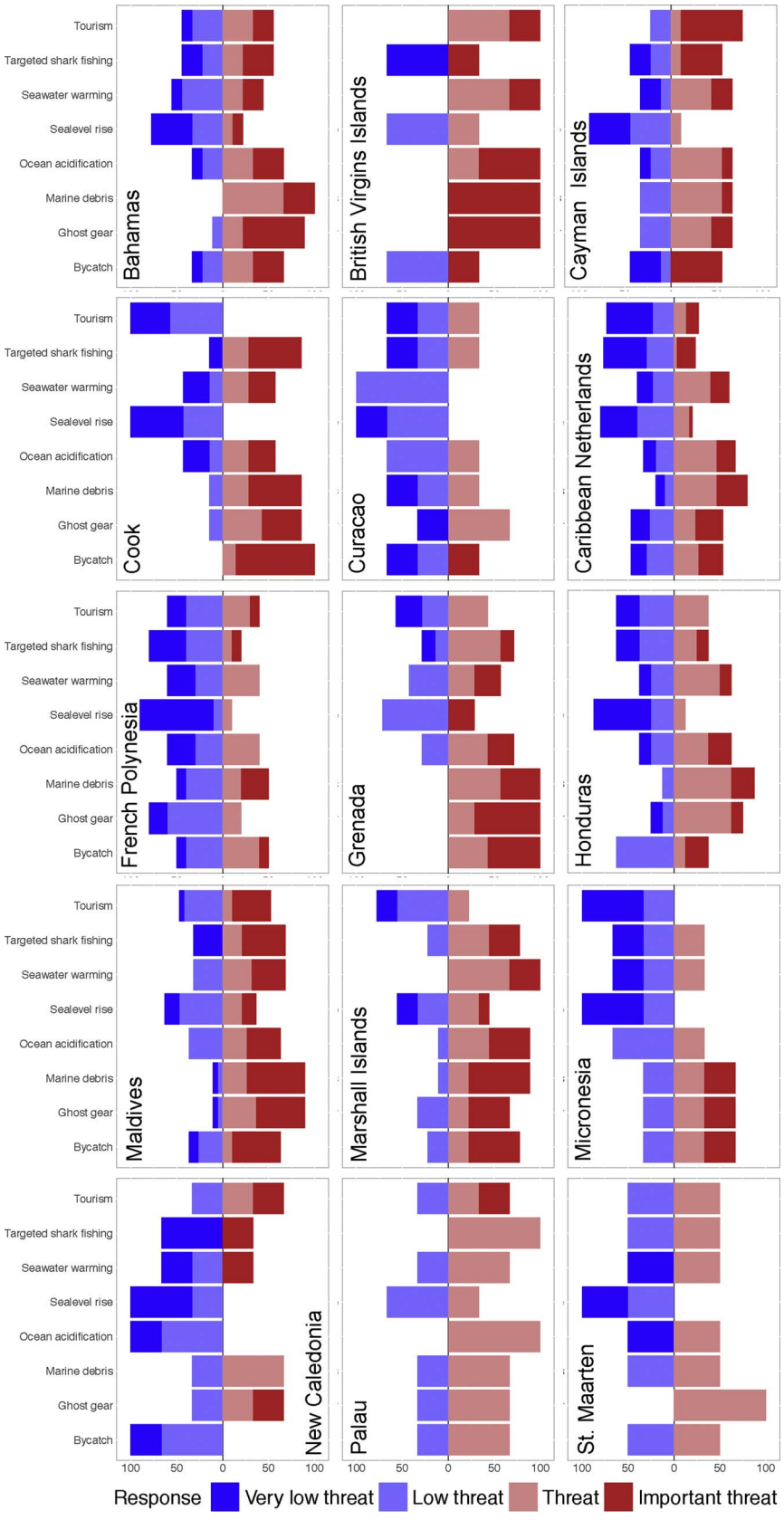

Fig. 6. Ranking of threats in shark sanctuaries. These were ranked using Likert analysis according to expert and intermediate participants in shark sanctuaries.

3.3.2. Human uses

Across all sampled countries, about half the participants reported shark-based tourism (56%), sharks being caught (49%) and sharks being sold in the markets in the area (46%, Table 7). For their personal activities, 21% reported spearfishing and 17% reported chumming (including berleying, feeding or otherwise attracting wildlife for viewing purposes), and 82% declared that further shark conservation strategies were needed in their country.

