Received: 24 July 2022 | Revised: 4 June 2023 | Accepted: 27 June 2023

DOI: 10.1002/aqc.3989

RESEARCH ARTICLE

WILEY

Marine megafauna catch in Thai small-scale fisheries

Thevarit Svarachorn[1] | Andrew J. Temple[1,2] | Per Berggren[1]

[1]School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK

[2]Red Sea Research Center, King Abdullah University of Science and Technology, Thuwal, Makkah, Saudi Arabia

Correspondence
Per Berggren, School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom.
Email: per.berggren@ncl.ac.uk

Funding information
Institute for the Promotion of Teaching Science and Technology; Development and Promotion of Science and Technology Talents Project (DPST)

Abstract

1. Small-scale fisheries are a global conservation threat to marine megafauna (marine mammals, sea turtles, and elasmobranchs). There is currently limited information about marine megafauna catch in Thailand's small-scale fisheries, which is required for effective management.
2. This study represents the first independent catch assessment of marine megafauna in Thai small-scale fisheries. Data on catch and fisheries effort across 1 year (2016–2017) were collected from questionnaire interviews with 535 fishers in 17 provinces along the Gulf of Thailand and the Andaman Sea coasts. Catch per unit effort was calculated for marine megafauna by fishing gear types and extrapolated to estimate annual catches using Thai official fisheries statistics.
3. The annual estimated catches were 5.66 million (95% confidence interval, CI: 4.10–7.82 million) rays, 457,864 (95% CI: 192,352–969,166) sharks, 2,400 (95% CI: 1610–3,537) sea turtles, 790 (95% CI: 519–1,167) small cetaceans, and 72 (95% CI: 19–194) dugongs in Thai small-scale fisheries.
4. Gillnets had the highest catch per unit effort for all megafauna groups in both sea areas except for sea turtles, where pound nets had the highest catch per unit effort in the Gulf of Thailand. Further, among gillnets, crab gillnets had the highest catch per unit effort for all groups except dugongs, where ray gillnets had the highest catch per unit effort. Accounting for effort, crab gillnets and shrimp trammel nets were responsible for most of the megafauna catch, where crab gillnets contributed 72%–95% of the annual estimated marine megafauna catch. Crab gillnets and shrimp trammel nets were used by 46% and 40% respectively of the interviewed fishers and by 27% and 15% respectively of all small-scale fishers operating in Thai waters.
5. Restrictions for gillnet fishing effort (crab gillnets specifically) are needed to prevent extirpation of threatened megafauna species that are important for ecosystem resilience and productivity.

KEYWORDS
artisanal fisheries, by-catch, elasmobranch, marine mammal, sea turtle, Thailand

1 | INTRODUCTION

Marine megafauna (cetaceans, dugongs, sea turtles, and elasmobranchs) are threatened by a range of anthropogenic activities including: fisheries catch (i.e. catch and by-catch) (Reeves, McClellan & Werner, 2013; Dulvy et al., 2014; Burgess et al., 2018), habitat destruction (Muir et al., 2003; Karczmarski et al., 2017; Balladares & Barrios-Garrido, 2021; Dulvy et al., 2021), and vessel-based tourism (Christiansen & Lusseau, 2014; Schofield et al., 2015; Healy et al., 2020). Catch and by-catch in fisheries (hereafter referred to as 'catch') represent the greatest threat to marine megafauna (Read, Drinker & Northridge, 2006; Lewison et al., 2014; Dulvy et al., 2021) currently threatening a number of populations and species with extirpation and extinction (Brownell et al., 2019). Thai large-scale/industrial/commercial fisheries catches have been recognized for their detrimental impacts on marine megafauna (Krajangdara, 2014; Teh, Zeller & Pauly, 2015); however, impact from catch in small-scale/artisanal fisheries (SSFs) have received comparatively little attention to date (e.g. Temple, Westmerland & Berggren, 2021).

Thai SSFs are likely to be an important contributor to the catch of marine megafauna in Thailand. The average annual estimated marine catch in the SSFs between 2015 and 2017 was 84,075 tons in the Gulf of Thailand (9% of all fisheries catch in the Gulf of Thailand) and 76,996 tons in the Andaman Sea (20% of all fisheries catch in the Andaman Sea) (De Leon & Derrick, 2020). Thai SSFs are primarily conducted for local subsistence and local commercial purposes with <10 tons of vessel capacity, and they use a broad range of hand-operated fishing gears, including gillnets and longlines, known to catch marine megafauna (Pimoljinda, 2002; Lymer et al., 2008). According to the Thai official fisheries statistics, the dominant SSF gears in the Gulf of Thailand are crab gillnets (29% of all gears used), other gillnets (25%), and squid falling nets (18%), whereas in the Andaman Sea other gillnets dominate (39% of all gears used), followed by shrimp trammel nets (24%) and crab gillnets (21%) (DOF, 2016). SSFs are economically essential as sources of income and livelihood for Thai coastal communities (Teh, Zeller & Pauly, 2015).

Depending on geographical area and fishery, marine megafauna may be considered as either target or nontarget species in Thai SSFs, and most have some commercial value as consumable and marketable products (Krajangdara, 2014; Krajangdara, 2017). Elasmobranchs (rays, skates, and sharks) are caught by a wide range of SSF gears, including gillnets, long/hand lines, and traps (Krajangdara, 2017). Their fins and meat are commercially valuable and are traded among communities or sold to restaurants (Krajangdara, 2014). Elasmobranch skins are also sold to the leather-wear industry (Krajangdara, 2014). In contrast, intentional catches of cetaceans (toothed and baleen whales), dugongs (*Dugong dugon*), and sea turtles are prohibited (GG, 1992; GG, 2014; GG, 2019). However, fisheries incidental catch has been identified as a cause for concern for cetaceans, as indicated by the more than 550 recorded cases of strandings in Thailand during the past three decades, where fishing gear entanglement and disease were identified as likely causes of mortality (Adulyanukosol, Thaongsukdee & Kittiwattanawong, 2012).

Understanding the current megafauna catch in Thailand is key to assessing whether current levels of exploitation of the marine environment are sustainable. As apex/mesopredators (cetaceans and elasmobranchs), primary consumers (sea turtles), and mega-grazers (dugongs), marine megafauna contribute to the stability and productivity of marine ecosystems (Heithaus et al., 2008; Kiszka, Heithaus & Wirsing, 2015; Tavares et al., 2019). Hence, the decline, extirpation, or extinction of megafauna species risks destabilizing and/or restructuring ecosystems through trophic cascade (Pinnegar et al., 2000). There are currently 158 elasmobranch (82 rays and 76 sharks), 27 cetacean (22 toothed whales and 5 baleen whales), 5 sea turtle, and 1 sirenian (i.e. dugong) species known to occur in Thai waters of the Gulf of Thailand and the Andaman Sea (Adulyanukosol et al., 2014; Krajangdara, 2017). Despite the relatively high diversity of marine megafauna in Thailand, there is little available information on species abundance and fisheries interactions. Basic data on SSFs catch and effort for the different gear types used are essential for assessment and monitoring of megafauna catch, fisheries management, and informing any need for conservation action.

This study aims to provide the first independent assessment of marine megafauna catch in Thai SSFs by combining catch composition and catch per unit effort (CPUE) data derived from interviews with SSF fishers in the Gulf of Thailand and the Andaman Sea with official fisheries effort statistics from the Department of Fisheries, Thailand.

2 | MATERIALS AND METHODS

2.1 | Study sites

Face-to-face questionnaire-based interviews ($n = 535$) were conducted in Thai with fishers during September to December 2017 at 32 fishing communities across 17 provinces (Figure 1). The 535 fishers interviewed represented 5.1% of the 10,413 SSF vessels in the 17 provinces (DOF, 2016) (Supporting Information Data S1) where the questionnaire was implemented, with a 4.1% margin of error at the 95% confidence level (https://www.surveymonkey.com/mp/sample-size-calculator/). Of the total 535 interviews, 335 were conducted in 11 provinces in the Gulf of Thailand and 200 in six provinces in the Andaman Sea. The sample sizes of 335 and 200 for the Gulf of Thailand and the Andaman Sea respectively represented a 5.2% and a 6.7% margin of error respectively at the 95% confidence level of the populations of vessels in the two sea areas (7,661 and 2,752 respectively) (https://www.surveymonkey.com/mp/sample-size-calculator/). In each fishing community, 30–35 randomly selected fishers were interviewed (normally the captain and ensuring only one respondent per vessel). Seven out of the 24 provinces were excluded from the interviews due to low fishing effort and safety risk from insurgency in some provinces.

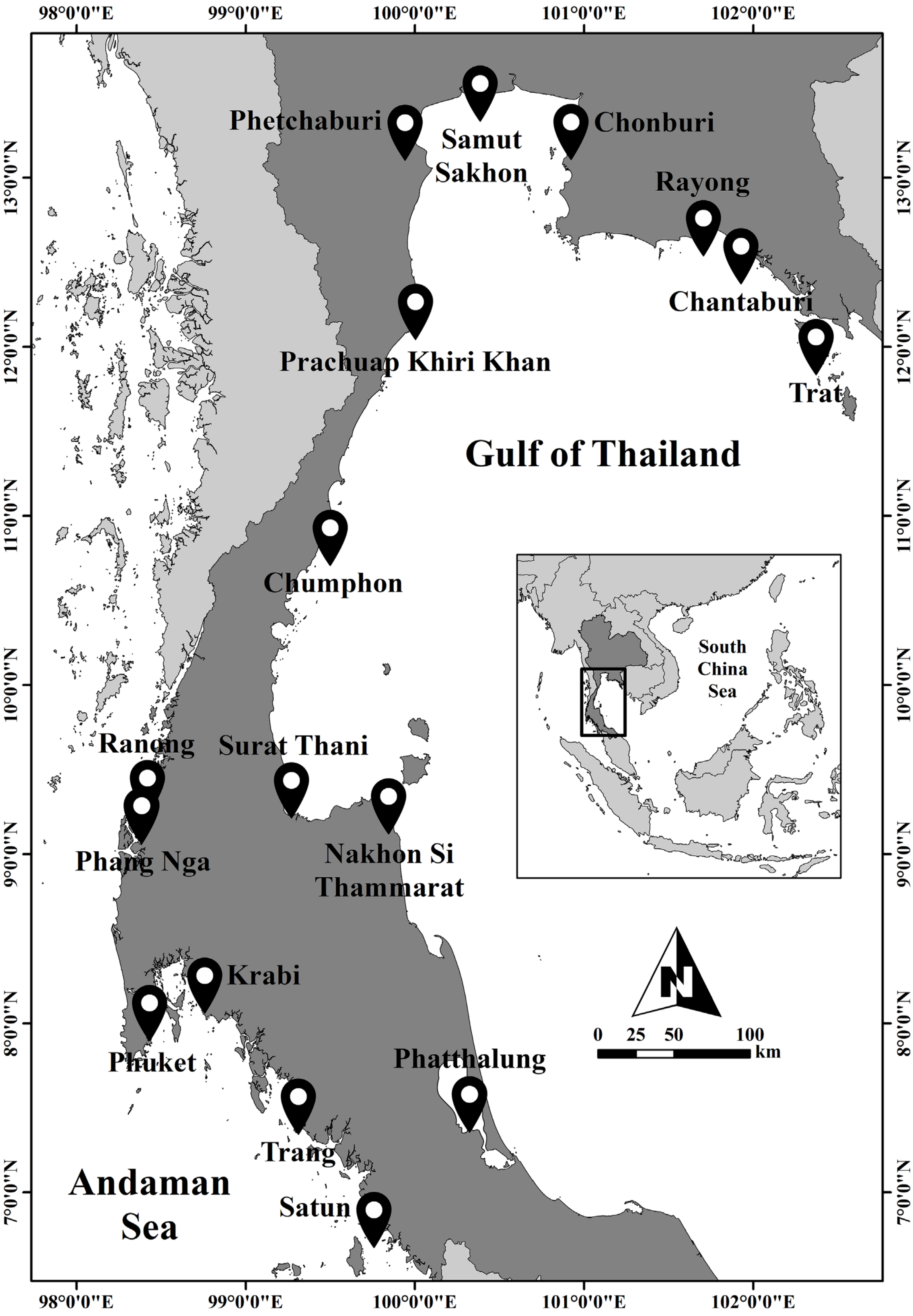

FIGURE 1 Location of the sites in the 17 provinces where 535 questionnaire interviews were conducted to assess marine megafauna catch in the small-scale fisheries in the Gulf of Thailand and the Andaman Sea between September 2016 and December 2017.

2.2 | Questionnaire interview and data

Before conducting the interviews, the respective community/village leaders were contacted to ask for permission to conduct the interviews. On the day of the interviews, the interviewer was escorted by the community/village leader, or the leader's assistant, to access the community areas, where the interviews were conducted. The interviews took 5–10 min, depending on the level of detail in which fishers reported their catches and fishing activities. Verbal consent was obtained prior to the interviews. Fishers were advised that they could choose not to answer any particular question and that they could end the interview at any time. The interviews were strictly confidential to protect fishers' identities (Supporting Information Data S2).

The semi-structured interview protocol (Supporting Information Data S2) was adapted from previously used protocols (Moore et al., 2010; Alfaro-Shigueto et al., 2018; Temple et al., 2020) and covered fishing activities conducted during the 12 months (1 year) preceding when the interview took place. The interviews included two sections: (1) fishing effort, and (2) marine megafauna catch. The fishing effort section covered gear type and gear configuration, effort (number of gears used per fishing day and number of days fished per month/year), fishing location (including kilometres from shore), and target species. The marine megafauna catch section included species group caught, catch number of each species group, month of catch, gear used, location, and utilization of catch.

A marine megafauna species identification photobook (Supporting Information Data S3), adapted from Adulyanukosol et al. (2014) and Krajangdara (2017), was used during the interviews to help confirm the species identity of catches. Where possible, catches were resolved to species or genus levels; in some cases, several genera were grouped where identification before the family level was difficult or inconsistent (Supporting Information Data S4). The gears declared by the fishers were classified into the 21 categories (Supporting Information Data S5) used in the Thai fishing vessels statistics in 2014 (DOF, 2016) (Supporting Information Data S1).

2.3 | Data analyses

CPUE was calculated for each species group by gear type and province using the data from the interviews. CPUEs were then raised to the regional and national levels using total fisheries effort (number of vessels using respective gear in each region: Gulf of Thailand and Andaman Sea) from the official Thai fishing vessels statistics in 2014 (DOF, 2016).

2.3.1 | Catch per unit effort

CPUEs for each megafauna group by gear for each province were calculated using the formula

$$\mathrm{CPUE_P} = \sum_{i=1}^{n} \frac{C_i}{E_i}$$

where $\mathrm{CPUE_P}$ is the CPUE by gear type generated from each province, C_i is the total number of animals (for each megafauna group) caught per year using the corresponding fishing gear type (as reported by the respondents to the questionnaire interviews), and E_i is the number of interviewees using the corresponding fishing gear type. A percentile bootstrap procedure (IBM SPSS Statistics 25) was used to determine the asymmetric 95% confidence interval (CI) for each CPUE value.

CPUEs were calculated separately for the two regions (Gulf of Thailand and Andaman Sea). Regional weighted CPUEs were calculated using the formula

$$\mathrm{CPUE_R} = \sum_{i=1}^{n} \left(\mathrm{CPUE_P} \times \frac{E_\mathrm{P}}{E_\mathrm{R}} \right)$$

where $\mathrm{CPUE_R}$ is the catch per year per vessel at the regional level, E_P is the total number of fishing vessels using the corresponding fishing gear type in each province as reported by the Thai fisheries statistics (DOF, 2016), and E_R is the total number of fishing vessels using the corresponding fishing gear type in each sea region (Gulf of Thailand/Andaman Sea) as reported by the Thai fisheries statistics (DOF, 2016). Regional asymmetrical 95% CIs corresponding to their regional weighted CPUEs were calculated using the following formulas:

$$L_\mathrm{R} = \mathrm{CPUE_R} - \sqrt{\sum_{i=1}^{n} \left((\mathrm{CPUE_P} - L_\mathrm{P}) \frac{E_\mathrm{P}}{E_\mathrm{R}} \right)^2}$$

and

$$U_\mathrm{R} = \mathrm{CPUE_R} + \sqrt{\sum_{i=1}^{n} \left((U_\mathrm{P} - \mathrm{CPUE_P}) \frac{E_\mathrm{P}}{E_\mathrm{R}} \right)^2}$$

where L_R is the lower limit of $\mathrm{CPUE_R}$, U_R is the upper limit of $\mathrm{CPUE_R}$, L_P is the lower limit corresponding to the $\mathrm{CPUE_P}$, and U_P is the upper limit corresponding to the $\mathrm{CPUE_P}$. Furthermore, CPUE per vessel per trip and its corresponding 95% CI were calculated using the following formulas:

$$\mathrm{CPUE_T} = \frac{\mathrm{CPUE_R}}{\sum_{i=1}^{n} E_\mathrm{r}/n}$$

$$L_\mathrm{T} = \frac{L_\mathrm{R}}{\sum_{i=1}^{n} E_\mathrm{r}/n}$$

$$U_\mathrm{T} = \frac{U_\mathrm{R}}{\sum_{i=1}^{n} E_\mathrm{r}/n}$$

where $\mathrm{CPUE_T}$ is the catch per vessel per trip at the regional level, E_r is the total number of days each fishing gear type was used in each sea region (Gulf of Thailand/Andaman Sea) as reported by the respondents to the questionnaire interviews, n is the number of interviewees using the corresponding fishing gear type, U_T is the lower limit of $CPUE_T$, and U_R is the upper limit of $CPUE_T$. All fishers reported having one fishing trip per day.

2.3.2 | Annual estimated catch

Annual estimated catch was extrapolated for each sea region by multiplying the calculated $CPUE_R$ by the total number of fishing vessels using the corresponding gear in the Gulf of Thailand and the Andaman Sea, respectively as reported in the Thai fishing vessels statistics (DOF, 2016) (Data S1). Annual estimated catches and corresponding 95% CIs were calculated as:

$$AEC = CPUE_R \times E_R$$

and

$$CI_{AEC} = CI_R \times E_R$$

where AEC is the annual estimated catch, CI_{AEC} is the 95% CI corresponding to the AEC, and CI_R is the 95% CI corresponding to the $CPUE_R$.