Table 6
Shark populations within and outside shark sanctuaries. These were assessed for expert participants only. Number of species (richness), summation of maximum school size across species (abundance), observed changes in maximum school size or sites with sharks, proportion of sites with sharks and percent of participants reporting the presence of a shark nursery for at least one species. Reported p-values from Chi-square-tests indicate significant differences between shark sanctuary countries and non-shark sanctuary countries ($p < 0.05$, in bold).

Type	Richness (max)	Richness (mean)	Abundance (max)	Abundance (mean)	Change in max. school size (mean)	Change in number of sites (mean)	Percent of sites with sharks (mean)	Nursery (%)
Shark sanctuaries	20	6.3	245	37.9	−0.06	0.00	38.9	43.0
Non-shark sanctuaries	20	6.2	286	32.9	−0.23	−0.14	38.7	56.0
Total		6.3	286	35.4	−0.15	−0.07	38.8	49.5
p		0.86		0.37	**0.04**	0.09	0.97	**0.04**

3.3.2.1. Tourism. Shark-based tourism did not significantly differ between all shark sanctuaries and non-shark sanctuaries ($p = 0.50$; Table 7). Participants made general comments about tourists wanting to see sharks, even if they are not explicitly targeting sharks in their tourist activities, where "although divers like seeing nurse sharks they do not come specifically to Aruba expecting to see any sharks" (Aruba, 500 dives, since 2010). Others more clearly stated the importance of shark-based tourism, where "many dive customers come all year around wanting to see sharks" (Indonesia, 2500 dives, since 2011) and that "sharks valued @ USD 42m/year" (Fiji, 3000 dives, since 2003). Others mentioned fishing tourism, where "shark fishing is a very popular sport" (US – Atlantic Ocean, 10,000 dives, since 1987). Only a few commented on the negative perception of sharks for tourism, where "tourism decreased because of shark attack…" (Réunion, 80 dives, since 2013) and "after numerous shark attacks on humans people want to eradicate sharks." (Réunion, 30 dives, since 2003).

3.3.2.2. Catches. Observations of sharks caught did not significantly differ between shark sanctuaries and non-shark sanctuaries ($p = 0.34$; Table 7). Many commented on catching sharks, where "I have caught some myself… whilst conducting research" (Australia −Southern Ocean, 150 dives, since 2008). Many commented on sharks being caught by accident, where "Pelagic Thresher accidental bycatch by local fisherman" (Philippines, 4000 dives, since 2002). Some describe explicit examples, such as "on Gili T I have seen them land a juvenile whale shark 3 years ago" (Indonesia, 2000 dives, since 2003). Others described broad circumstances, such as in "industrial and artisanal fisheries" (Brazil, 300 dives, since 2010), "fisherman" (Costa Rica, 4000 dives, since 2006), and "commercial long line" (Costa Rica, 3000 dives, since 1997).

3.3.2.3. Markets. Sharks or shark parts observed in the markets were significantly higher in non-shark sanctuaries compared to shark sanctuaries (56% compared to 35%, $p = < 0.0001$; Table 7). Most comments recounted the commonality of sharks in the markets, such as "I have observed hundreds of sharks in fish markets in Belize City and Dangriga town …" (Belize, 160 dives, since 2000), and "all body parts seen in markets…." (Indonesia, 600 dives, since 1999).

3.3.3. Catches, market observations and abundance

Data on the historical shark catch per square kilometer of EEZ (Fig. 7) was used as a proxy of the relative threat to sharks from fisheries (targeted or bycatch). Across all sampled countries, average catch was ~22 t/km^2 (stdev ± 55). Sampled countries ranked among the highest and lowest with respect to total catch per unit area. The country with the highest catch per area was Thailand, at 313 t/km^2, which exceed the next highest countries by an order of magnitude. St. Maarten (a recent shark sanctuary) was second at ~72 t/km^2, followed by Egypt, the United States, Indonesia, Philippines, Mexico, Mozambique, Brazil and Belize (in descending order), which all exceeded 11 t/km^2. Shark sanctuaries Grenada and Caribbean Netherlands (Bonaire) followed at ~9 t/km^2. Countries with the lowest reported catch per area, all with < 0.3 t/km^2, were the Cocos (Keeling) Islands, and the Cayman Islands, Cook Islands, and French Polynesia − all three are now shark sanctuaries.