2.3.3 | Comparison of CPUEs among fishing gears

A generalized linear model (GLM) was used to investigate potential variability of megafauna group reported CPUEs among fishing gears. The GLM model is as follows:

$$\text{Catch rate} = \beta_0 + \beta_1(\text{CPUE}_P : \text{gear } 1) + \ldots + \beta_n(\text{CPUE}_P : \text{gear } n)$$

where β_0 is the intercept and β_1 to β_n are coefficients. The negative binomial family was fitted to account for the overdispersion of the catch data. The Huber–White standard errors (Huber, 1967; White, 1980) approach was used to allow the fitting of a model that does contain heteroscedastic residuals, and the Bonferroni correction (Bonferroni, 1936) was applied in the post hoc tests to adjust significance levels for multiple tests to avoid type I error. Post hoc tests (pairwise comparisons; Shiraishi, Sugiura & Matsuda, 2019) were conducted to investigate if there were significant differences in the CPUEs between gears for each megafauna group using estimated marginal means as a measure. All statistical tests were performed using IBM SPSS Statistics 25.

3 | RESULTS

3.1 | Reported catches

The annual marine megafauna catches in 2016–2017 as reported by respondents to the questionnaire were 419,821 rays, 28,920 sharks, 269 sea turtles, 47 small cetaceans, and 6 dugongs, of which 231,992 rays, 20,084 sharks, 246 sea turtles, 44 small cetaceans, and 5 dugongs were reported for the Gulf of Thailand and 187,642 rays, 8,836 sharks, 23 sea turtles, 3 small cetaceans, and 1 dugong for the Andaman Sea.

3.2 | Catch per unit effort

3.2.1 | CPUE per vessel per year

In the Gulf of Thailand, crab gillnets (Supporting Information Data S6) had the highest CPUE for rays (1,040 rays per vessel per year; 95% CI: 608–1,631), sharks (86 sharks per vessel per year; 95% CI: 15–224), and small cetaceans (0.22 cetaceans per vessel per year; 95% CI: 0.14–0.32), whereas pound nets had the highest CPUE for sea turtles (7.6 sea turtles per vessel per year; 95% CI: 4.1–12.3) and ray gillnets for dugongs (0.2 dugongs per vessel per year; 95% CI: 0.0–0.6) (Figure 2 and Table 1). In the Andaman Sea, crab gillnets also had the highest CPUE for rays (1,504 rays per vessel per year; 95% CI: 1,059–2,047) and sharks (57 sharks per vessel per year; 95% CI: 23–118), whereas squid trammel nets had the highest CPUE for sea turtles (0.5 sea turtles per vessel per year; 95% CI: 0.0–1.0). Shrimp trammel nets (Supporting Information Data S6) were the only gear that caught small cetaceans and dugongs, with CPUEs of 0.04 small cetaceans per vessel per year (95% CI: 0.00–0.10) and 0.01 dugongs per vessel per year (95% CI: 0.00–0.04) (Figure 3 and Table 1).

3.2.2 | CPUE per vessel per trip

In the Gulf of Thailand, ray gillnets had the highest $CPUE_T$ for rays (6.64 rays per vessel per trip; 95% CI: 1.89–13.04), sea turtles (36.19×10^{-3} sea turtles per vessel per trip; 95% CI: 9.05×10^{-3}–69.94×10^{-3}), small cetaceans (1.97×10^{-3} small cetaceans per vessel per trip; 95% CI: $0.00–3.93 \times 10^{-3}$), and dugongs (1.57×10^{-3} dugongs per vessel per trip; 95% CI: $0.00–5.25 \times 10^{-3}$), whereas shrimp trammel nets had the highest $CPUE_T$ for sharks (0.45 sharks per vessel per trip; 95% CI: 0.01–1.27) (Table 1). In the Andaman Sea, crab gillnets had the highest $CPUE_T$ for rays (7.29 rays per vessel per trip; 95% CI: 5.13–9.93), whereas fish bottom gillnets had the highest CPUE for sharks (0.38 rays per vessel per trip; 95% CI: 0.10–0.93). Squid trammel nets had the highest $CPUE_T$ for sea turtles (11.11×10^{-3} sea turtles per vessel per trip; 95% CI: $0.00–22.22 \times 10^{-3}$), whereas shrimp trammel nets were the only gear that caught small cetaceans and dugongs, with $CPUE_T$ of 0.26×10^{-3} small cetaceans per vessel per trip (95% CI: $0.00–0.66 \times 10^{-3}$) and 0.09×10^{-3} dugongs per vessel per trip (95% CI: $0.00–0.28 \times 10^{-3}$) (Table 1).

3.3 | Annual estimated catches

The annual estimated catches for Thai SSFs were as follows: 5,662,024 (95% CI: 4,097,779–7,817,707) rays, 457,864 (95% CI: 192,352–969,166) sharks, 2,400 (95% CI: 1,610–3,537) sea turtles,

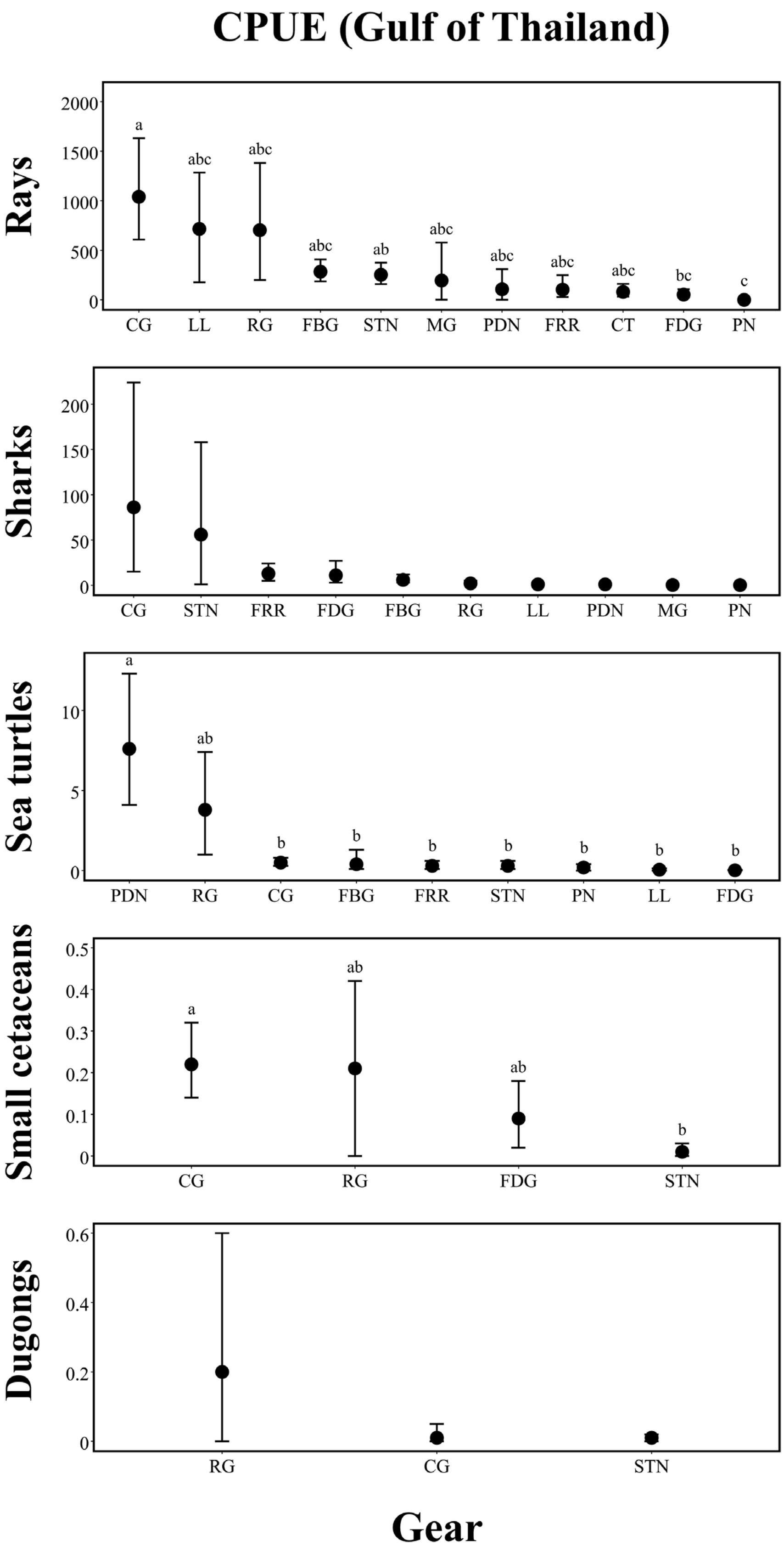

FIGURE 2 Mean catch per unit effort (CPUE; number of animals caught per vessel per year) of marine megafauna in small-scale fisheries based on questionnaire interviews from 11 provinces in the Gulf of Thailand ($n = 335$) covering the fishing activity over 12 months during the period between September 2016 and December 2017. Error bars represent asymmetric 95% confidence intervals. Different letters above the error bars indicate the gear pairs with significant differences in estimated marginal means reported CPUEs ($P < 0.05$). CG: crab gillnets; CT: crab traps; FBG: fish bottomset gillnets; FDG: fish drift gillnets; FRR: fishing rods and reels; LL: longlines; MG: mackerel gillnets; PDN: pound nets; PN: push nets; RG: ray gillnets; STN: shrimp trammel nets.

790 (95% CI: 519–1167) small cetaceans, and 72 (95% CI: 19–194) dugongs based on catches declared during a 12 month period between September 2016 and December 2017 (Table 2). In the Gulf of Thailand, the annual estimated catches of rays, sharks, sea turtles, small cetaceans, and dugongs were 4,364,690 (95% CI: 2,829,717–6,489,806), 391,711 (95% CI: 127,354–901,025), 2,279 (95% CI:

TABLE 1 Mean catch per unit effort (CPUE; number of animals caught per vessel per year) and $CPUE_T$ (number of animals caught per trip) with 95% confidence interval (CI) of marine megafauna in small-scale fisheries based on questionnaire interviews from 11 provinces in the Gulf of Thailand ($n = 335$) and six provinces in the Andaman Sea ($n = 200$) covering the fishing activity over 12 months between September 2016 and December 2017.

		Gulf of Thailand				Andaman Sea			
Marine megafauna	Gear	CPUE	95% CI	$CPUE_T$	95% CI	CPUE	95% CI	$CPUE_T$	95% CI
Rays	CG	1,040	608–1,631	4.77	2.79–7.48	1,504	1,059–2,047	7.29	5.13–9.93
	CT	80	34–162	0.27	0.12–0.55	94	32–198	0.40	0.14–0.83
	FBG	285	186–409	1.30	0.85–1.86	100	33–224	0.96	0.32–2.15
	FDG	53	22–107	0.27	0.11–0.55	30	1–92	0.22	0.01–0.69
	FRR	104	29–249	0.61	0.17–1.46	136	1–403	1.22	0.00–3.63
	HL	–	–	–	–	8	0–24	0.09	0.00–0.26
	LL	717	178–1,284	6.10	1.51–10.92	63	25–98	0.50	0.20–0.78
	MG	195	2–578	1.52	0.02–4.53	22	4–58	0.21	0.04–0.55
	PDN	107	1–310	0.30	0.00–0.86	–	–	–	–
	PN	1	0–2	0.01	0.00–0.01	–	–	–	–
	RG	703	200–1,381	6.64	1.89–13.04	811	136–1,880	5.39	0.91–12.49
	STN	254	159–376	2.04	1.28–3.02	611	375–880	4.07	2.50–5.87
	XG	–	–	–	–	18	3–35	0.45	0.07–0.89
	XT	–	–	–	–	453	5–900	1.32	0.01–2.63
Sharks	CG	86	15–224	0.39	0.07–1.03	57	23–118	0.27	0.11–0.57
	CT	–	–	–	–	2	1–5	0.01	0.00–0.02
	FBG	6	3–12	0.03	0.01–0.06	39	10–96	0.38	0.10–0.93
	FDG	11	3–27	0.06	0.01–0.14	0.2	0.0–0.4	0.001	0.000–0.003
	FRR	13	5–24	0.08	0.03–0.14	30	4–82	0.27	0.04–0.74
	HL	–	–	–	–	1	0–3	0.01	0.00–0.03
	LL	1	0–3	0.02	0.00–0.03	1	0–2	0.01	0.00–0.01
	MG	0.3	0.0–0.9	0.002	0.00–0.01	3	1–4	0.02	0.01–0.04
	PDN	1	0–2	0.003	0.001–0.004	–	–	–	–
	PN	0.2	0.0–0.4	0.001	0.000–0.002	–	–	–	–
	QT	–	–	–	–	0.2	0.0–0.6	0.001	0.000–0.002
	RG	2	1–5	0.02	0.01–0.05	4	1–11	0.03	0.00–0.07
	STN	56	1–158	0.45	0.01–1.27	50	27–92	0.34	0.18–0.62
	XT	–	–	–	–	22	6–40	0.06	0.02–0.12

(Continues)

TABLE 1 (Continued)

		Gulf of Thailand				Andaman Sea			
Marine megafauna	Gear	CPUE	95% CI	$CPUE_T$	95% CI	CPUE	95% CI	$CPUE_T$	95% CI
Sea turtles	CG	0.5	0.3–0.8	2.39	1.44–3.63	0.2	0.1–0.3	0.82	0.41–1.34
	FBG	0.4	0.1–1.3	2.05	0.30–6.03	—	—	—	—
	FDG	0.02	0.01–0.05	0.10	0.03–0.26	—	—	—	—
	FRR	0.3	0.1–0.6	1.72	0.38–3.39	—	—	—	—
	LL	0.05	0.00–0.14	0.41	0.00–1.22	—	—	—	—
	MG	—	—	—	—	0.1	0.0–0.1	0.54	0.00–1.25
	PDN	7.6	4.1–12.3	21.18	11.36–34.26	—	—	—	—
	PN	0.2	0.0–0.4	0.98	0.00–2.10	—	—	—	—
	QT	—	—	—	—	0.2	0.0–0.8	0.79	0.00–2.75
	QTN	—	—	—	—	0.5	0.0–1.0	11.11	0.00–22.22
	RG	3.8	1.0–7.4	36.19	9.05–69.94	—	—	—	—
	STN	0.3	0.1–0.6	2.09	0.50–5.15	0.03	0.00–0.07	0.18	0.00–0.45
Small	CG	0.22	0.14–0.32	0.99	0.63–1.48	—	—	—	—
cetaceans	FDG	0.09	0.02–0.18	0.46	0.13–0.94	—	—	—	—
	RG	0.21	0.00–0.42	1.97	0.00–3.93	—	—	—	—
	STN	0.01	0.00–0.03	0.07	0.00–0.23	0.04	0.00–0.10	0.26	0.00–0.66
Dugongs	CG	0.01	0.00–0.05	0.07	0.00–0.22	—	—	—	—
	RG	0.2	0.0–0.6	1.57	0.00–5.25	—	—	—	—
	STN	0.01	0.00–0.02	0.06	0.00–0.19	0.01	0.00–0.04	0.09	0.00–0.28

Note: Dashes indicate no reported gear effort. $CPUE_T$ for sea turtles, cetaceans, and dugongs is $\times 10^{-3}$.
Abbreviations: CG: crab gillnets; CT: crab traps; FBG: fish bottomset gillnets; FDG: fish drift gillnets; FRR: fishing rods and reels; HL: handlines; LL: longlines; MG: mackerel gillnets; PDN: pound nets; PN: push nets; QT: squid traps; QTN: squid trammel nets; RG: ray gillnets; STN: shrimp trammel nets; XG: other gillnets; XT: other traps.

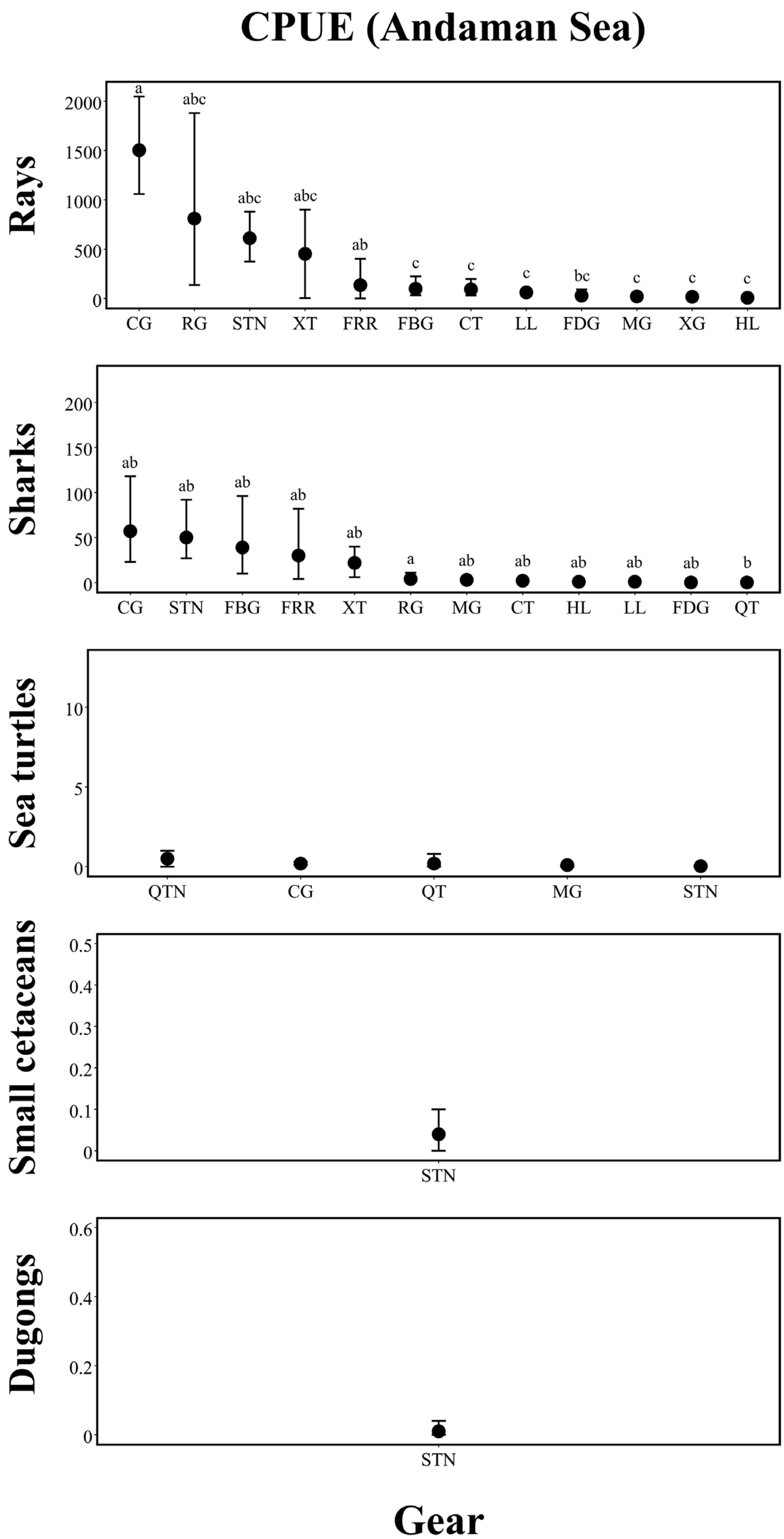

FIGURE 3 Mean catch per unit effort (CPUE; number of animals caught per vessel per year) of marine megafauna in small-scale fisheries based on questionnaire interviews from six provinces in the Andaman Sea ($n = 200$) covering the fishing activity over 12 months during the period between September 2016 and December 2017. Error bars represent asymmetric 95% confidence intervals. Different letters above the error bars indicate the gear pairs with significant differences in estimated marginal means reported CPUEs ($P < 0.05$). CG: crab gillnets; CT: crab traps; FBG: fish bottomset gillnets; FDG: fish drift gillnets; FRR: fishing rods and reels; HL: handlines; LL: longlines; MG: mackerel gillnets; QT: squid traps; QTN: squid trammel nets; RG: ray gillnets; STN: shrimp trammel nets; XG: other gillnets; XT: other traps.