Comparing these catch values to the prevalence of shark market observations and shark abundance (Fig. 7) provides insight on the spatial patterns of fishing threat and what is observed. Only Mexico had high catch, high markets and high abundance (dark polygon, red square, black cross). Countries with high catch, high markets, and medium abundance (dark polygon, red square, black cross) included Costa Rica, Brazil, Mozambique, Kenya, Philippines, St. Maarten and Thailand – one of eight are shark sanctuaries. In contrast, those with low catch, low markets, and high abundance (light polygon, black square, black cross) were French Polynesia, South Africa, Bahamas, and Fiji. Similar countries, with low catch, low markets, and medium abundance included the Cocos (Keeling) Islands, Cook Islands, Marshall Islands, British Virgin Islands and Australia – five of nine are shark sanctuaries.

Some countries had high catch, low markets, and high or medium abundance, including Palau, Micronesia, Honduras, Belize and Egypt – three of five are shark sanctuaries. Others, however, had the opposite trend, with low catch and high markets, including New Caledonia and Seychelles with high and medium abundance, respectively, and the Cayman Islands and Réunion each with low abundance – two of four are shark sanctuaries. The United States, Turks and Caicos, Grenada and Indonesia – only one shark sanctuary – all had high catches, with medium markets and medium abundance. The Maldives and Aruba – the former a shark sanctuary – had similarly high catches and medium markets, but with high and low abundance, respectively. Two countries fell into unique categories, where Curaçao had high catch, high markets and low abundance, and Bonaire had high catch, low markets and low abundance – both are shark sanctuaries.

Table 7
Human use observations within and outside shark sanctuaries. These were assessed for expert and intermediate level participants. Shown is the percent of respondents who observed tourism, catching and markets for sharks, deploying spearfishing or chumming activities in the area, and the percent of respondents reporting the need for further shark conservation in the area. Reported p-values from Chi-square-tests indicate significant differences between shark sanctuary countries and non-shark sanctuary countries ($p < 0.05$, in bold).

Type	Tourism (%)	Catching (%)	Markets (%)	Spearfishing (%)	Chumming (%)	Further conservation needed (%)
Shark sanctuaries	53	52	35	28	20	78
Non-shark sanctuaries	59	45	56	14	13	86
Total	56	49	46	21	17	82
p	0.50	0.34	**< 0.001**	**< 0.01**	**< 0.01**	**0.05**

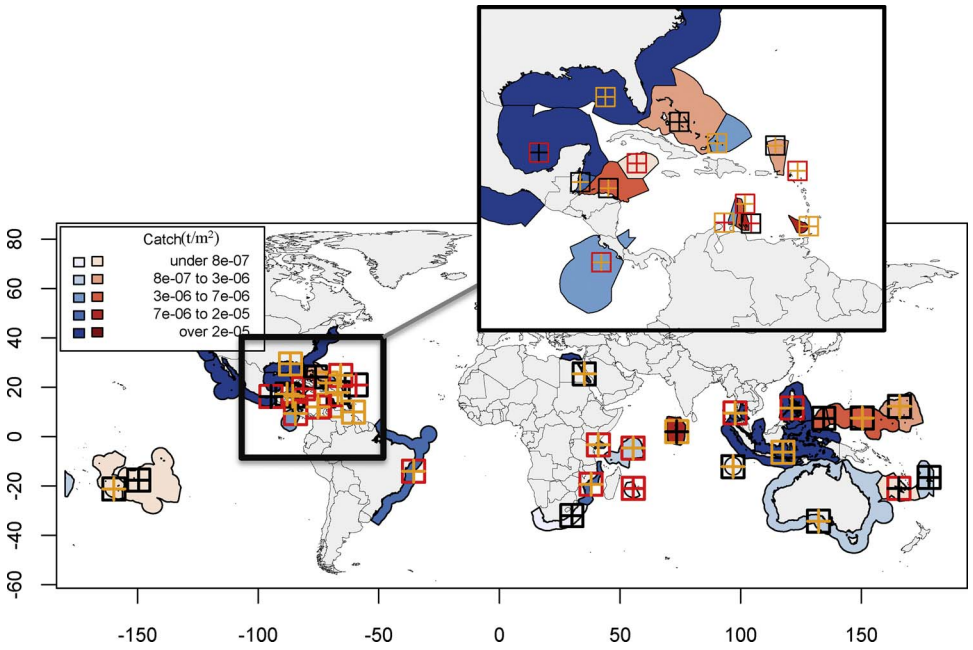

Fig. 7. Observed shark abundance and market prevalence with fishing pressure. Shark abundance depicted by crosses, where black = > 50, orange = 20–50, red = < 10. Market prevalence (% of respondents) depicted by squares, where black = < 40%, orange = 40–60%, red = > 60%; Catches (tonnes/km^2) from Pauly and Zeller (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.4. Conservation awareness

The reported need for further shark conservation strategies was marginally higher in non-shark sanctuaries compared to shark sanctuaries (86% compared to 78%, p = 0.05; Table 7). Participants who selected "no need for further shark conservation" made comments such as "there is no decrease in shark population" (Aruba, 2000 dives, since 1982), "not a major interest here" (Indonesia, 1500 dives, since 2009), "Sharks plentiful and not actively hunted here, and on the increase" (South Africa, 5000 dives, since 1995), "I think there's a lot of recreational fishing for sharks in my area and usually they are caught and released but not always and that's a problem." (US – Atlantic Ocean, 200 dives, since 2000), "The island of Bonaire is surrounded by a marine sanctuary. All species are protected. Not just sharks." (Bonaire, 500 dives, since 2003), "Too few sharks around here – no danger of extinction" (Bonaire, 100 dives, since 1954), and "as long as the shark sanctuary regulation passes in 2016" (Turks and Caicos, 1000 dives, since 1993).

Despite this, the majority said there was "need for further shark conservation". Comments to support this decision varied, such that "Finning is a real issue here and the government is turning a blind eye" (Costa Rica, 365 dives, since 2005), and the "shark fishery currently not managed trade is unregulated" (Fiji, 3000 dives, since 2003). Others suggested there has been progress, but still lack effective implementation and enforcement, such that "There is no need for new strategies until the current ones are properly enforced." (Mexico – Pacific Ocean, 1000 dives, since 1995), "Fiji needs to adopt its draft NPOA and set out an implementation work-plan to meet NPOA objectives." (Fiji, 50 dives, since 2012) and "NPOA has been developed but not implemented." (Philippines, 20 dives, since 1993).

Some suggested the need for more informed discussion and transparency, especially where there have been negative interactions with sharks (i.e., bite incidents), such as "Shark Nets need to be removed." (South Africa, 7000 dives, since 1995), while others thought "conservation strategies would not be accepted by local people because of shark crisis in Réunion island" (Réunion, 30 dives, since 2003). Others cited threats due to environmental factors, besides fishing, such that "Sharks and the reefs are suffering badly from overfishing, mass tourism and pollution, and now also bleaching coral. Too many stress factors" (Thailand – Indian Ocean, 2000 dives, since 2010)

Many observers suggested education as a priority, such that "People do not understand the importance of sharks" (Aruba, 1000 dives, since 2000) and the need for "some awareness programs for the community" (Bonaire, 1000 dives, since 1973). Finally, a few comments involved the need for defining and specifically protecting shark essential habitats for different life stages, such that conservation should aim "to protect nursery grounds to prevent further decline of species to allow migration of species (whale sharks and leopard sharks) to stop illegal fishing activity in low season" (Thailand – Indian Ocean, 800 dives, since 2007) and "no take zones during shark migration periods" (US – Atlantic Ocean, 1000 dives, since 2009).

3.3.5. Ongoing threats

A comparison of existing threats between shark sanctuaries and non-shark sanctuaries, including the effects of tourism, targeted shark fishing, global warming, sea level rise, ocean acidification, marine debris, ghost gear and bycatch, showed very similar ranking between the two treatment groups (Fig. 8). The total weight of concern – 'threat" or "important threat" compared to "low threat" and "very low threat" – across all threats was lower (55%) in shark sanctuaries compared to non-shark sanctuaries (61%) overall. The only two threats that differed significantly between shark sanctuaries and non-shark sanctuaries were targeted shark fishing and bycatch, which were ranked as higher threats in non-shark sanctuaries than in shark sanctuaries.

4. Discussion

4.1. Summary

This study provides a first global assessment of shark sanctuaries, which cover > 3% of ocean area. Through a structured survey of 438 divers representing a collective observation base of > 600,000 dives, we were able to show that shark sanctuaries support larger relative abundance, but not diversity of sharks, fewer incidences of declines in shark abundance, fewer sharks being sold in local markets, and a more optimistic perception of sharks, when compared to non-sanctuaries. Observed incidence of shark catch or tourism, did not vary systematically between sanctuaries and non-sanctuaries. Shark sanctuaries included countries with both very high (e.g. Micronesia) and very low (e.g. French Polynesia) historic shark catches, demonstrating that they have been implemented across a range of threat levels. Taken together, these observations suggest that shark sanctuaries may have real benefits. However, given that shark sanctuaries primarily target commercial