1,491–3,413), 765 (95% CI: 495–1,139), and 64 (95% CI: 11–184) respectively. In the Andaman Sea, the annual estimated catches of rays, sharks, sea turtles, small cetaceans, and dugongs were 1,297,333 (95% CI: 996,140–1,659,074), 66,153 (95% CI: 41,415–111,191), 121 (95% CI: 69–190), 25 (95% CI: 0–65), and 8 (95% CI: 0–28) respectively (Table 2).

TABLE 2 Annual estimated catch (AEC) plus/minus 95% confidence interval (CI) of marine megafauna per gear type in small-scale fisheries in the Gulf of Thailand and the Andaman Sea between September 2016 and December 2017. Only gear types for which official Thai fishing vessels statistics were available are included (DOF, 2016).

		Gulf of Thailand (GOT)		Andaman Sea (AS)	
Marine megafauna	Gear	AEC	95% CI	AEC	95% CI
Rays	CG	3,626,897	2,119,886–5,686,797	872,231	613,976–1,187,379
	LL	78,113	19,399–139,997	3,603	1,449–5,572
	MG	242,377	2,638–720,363	2,299	421–6,020
	PN	185	28–397	—	—
	STN	417,118	261,747–618,677	400,058	245,943–576,639
	XG	—	—	19,143	2,948–37,571
	Total	4,364,690	2,829,717–6,489,806	1,297,333	996,140–1,659,074
	Grand total	5,662,024	4,097,779–7,817,707		
Sharks	CG	299,501	51,030–780,285	32,793	13,494–68,459
	LL	97	0–324	56	13–90
	MG	374	0–1,121	267	107–409
	PN	28	0–67	—	—
	STN	91,711	1,450–259,779	33,038	17,560–60,538
	Total	391,711	127,354–901,025	66,153	41,415–111,191
	Grand total	457,864	192,352–969,166		
Sea turtles	CG	1,815	1,098–2,759	98	49–160
	LL	5	0–16	—	—
	MG	—	—	6	0–14
	PN	32	0–67	—	—
	STN	428	102–1,055	18	0–44
	Total	2,279	1,491–3,413	121	69–190
	Grand total	2,400	1,610–3,537		
Small cetaceans	CG	751	482–1,124	—	—
	STN	14	0–46	25	0–65
	Total	765	495–1,139	25	0–65
	Grand total	790	519–1,167		
Dugongs	CG	52	0–169	—	—
	STN	12	0–38	8	0–28
	Total	64	11–184	8	0–28
	Grand total	72	19–194		

Note: Dashes indicate no reported gear efforts.
Abbreviations: CG: crab gillnets; LL: longlines; MG: mackerel gillnets; PN: push nets; STN: shrimp trammel nets; XG: other gillnets. Grand total = GOT + AS.

Crab gillnets generated the highest annual estimated catches for all marine megafauna groups in the Gulf of Thailand (Table 2) with 83%, 77%, 80%, 98%, and 81% of total catch contributions for rays, sharks, sea turtles, small cetaceans, and dugongs respectively (Figure 4). In the Andaman Sea, shrimp trammel nets were responsible for the highest annual estimated catches for sharks (50%), small cetaceans (100%), and dugongs (100%), whereas crab gillnets had the highest annual estimated catches for rays (67%) and sea turtles (81%) (Figure 4 and Table 2).

The species groups in each megafauna group that had the highest annual estimated catch in the Gulf of Thailand were small sting/whip rays (*Brevitrygon* spp.; 91%), bamboo sharks (*Chiloscyllium* spp.; 80%), green turtle (*Chelonia mydas*; 70%), listed as Endangered (Seminoff, 2004) by the IUCN Red List of Threatened Species, and Indo-Pacific bottlenose dolphin (*Tursiops aduncus*; 45%), listed as Near Threatened (Braulik et al., 2019) (Figure 5 and Table 3). In the Andaman Sea, they were small sting/whip rays (94%), bamboo sharks (94%), hawksbill turtle (*Eretmochelys imbricata*; 52%), listed as Critically Endangered (Mortimer & Donnelly, 2008), and Indo-Pacific finless porpoise (*Neophocaena phocaenoides*; 67%), listed as Vulnerable (Wang & Reeves, 2017) (Figure 5 and Table 3).

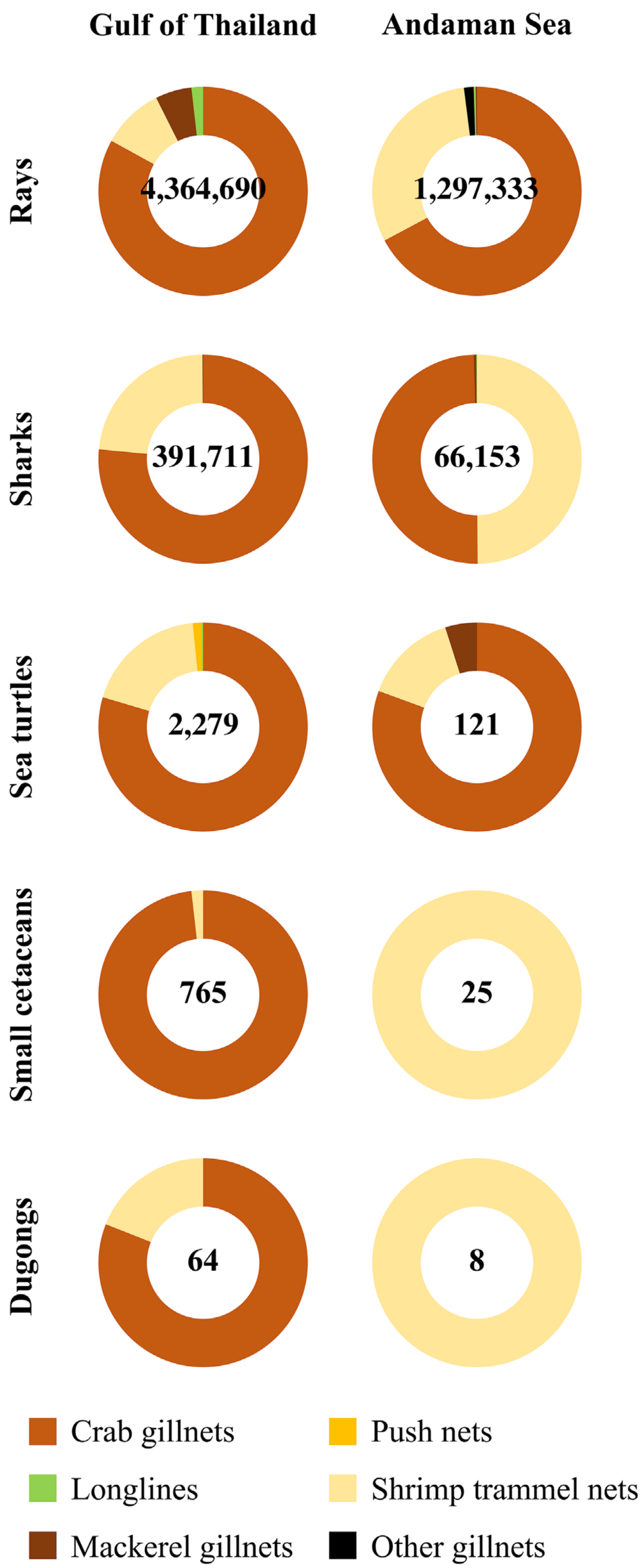

FIGURE 4 Percentage of catch contribution by fishing gear to annual estimated marine megafauna catch in small-scale fisheries in the Gulf of Thailand and the Andaman Sea between September 2016 and December 2017. Annual estimated catch is displayed in the centre of each chart.