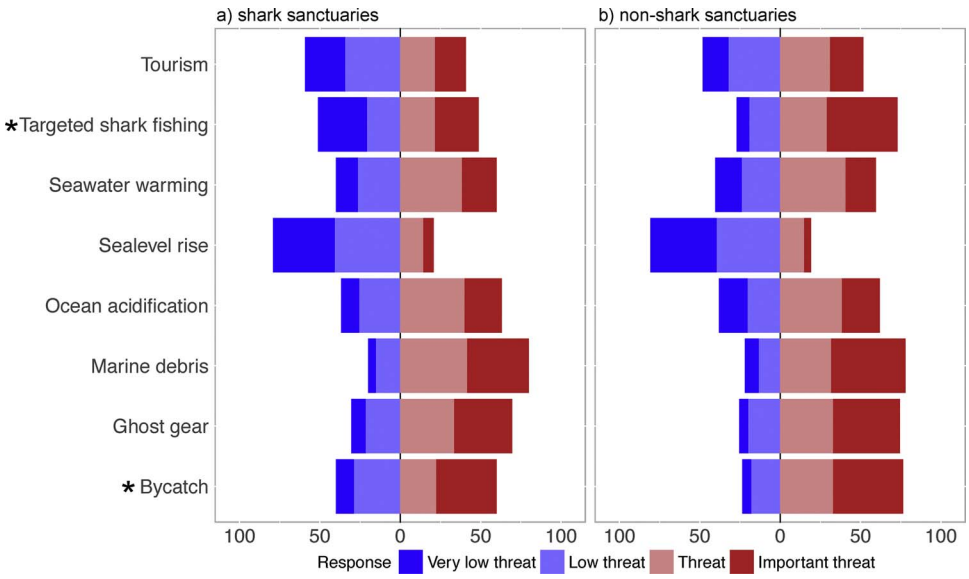

Fig. 8. Ranking of threats in shark sanctuaries and non-shark sanctuaries. These were ranked using Likert analysis according to expert and intermediate participants. Stars (*) denote significant differences between the two treatments.

shark fishing and that the locally identified threats to sharks are numerous – bycatch, ghost gear and marine debris were ranked as important local threats – this conservation strategy is likely not sufficient in isolation and requires added ecosystem-based conservation measures.

4.2. Caveats

Shark sanctuary policies are relatively recent (< 10 years) and evolving. Our results, therefore, do not suggest that shark sanctuaries have caused the reported changes to shark populations, but rather they provide a contemporary snapshot on the condition of observed populations for which future trends may be compared. As well, since the survey and analysis were completed, Curaçao and Grenada, which cover < 0.4% of the total shark sanctuary area, appear to have delayed implementing shark sanctuary laws, and Kiribati has moved to implement the second largest shark sanctuary in the world (3.4 million km^2; http://www.pewtrusts.org/en/about/news-room/press-releases/2016/11/21/pew-applauds-new-shark-sanctuary-in-kiribati).

Species identification is a concern with citizen science data where photos are not submitted. However, this is not considered an important issue within the current study. With shark species in shallow coastal waters, the relative number of species is limited (as compared to birds or many other species groups reported on my citizen observers) and, since sites are often repeatedly visited by divers, the majority of sharks are typically repeatedly observed to the point where many become named individuals (e.g., Bolette, a blacktip reef shark in Thailand; http://orientalsea.com/ID-15.htm, accessed 11 November, 2016). An evaluation of the species reported in each country was conducted, where websites, local researchers and other experts were consulted for commonly sighted species lists and compared to those reported. Considering that only one record had two species that were out of range (it was excluded), and many reports included Latin names in the comments, it is expected that species identification was highly accurate for this purpose. For the rare species, the level of analysis used here would be unaffected by identification errors (e.g., among different species of bamboo shark) since a simple accumulation of number of species was used for each area.