3.4 | Comparison of CPUEs among fishing gears

In the Gulf of Thailand, ray gillnets had the highest catch rate on ray CPUE (GLM, $\chi^2 = 7.96$, $df = 1$, $P = 0.005$). Pound nets had the highest catch rate on sea turtle CPUE (GLM, $\chi^2 = 23.31$, $df = 1$, $P < 0.001$). Ray gillnets had the highest catch rate on small cetacean CPUE (GLM, $\chi^2 = 7.26$, $df = 1$, $P = 0.007$) (Supporting Information Data S7). In the Andaman Sea, crab gillnets had the highest catch rate on ray CPUE (GLM, $\chi^2 = 29.26$, $df = 1$, $P < 0.001$) and sea turtle CPUE (GLM, $\chi^2 = 4.34$, $df = 1$, $P = 0.037$) (Supporting Information Data S7). Comparisons among gears with significant differences ($P < 0.05$) in estimated marginal means reported CPUEs with corresponding *P*-values based on the GLM are summarized in Supporting Information Data S8.

4 | DISCUSSION

4.1 | Dominant catching gears

This study presents the first estimates of annual catch of marine megafauna species (rays, sharks, sea turtles, small cetaceans, and dugongs) and their respective CPUE in Thai SSFs. Crab gillnets and shrimp trammel nets contributed most of the megafauna catch in the Gulf of Thailand and the Andaman Sea. Crab gillnets were responsible for 79%, 73%, 80%, 95%, and 72% of the annual estimated catches for rays, sharks, sea turtles, small cetaceans, and dugongs respectively, whereas shrimp trammel nets were responsible for 14%, 27%, 19%, 5%, and 28% of the annual estimated catches of the respective groups. The high annual catch in crab gillnets was a product of high CPUE and relatively high effort, whereas the high annual catch in shrimp trammel nets was mainly driven by a very high effort in the gear type compared with other gears. Crab gillnets and shrimp trammel nets were used by 46% and 40% of the fishers interviewed respectively and were used by 27% and 15% of all SSF fishers operating in Thai waters (DOF, 2016) respectively.

Gillnets are globally recognized as the gear type responsible for the highest catches and mortalities of elasmobranchs (Ramírez-Amaro et al., 2013; Dulvy et al., 2014), sea turtles (Wallace et al., 2013; Lewison et al., 2014; Alfaro-Shigueto et al., 2018), and cetaceans (Reeves, McClellan & Werner, 2013; Brownell et al., 2019; Temple, Westmerland & Berggren, 2021). As the two dominant gears contributing the majority of the Thai SSF megafauna catch, crab gillnets and shrimp trammel nets represent the greatest threat to marine megafauna in Thailand and should be considered priority gear in need of mitigation and management in the context of marine megafauna catches (e.g. see Wade et al., 2021).

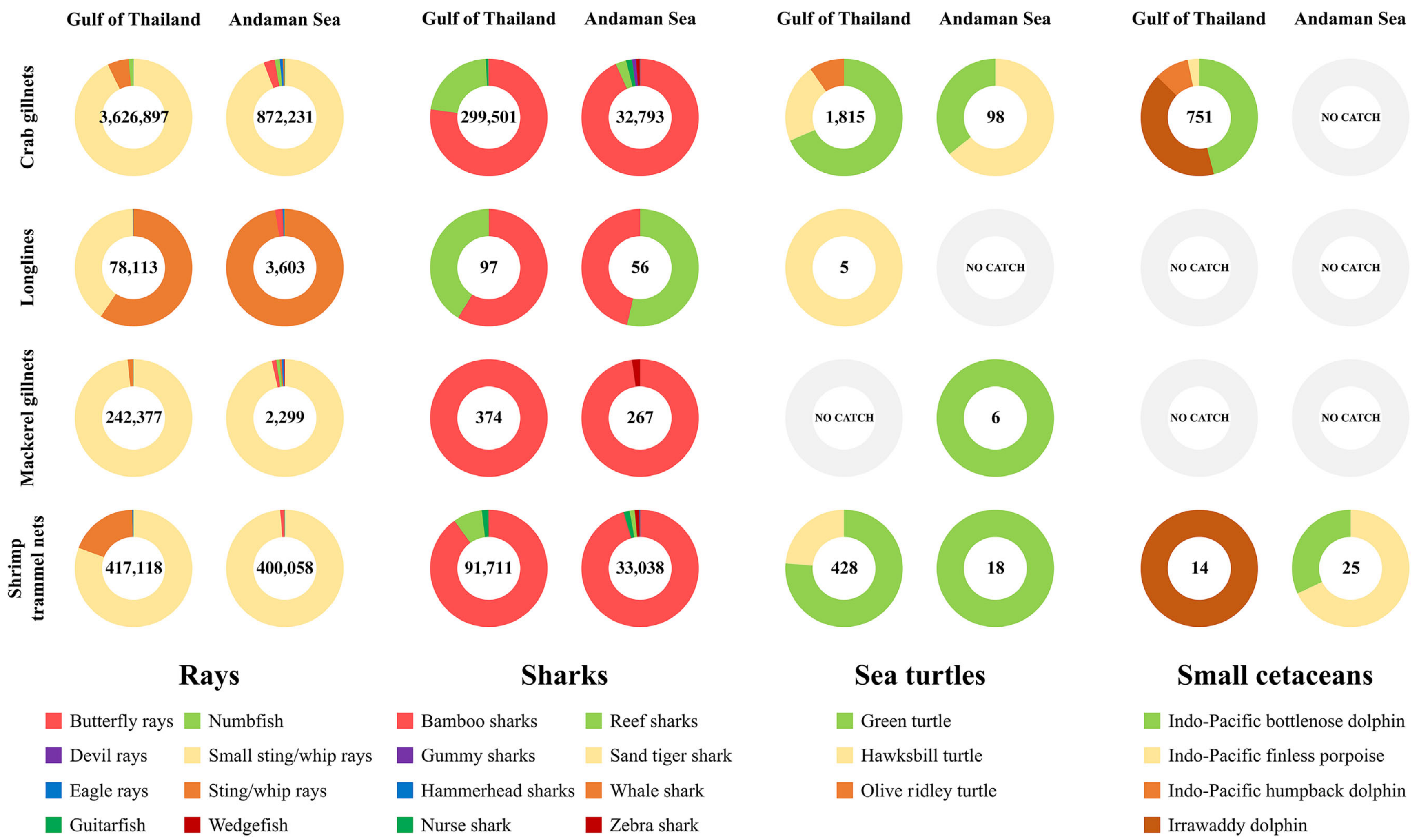

FIGURE 5 Percentage of catch contribution by fishing gear and species group to annual estimated marine megafauna catches in small-scale fisheries in the Gulf of Thailand and the Andaman Sea between September 2016 and December 2017. Annual estimated catch is displayed in the centre of each chart.

TABLE 3 Annual estimated catch (AEC) plus/minus 95% confidence interval (CI) per marine megafauna group based on species groups in small-scale fisheries in the Gulf of Thailand and the Andaman Sea between September 2016 and December 2017.

	Gulf of Thailand		Andaman Sea	
Marine megafauna species group	**AEC**	**95% CI**	**AEC**	**95% CI**
Rays				
Butterfly rays	—	—	38,513	28,233–50,731
Devil rays	—	—	5	1–14
Eagle rays	3,966	2,902–5,410	7,582	5,508–10,110
Guitarfish	35	20–54	475	334–646
Numbfish	46,151	26,975–72,362	12,331	8,740–16,713
Small sting/whip rays	3,972,401	2,548,463–5,947,778	1,218,089	931,326–1,562,156
Sting/whip rays	342,080	242,478–474,307	20,316	10,521–31,389
Wedgefish	58	34–90	21	15–31
Sharks				
Bamboo sharks	314,297	105,918–715,228	62,380	39,107–104,732
Gummy sharks	—	—	363	149–758
Hammerhead sharks	—	—	90	57–150
Nurse shark	3,949	1,444–8,720	1,088	679–1,831
Reef sharks	72,985	18,099–179,120	1,456	847–2,576
Sand tiger shark	211	54–356	—	—
Whale shark	46	16–102	—	—
Zebra shark	222	80–495	776	492–1,290
Sea turtles				
Green turtle	1,590	1,039–2,395	58	33–94
Hawksbill turtle	514	339–768	63	31–103
Olive ridley turtle	175	106–266	—	—
Small cetaceans				
Indo-Pacific bottlenose dolphin	346	222–518	8	0–22
Indo-Pacific finless porpoise	24	15–36	17	0–43
Indo-Pacific humpback dolphin	72	46–107	—	—
Irrawaddy dolphin	324	212–481	—	—
Dugongs				
Dugong	64	11–184	8	0–28

Note: Dashes indicates no reported catch.

4.2 | Concerns regarding ray and shark catches

This study further indicates that Thai SSFs affect populations of threatened species of rays and sharks. Ray catches were dominated by small sting/whiprays (92%), which are commonly found in Thai waters (Krajangdara, 2017). The remaining 8% consisted mainly of butterfly rays (*Gymnura* spp.) and eagle rays (*Aetobatus* spp. and *Aetomylaeus* spp.), genera that include a number of species listed as threatened (Vulnerable, Endangered, or Critically Endangered) by the IUCN Red List of Threatened Species such as the Endangered zonetail butterfly ray (*Gymnura zonura*) (Sherman et al., 2021) and mottled eagle ray (*Aetomylaeus maculatus*) (Rigby et al., 2020). Bamboo sharks and reef sharks (*Carcharhinus* spp.) also included several species listed as Endangered (Simpfendorfer et al., 2020; VanderWright et al., 2020b) and Vulnerable (VanderWright et al., 2020a; Rigby et al., 2021), which contributed 82% and 16% to annual estimated shark catch, respectively. The remaining 2% was contributed by nurse shark (*Nebrius ferrugineus*), listed as Vulnerable (Simpfendorfer et al., 2021), zebra shark (*Stegostoma fasciatum*), listed as Endangered (Dudgeon, Simpfendorfer & Pillans, 2019), and hammerhead sharks (*Sphyrna* spp.), listed as Critically Endangered (Rigby et al., 2019). The high annual estimated catches of rays (5,662,024; 95% CI: 4,097,779–7,817,707) and sharks (457,864; 95% CI: 192,352–969,166) indicate that the SSFs in Thailand have negative impacts in general and more specifically for the species that are already threatened with extinction.