There are other potential concerns. First, the data are not event-based and rely on memories. Much of this error is overcome by only asking for the maximum number observed at any time combined with the time period of sampling, rather than asking for yearly accounts, where rare events are more accurately recalled (Ward-Paige and Lotze, 2011). Second, depending on geography (e.g., size of the country) and cultural preferences, fisheries landing ports may be concealed from the general public, which can limit observations of shark catches in some countries. This is similarly true for markets, where divers' and other members of the general public may not be easily exposed to local fisheries markets. For example, one participant commented that "this is a tourist area and tourists don't like to see this [fish markets] so there is an incentive not to do it here" (Mozambique, 1200 dives, since 2009). Third, the survey was not exhaustive, being deployed via social media and direct emails to online dive shops and divers communicating in English, and therefore missed participants that are offline, with limited Internet access or not able to respond to an English questionnaire. Fortunately, in a few areas, especially those with strong regional leaders who shared the survey with their networks, including taking a printed survey to local experts that are offline – e.g., Manta Trust in the Maldives, Shark Guardian in Thailand, Gili Shark Conservation in Indonesia – increased coverage was made. However, given that many of the responses, and particularly the comments, were similar between participants within countries more effort in most areas would likely have unchanged the main results. This potential bias, however, would likely increase with country size (e.g., in Australia, the United States and Thailand, where different coasts have different species, threats and views towards coastal ecosystems). On the other hand, some countries were particularly challenging to gain participation where populations were small, and where politics, lack of reliable Internet access, and other factor limited participation. Fourth, the varying timelines between countries could potentially introduce a bias, whereas those with longer timelines may observe more pronounced changes in shark populations. We tested for this, but found only one significant trend, possibly because much of the observed change happened relatively recently. Fifth, there is a possibility of underreporting on chumming or spearfishing, especially if these activities are illegal or objectionable. Sixth, although all participants were divers, some observations may have been made during other activities – it is a challenge to separate these observations. However, since we are looking at relative differences and broad patterns, this is unexpected to influence the results overall. Finally, a few countries were difficult to get participants from because sharks are so rarely observed, and the response to the survey request, despite clarifying the value of negative observations, was simply 'there are no sharks here' (i.e., Jamaica).

4.3. Effort and observations

Despite these limitations, hundreds of divers contributed hundreds of thousands of dive observations across thousands of sites dating back to 1954. The majority of participants were expert divers, many with decades of local experience. Across all submitted countries, shark abundance was high enough to be detected by divers at the level of effort provided. Gaining these perspectives was an initial concern, especially for some of the Caribbean shark sanctuaries where shark abundance has been low in recent decades (Ward-Paige et al., 2010a). This variability in shark population status and human uses, even between adjacent countries, indicates the importance of local factors, such as the history of fishing, management and shark awareness. For example, the Bahamas has seen decades of shark-focused research through the Bimini Shark Lab, a longstanding ban on commercial longline fishing (officially since early 1990's; Hepp and Wilson, 2014), a fishery known to have high shark bycatch (Oliver et al., 2015), and a lucrative shark-based dive tourism industry (Cline, 2008). All of these factors make the Bahamas a best-case scenario for a shark sanctuary. Thriving and protected shark populations in the Bahamas, with well described shark habitats and identified nurseries (Brooks et al., 2013; Jennings et al., 2008; Murchie et al., 2010), means that adjacent areas may benefit from spillover (e.g., Turks and Caicos, see Fig. 7). However, in other areas where sharks are relatively rare (e.g., Aruba, Bonaire and Curaçao), the effects of protection may be imperceptible on short timescales, suggesting the importance of continuous monitoring to document changes and potential spillover effects at this scale.

4.4. Shark sanctuary awareness

There was generally good awareness of shark sanctuaries, and what motivated their designation, across most relevant countries. The exceptions were Grenada and Curaçao, but these participants filled out the questionnaire in the months preceding the 2016 shark sanctuary announcement; since then awareness has likely increased. As the main objective is to ban commercial shark fishing, divers are not directly impacted by the regulations. An exception is the ban on shark provisioning (chumming) in some countries. These countries, with previous chumming practices included: French Polynesia (55%), New Caledonia (33%), the Cook Islands (14%), Palau (13%), and the British Virgin Islands (0%). A high level of awareness of sanctuary policy suggests high interest in shark conservation, and more generally marine conservation, and may also be a result of recent education and publicity surrounding the shark sanctuary. How this awareness changes through time, has yet to be seen: 100% of respondents were fully aware of the shark sanctuary in Palau, the oldest shark sanctuary, thus awareness among the public may very well increase over time.