It is also important to note that rays and sharks hold a market value as raw materials for restaurants and leather-wear industries (Krajangdara, 2014), and also being consumed and sold locally by 87% of the fishers interviewed. Although rays and sharks are generally considered as nontarget species in Thai SSFs, and it has previously been stated that there are no specific gears to catch rays and sharks in Thailand (Krajangdara, 2014), the results of this study indicate otherwise. Many of the fishers interviewed reported using ray gillnets and longlines to target rays (and possibly sharks). These were also the gear, in addition to crab gillnets, with the highest CPUEs for rays. However, longlines contributed relatively little to the annual estimated catch due to low effort (DOF, 2016).

4.3 | Concerns regarding sea turtle catch

The results indicate that gillnets, including pound nets and ray and crab gillnets, are of particular concern and threat to sea turtles in Thailand. These results resonate with assessments in other regions; for example, Ecuador, Peru, and Chile (Wallace et al., 2013; Alfaro-Shigueto et al., 2018). Although crab gillnets appeared to dominate the sea turtle catch with respect to the annual estimated catch, pound nets and ray gillnets (which had relatively higher CPUEs than crab gillnets) may also have a significant catch, but these gears were excluded from the total catch extrapolation since effort for these gears was not available in the Thai official statistics (DOF, 2016). Beside gillnets, longlines have been reported as another major SSF gear responsible for sea turtle catch with high sea turtle mortalities in many regions; for example, the south-eastern Pacific (Alfaro-Shigueto et al., 2011; Alfaro-Shigueto et al., 2018), the North Pacific (Peckham et al., 2007), and the south-western Indian Ocean (Temple et al., 2018). In contrast, the results in this study showed that both CPUEs and annual estimated catch of sea turtles in longlines were low, indicating that this gear is of lesser concern to sea turtles in Thai waters. Longlines were used by 8% of the fishers interviewed and only 1% of all Thai SSF fishers (DOF, 2016).

Given the current lack of information about sea turtle species found in Thai waters, this study cannot conclude if the estimated sea turtle catch is sustainable. However, the annual estimated catch (2,400; 95% CI: 1,610–3,537) is a serious cause for concern given that all species caught, namely green turtle (69%), hawksbill turtle (24%), and olive ridley turtle (*Lepidochelys olivacea*) (7%), are listed by the IUCN Red List as Endangered (Seminoff, 2004), Critically Endangered (Mortimer & Donnelly, 2008), and Vulnerable (Abreu-Grobois & Plotkin, 2008) respectively. Moreover, it is possible that the fishers may have underreported their catch to avoid potential legal prosecution even though the interviews were strictly confidential. Despite being experienced in how to utilize sea turtles (e.g. meat, shell, and egg), all the fishers interviewed were aware of the Wild Animal Reservation and Protection Act (GG, 1992; GG, 2014; GG, 2019), and 92% reported that they released any live caught sea turtles and the remaining 8% reported discarding any sea turtles found dead in the nets.

4.4 | Concerns regarding small cetacean and dugong catches

The annual estimated catches presented in this study—790 (95% CI: 519–1167) small cetaceans and 72 (95% CI: 19–194) dugongs—indicated that SSFs represent potential serious threats to both small cetaceans and the dugongs. As the dugong and a number of small cetacean species in Thailand are coastal inhabitants (Adulyanukosol et al., 2014), and coupled with intrinsic factors of slow growth and low fecundity rates, they are particularly vulnerable to fisheries catch (Pusineri et al., 2013; Brownell et al., 2019). There are concerns for the species that are already listed as threatened by the IUCN Red List of Threatened Species, including Irrawaddy dolphin (*Orcaella brevirostris*), listed as Endangered (Minton et al., 2017), Indo-Pacific humpback dolphin (*Sousa chinensis*), listed as Vulnerable (Jefferson et al., 2017), Indo-Pacific finless porpoise, listed as Vulnerable (Wang & Reeves, 2017), dugong, listed as Vulnerable (Marsh & Sobtzick, 2015), and Indo-Pacific bottlenose dolphins, listed as Near Threatened (Braulik et al., 2019).

According to the responses during the interviews, 77% of the small cetaceans and 100% of the dugongs caught in fishing gears were released alive by the fishers, although the fate of the animals post-release were unknown. The remaining 23% of the small cetacean catches were discarded dead and represent an anthropogenic mortality of concern for the species affected. Furthermore, the annual estimated catches of small cetaceans and dugongs reported in this study should be considered as minimum estimates. Notwithstanding that most fishers were positive and cooperative during the interviews, signs of anxiety and defensiveness were expressed by many. Potential fear of prosecution, despite assurances of confidentiality, may have influenced some fishers to not report their catch, since cetaceans and dugongs are legally protected from hunting, possessing, and importing and exporting without a permit in Thailand (GG, 1992; GG, 2014; Ezekiel, 2018; GG, 2019).

Despite more than 550 dead cetacean stranding cases recorded in Thailand from 1993 to 2009 where gillnet entanglement was identified as the likely cause of mortality (Adulyanukosol, Thaongsukdee & Kittiwattanawong, 2012), there is currently no monitoring, mitigation or management in place in Thailand to investigate and address the issue of cetacean catches. There are 27 cetacean and one sirenian species identified from Thai coastal waters (Adulyanukosol et al., 2014), but published information regarding population size and abundance is limited to a few species within a few areas (Jaroensutasinee, Jutapruet & Jaroensutasinee, 2010; Hines et al., 2015; Jutapruet et al., 2015). To date, the results presented in this study represent the only available assessment of cetacean catches in SSFs in Thailand.

4.5 | Recommendations and future works

Questionnaire interviews with local fishers have been demonstrated as a quick initial method to assess and provide useful information of fishery catch in regions where catch information is lacking (Amir, Berggren & Jiddawi, 2002; Moore et al., 2010; Temple et al., 2020; Mustika et al., 2021). Furthermore, questionnaire interviews can be logistically and financially feasible for gathering catch data in SSFs where there may be limited resources available (Moore et al., 2010; Alfaro-Shigueto et al., 2018; Mustika et al., 2021). However, questionnaire interviews rely on fishers' memories, which may cause a cognitive bias in the data by either increasing or decreasing the reported catches. In this study, fishers were asked to report their catches for the past (preceding) 12 months and used a relatively large sample size to mitigate the potential bias that likely occurs in questionnaire studies.

The annual estimated catches reported in this study should likely be considered as minimum estimates. This is due to the fact that the Thai official fisheries statistics (DOF, 2016) used for the extrapolation of annual catch estimates represents minimum SSF effort as it only included 14,946 SSF vessels classified by gear types (Supporting Information Data S1), whereas there was an average of 56,001 SFF vessels operating in the Gulf of Thailand and the Andaman Sea between 2005 and 2018 as reported to the Food and Agriculture Organization (FAO, 2020).

The questionnaire interviews reported that megafauna catches occurred in 21 SSF gear types used by fishers in 2016–2017; however, only six of the 21 gears reported had vessel numbers/efforts available in the official statistics (DOF, 2016). Hence, we were unable to include catch estimates for 15 other gears in the extrapolated annual total catch estimates. Gillnets have been identified as the gear type with the highest catch numbers of megafauna in many other regions (Kiszka et al., 2009; Reeves, McClellan & Werner, 2013; Alfaro-Shigueto et al., 2018). In this study, fish bottomset gillnets, fish drift gillnets, and ray gillnets were examples of the SSF gears that had high CPUEs according to the questionnaire data but lacked effort data in the official statistics (DOF, 2016) and which, if included, may substantially add to the annual estimated catches presented here. However, it is possible that these three gillnet types are included in the official statistics category ‘other gillnets’ and the extent to which these gears increase the annual estimated catch is unclear. Therefore, in future research it is recommended that systematic assessment and documentation (whether these are official or independent) should cover all the SSF gears used by the fishers. In future investigations, it is further recommended to include these additional gear types to allow more comprehensive assessment; however, this would also require that the official statistics are extended to cover all gears used by Thai SSFs.

The next step following this study should be to start recording all marine megafauna catch at landings sites. Following this, an onboard vessel sampling scheme could be initiated with independent observers or using remote electronic video monitoring (WWF, 2017; Bartholomew et al., 2018). Furthermore, future research would also benefit if the official Thai fisheries efforts and catch per gear type were made available and/or published to allow comprehensive assessments.

To reduce the annual catch of marine megafauna in SSFs, the use of crab gillnets and shrimp trammel nets needs to be restricted and ideally replaced by other gear to catch the target species without catching marine megafauna. Traps and pots are potential alternative fishing gears for gillnets and trammel nets because of their relatively low CPUE for marine megafauna. Light-emitting diode lights on gillnets (Lucas & Berggren, 2022), acoustic deterrent devices or ‘Pingers’ (Gazo, Gonzalvo & Aguilar, 2008; Dawson et al., 2013), by-catch reduction devices, and turtle excluder devices (Willems et al., 2016) can reduce megafauna catch and should be considered as part of future mitigation methods and regulations. Furthermore, if training is provided for the fishers and marine/coastal officers on best practice to release any live caught cetacean, dugong, sea turtle, or elasmobranch, this may substantially decrease by-catch mortality and increase post-capture survival (Zollett & Swimmer, 2019; Hamer & Minton, 2020). This requires collaboration from fishers, manufacturers, and fisheries managers. As demonstrated in other areas, despite strict enforcement, success for any mitigation method or fisheries restriction is dependent on fishers' willingness, collaboration, and compliance (Alava et al., 2019).