4.5. Commercial fishing threats

The need to reduce the threat to sharks from existing commercial fishing was identified as the primary motivation for shark sanctuaries by survey participants. This corresponds to the publicized impetus for shark sanctuaries (officially since early 1990's; Hepp and Wilson, 2014) (www.pewtrusts.org, where, for example "… diminishing numbers have already had wide-ranging negative impacts" (Palau Senate Bill No. 8-105, 2009; see Ward-Paige, 2017). It also matches the reconstructed catch data for these countries, showing the relative importance of commercial fishing for shark landings (Ward-Paige, 2017), and the results of other studies based on various data sources (Dulvy et al., 2014; Worm et al., 2013). However, shark sanctuary legislation primarily only bans targeted shark fishing and the retention of shark bycatch. It does not deter commercial fishing for other species, and bycatch is a significant source of shark mortality across many commercial fisheries (Oliver et al., 2015). Even if discarded with the best intentions and under ideal conditions, bycaught sharks can still suffer lethal or sublethal injuries (Skomal, 2007). Therefore, unless there are other changes to mitigate bycatch, mortality rates may still be substantial. Notably, only a few countries implemented gear restrictions as part of the shark sanctuary legislation to reduce incidental shark catch and mortality (i.e., the Cook Islands, Marshall Islands, Micronesia and Caribbean Netherlands). However, detecting the differences between these management measures on shark populations will be a challenge, especially since bycatch is required to be discarded, largely without documentation. Possibly, catch data combined with examination of vessel monitoring systems data (VMS) and automatic identification systems (AIS) could be used to track any changes in fisheries behavior following shark sanctuary implementation (e.g., via Global Fishing Watch, McCauley et al., 2016).

4.6. Preventative situations

An added complication to examining changes in fishing behavior and catch rates as a result of shark sanctuary implementation is the case of preventative measures. The Bahamas for example, had long since banned commercial long-line fishing with relatively large marine protected areas and a thriving shark-dive tourism industry, all which help explain why sharks are relatively abundant (Ward-Paige et al., 2010a). Just prior to the implementation of the shark sanctuary, a commercial fishery venture applied to initiate a commercial shark fin export from the Bahamas (Hepp and Wilson, 2014). For such preemptive closures, changes to shark populations or to the fisheries may not be expected. Possibly, the long-term persistence and prevalence of sharks, combined with an enduring shark dive tourism industry, are proper indicators of success in these cases. Monitoring these metrics, and tracking changes in either of them, could be useful indicators of sanctuary performance.

4.7. Other threats

Many participants also expressed concern about recreational and artisanal shark fishing, as well as habitat destruction, ghost gear and marine debris. Reconstructed catch data suggested that the Maldives, Honduras and the Cook Islands had significant artisanal and subsistence shark catch, and the Bahamas had significant recreational shark catch before shark sanctuary implementation (Ward-Paige, 2017). However, none of these countries made exemptions for subsistence, artisanal or recreational uses (only Palau, Marshall Islands and the British Virgins Islands made some allowances for personal use, see Ward-Paige, 2017). So, these concerns may be diminished, if there is compliance and enforcement. Ghost gear, marine debris, habitat destruction and general land-based pressures have been documented in many shark species and marine ecosystems (Jennings et al., 2008; Sandin et al., 2008; Ward-Paige et al., 2010a; Whitney et al., 2011); however, with the exception of habitat destruction across many coastal and marine ecosystems, which is widespread and comprehensively investigated (Lotze et al., 2006; Orth et al., 2006; Pandolfi, 2003; Polidoro et al., 2010), other threats are just beginning to be described on a global scale (Jambeck et al., 2015; Stelfox et al., 2016) and the significance of these threats to sharks has yet to be investigated.

Climate change and associated threats, including sea level rise, warming and acidification, were the lowest ranked threats across all countries. However, these are relatively inconspicuous to assess by observation on the spatiotemporal scales of participant experience. Despite this, one comment did refer to climate change, suggesting an ecosystem effect on sharks, where "Climate change related threats are important as most sharks we see are dependant on the reef and are therefore indirectly affected by climate change as the reef degrades" (Maldives, 1000 dives, since 2013).

4.8. Rebuilding

Some participants from countries with few sharks commented that

shark conservation might be unnecessary since sharks are so rarely observed. This was mostly the case in Caribbean nations where shark diversity and abundance was relatively low. This local rarity of sharks has been documented previously (Ward-Paige et al., 2010a); however, the same study showed that, based on habitat distribution models and historical information, that many shark species should be seen throughout the Caribbean in much higher abundance and frequency than what is observed today. Ward-Paige et al. (2010a) also used population viability analysis to show that even light levels of fishing mortality, well within the range expected for the area, could easily explain the large-scale absence of sharks. Therefore, although these areas are currently lacking sharks, it is possible that sharks could rebuild and become more common in these areas, given appropriate measures.

4.9. Needs for improved conservation measures

The majority of comments suggested the need for improved conservation, enforcement, education and monitoring measures. Prioritizing conservation tactics depends on local conditions and existing plans for sharks (e.g., shark finning bans, protected species, etc.; see Fischer et al., 2012 for summaries of some of the non-shark sanctuary countries, and Ward-Paige, 2017 or details on the shark sanctuary countries). Fig. 7 provides insight on what focal efforts could occur at the country scale, based on the data reviewed here. For example, in countries with low catches, low market observations and high abundance – French Polynesia, South Africa, the Bahamas and Fiji for example – conservation could be preventive. The focus may be on eliminating illegal, unreported and undocumented fishing (IUU), reducing bycatch, identifying and protecting essential habitat areas, mitigating non-fishing threats, supporting conservation-oriented industries (e.g., dive tourism) to use best-practices, and implement monitoring and education programs. Also, incorporating known locations and distributions of sharks into multi-species marine protected area planning, would be useful.

On the other hand, countries with high catches and market observations, and with high or medium observed abundance – Mexico, Costa Rica, Brazil, Mozambique, Kenya, Philippines, St. Maarten, Indonesia and Thailand for example – conservation and management needs to be proactive. Some of these are among the top shark fishing nations (Mexico, Brazil, Indonesia and Thailand; Fischer et al., 2012) and some do not yet have even the most basic conservation measures, such as shark-finning bans or National Plans of Action for sharks (NPOA Sharks; Fischer et al., 2012). These countries may employ the above-mentioned preventative measures, but also need much stronger legislation to reduce shark mortality. Eliminating illegal, unreported and undocumented fishing (IUU), enforcing fins naturally attached policy, reducing targeted shark fisheries and other fisheries that have high shark bycatch, imposing gear limits to reduce shark bycatch, and implementing limited entry and no-take protected areas (monitored by VMS) are some of the possible mechanisms.

Enforcement measures of shark sanctuary legislation are difficult to assess. In most countries, no news stories regarding compliance failures or enforcement of shark sanctuary regulations were found (Google News search for ‘shark sanctuary’ and ‘shark catch’ in each country). One exception was in the Bahamas in March 2016, where the killing of a tiger shark was ‘strongly condemned’ by the Bahamas National Trust, but no charges were made (http://www.tribune242.com/news/2016/mar/07/killing-tiger-shark-condemned-bnt/, accessed 11 November 2016). As well, a few news stories from Palau have documented some of the enforcement tactics used to catch and penalize illegal vessels fishing for sharks (http://www.nytimes.com/2016/02/21/magazine/palau-vs-the-poachers.html, accessed 11 November 2016). In most cases, compliance failure or enforcement may not be reported, or make it to international news, but these rare occurrences suggest that this is an area that could be improved.

For education and monitoring, the organization *Shark Guardian* (Sharkguardian.org) was recommended by multiple people in different countries for providing effective programming, with comments like “Shark Guardians are strong with this” (Indonesia, 2000 dives, since 1998), “Shark Guardian are doing their best”(Indonesia, 30 dives, since 2005), and “Through Shark Guardian research projects, educational talks and collaboration with local government there definitely seems to be a greater shift towards protecting sharks and rays.”(Thailand, 800 dives, since 2007). In addition to educational programming, Shark Guardian provides outreach and awareness for divers’ to participate in eShark event-based monitoring (an eOceans.org project). Through this collaborative effort, eShark has received > 19,000 dive records on 101 sites across Thailand, resulting in ongoing documentation of shark observations (including zeros) and scientific publications documenting spatiotemporal and priority conservation areas for sharks in Thailand (Ward-Paige, 2017). Although these results are recent, and have yet to result in policy or management changes, implementing similar education programs elsewhere may increase public understanding and awareness of sharks and help with the collection of baseline information.

5. Conclusion

In summary, this study provides the first baseline study of sharks, human use patterns and threats in shark sanctuaries, within a global context. Similar to previous work on manta and mobula rays (Ward-Paige et al., 2013), it highlights the value of integrating the analysis of citizen science data from recreational scuba divers with fisheries and catch data to identify priority conservation needs and strategies for elasmobranchs on a large scale. Our findings demonstrate that shark populations, human use patterns and threats are geographically heterogeneous, suggesting there is no ‘one size fits all’ conservation strategy for all countries. However, given that threats, declines in populations and overall concerns for sharks appear to be lower within shark sanctuaries compared to non-shark sanctuaries, and that general awareness of the shark sanctuary regulations is high, there is cause for optimism that shark sanctuaries may provide quantifiable benefits. Across all these countries, there is a need for better assessment of shark bycatch in commercial fisheries, in-situ monitoring of recreational fisheries catches, and event-based observations made by recreational divers and other ocean explorers, as well as other human use metrics (e.g., tourism and market composition) to measure the success of shark sanctuaries so that their benefits may be optimized over time.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2017.09.005.

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