The research and results presented in this study provide the first crucial data and estimates of marine megafauna catch in Thai SSFs necessary to build future conservation and management actions. It further highlights that some threatened megafauna species may be at risk in Thai coastal waters and warrants immediate attention to reduce catch in SSFs to prevent species extirpation or extinction.

AUTHOR CONTRIBUTIONS

Thevarit Svarachorn: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; validation; visualization; writing—original draft; writing—review and editing. **Andrew James Temple:** Conceptualization; methodology; validation; writing—review and editing. **Per Berggren:** Conceptualization; methodology; project administration; supervision; validation; writing—review and editing.

ACKNOWLEDGEMENTS

We would like to give a special thanks to all the fishers who participated in the interviews, and to all local officers and many individuals for their hospitality and assistance during the surveys. We also express our thanks to all Marine Megafauna Lab members and colleagues from Newcastle University for their support. This work was funded by the Development and Promotion of Science and Technology Talents Project (DPST), Institute for the Promotion of Teaching Science and Technology (IPST)/the Royal Thai Government Scholarship. Andrew Temple is supported by King Abdullah University of Science and Technology (KAUST) Global Fellowship Program.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest that may influence any aspect of the work conducted. Neither the funder nor the government played any part in the study design, analysis, data interpretation, writing of the paper, and the decision to submit the research for publication.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the questionnaire interviews and the Department of Fisheries, Ministry of Agriculture and Cooperatives, Thailand (https://www.fisheries.go.th/strategy-stat/_webold/yearbook/data_2557/ThaiVessel2557.pdf).

ORCID

Thevarit Svarachorn https://orcid.org/0000-0002-9755-0353
Andrew J. Temple https://orcid.org/0000-0002-8516-8296
Per Berggren https://orcid.org/0000-0001-8204-7256

REFERENCES

Abreu-Grobois, A. & Plotkin, P. (2008). *Olive Ridley Turtle (Lepidochelys olivacea)*. Available at: https://doi.org/10.2305/IUCN.UK.2008.RLTS.T11534A3292503.en [Accessed 27th February 2022].

Adulyanukosol, K., Thaongsukdee, S. & Kittiwattanawong, K. (2012). Cetaceans and mass strandings in Thai waters [conference paper]. *Journal of Cetacean Research and Management*, 12(1), 151–158.

Adulyanukosol, K., Thongsukdee, S., Prempree, T. & Cherdsukjai, P. (2014). *Field guide to marine mammals and sea turtles of Thailand*. Bangkok, Thailand: Marine and coastal resources Research and Development Center, the upper gulf of Thailand and organizational communication division, Department of Marine and Coastal Resources.

Alava, J.J., Tatar, B., Barragán, P.M.J., Castro, C., Rosero, P., Denkinger, J. et al. (2019). Mitigating cetacean bycatch in coastal Ecuador: governance challenges for small-scale fisheries. *Marine Policy*, 110, 1–9. https://doi.org/10.1016/j.marpol.2017.05.025

Alfaro-Shigueto, J., Mangel, J., Bernedo, F., Dutton, P., Seminoff, J. & Godley, B. (2011). Small-scale fisheries of Peru: a major sink for marine turtles in the Pacific. *Journal of Applied Ecology*, 48(6), 1432–1440. https://doi.org/10.1111/j.1365-2664.2011.02040.x

Alfaro-Shigueto, J., Mangel, J.C., Darquea, J., Donoso, M., Baquero, A., Doherty, P.D. et al. (2018). Untangling the impacts of nets in the southeastern Pacific: rapid assessment of marine turtle bycatch to set conservation priorities in small-scale fisheries. *Fisheries Research*, 206, 185–192. https://doi.org/10.1016/j.fishres.2018.04.013

Amir, O., Berggren, P. & Jiddawi, N. (2002). The incidental catch of dolphins in gillnet fisheries in Zanzibar, Tanzania. *Western Indian Ocean Journal of Marine Science*, 1(2), 155–162.

Balladares, C. & Barrios-Garrido, H. (2021). Habitat degradation of a sea turtle nesting site in Venezuela (years 2014 until 2020). *Boletín del Instituto Oceanográfico de Venezuela*, 60(2), 64–67.

Bartholomew, D.C., Mangel, J.C., Alfaro-Shigueto, J., Pingo, S., Jimenez, A. & Godley, B.J. (2018). Remote electronic monitoring as a potential alternative to on-board observers in small-scale fisheries. *Biological Conservation*, 219, 35–45. https://doi.org/10.1016/j.biocon.2018.01.003

Bonferroni, C. (1936). Teoria statistica delle classi e calcolo delle probabilita. *Pubblicazioni del R Istituto Superiore di Scienze Economiche e Commericiali di Firenze*, 8, 3–62.

Braulik, G., Natoli, A., Kiszka, J., Parra, G., Plön, S. & Smith, B. D. (2019). *Indo-Pacific Bottlenose Dolphin (Tursiops aduncus)*. Available at: https://doi.org/10.2305/IUCN.UK.2019-3.RLTS.T41714A50381127.en [Accessed 27th February 2022].

Brownell, R.L., Jr., Reeves, R.R., Read, A.J., Smith, B.D., Thomas, P.O., Ralls, K. et al. (2019). Bycatch in gillnet fisheries threatens critically endangered small cetaceans and other aquatic megafauna. *Endangered Species Research*, 40, 285–296. https://doi.org/10.3354/esr00994

Burgess, M., McDermott, G., Owashi, B., Peavey Reeves, L., Clavelle, T., Ovando, D. et al. (2018). Protecting marine mammals, turtles, and birds by rebuilding global fisheries. *Science*, 359(6381), 1255–1258. https://doi.org/10.1126/science.aao4248

Christiansen, F. & Lusseau, D. (2014). Understanding the ecological effects of whale-watching on cetaceans. In: Higham, J., Bejder, L. & Williams, R. (Eds.) *Whale-watching: sustainable tourism and ecological management*. Cambridge: Cambridge University Press, pp. 177–192 https://doi.org/10.1017/CBO9781139018166.016

Dawson, S., Northridge, S.P., Waples, D. & Read, A. (2013). To ping or not to ping: the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. *Endangered Species Research*, 19(3). https://doi.org/10.3354/esr00464

De Leon, S. & Derrick, B. (2020). Thailand: updated catch reconstruction for 2011–2018. In: Derrick, B., Khalfallah, M., Relano, V., Zeller, D. & Pauly, D. (Eds.) *Updating to 2018 the 1950-2010 marine catch reconstructions of the sea around us part II: the Americas and Asia-Pacific*. Fisheries Centre Research Report, pp. 320–328.

DOF. (2016). *Thai fishing vessels statistics 2014*. Bangkok, Thailand: Fishery Information Technology Center, Department of Fisheries, Ministry of Agriculture and Cooperatives. https://www.fisheries.go.th/strategy-stat/_webold/yearbook/data_2557/ThaiVessel2557.pdf [Accessed 13th April 2017].

Dudgeon, C. L., Simpfendorfer, C. & Pillans, R. D. (2019). *Zebra Shark (Stegostoma fasciatum)*. Available at: https://doi.org/10.2305/IUCN.UK.2019-3.RLTS.T41878A161303882.en [Accessed 27th February 2022].

Dulvy, N.K., Fowler, S.L., Musick, J.A., Cavanagh, R.D., Kyne, P.M., Harrison, L.R. et al. (2014). Extinction risk and conservation of the world's sharks and rays. *eLife*, 3, e00590. https://doi.org/10.7554/eLife.00590

Dulvy, N.K., Pacoureau, N., Rigby, C.L., Pollom, R.A., Jabado, R.W., Ebert, D.A. et al. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology*, 31(21), 4773–4787. https://doi.org/10.1016/j.cub.2021.08.062

Ezekiel, A. (2018). *Review of Marine Wildlife Protection Legislation in ASEAN*. Petaling Jaya, Malaysia: S. TRAFFIC.

FAO. (2020). FAO Yearbook Fishery and Aquaculture Statistics 2018. *FAO Yearbook of Fishery and Aquaculture Statistics*. https://doi.org/10.4060/cb1213t

Gazo, M., Gonzalvo, J. & Aguilar, A. (2008). Pingers as deterrents of bottlenose dolphins interacting with trammel nets. *Fisheries Research*, 92(1), 70–75. https://doi.org/10.1016/j.fishres.2007.12.016

GG. (1992). *Wild Animal Reservation and Protection Act B.E. 2535*. Bangkok, Thailand: Royal Thai Government Gazette, The Secretariat of the Cabinet. http://www.ratchakitcha.soc.go.th/DATA/PDF/2535/A/015/1.PDF [Accessed 27th February 2022].

GG. (2014). *Wild Animal Reservation and Protection Act B.E. 2557*. Bangkok, Thailand: Royal Thai Government Gazette, The Secretariat of the Cabinet. https://nelac.kku.ac.th/laws/wildanimal.pdf [Accessed 27 February 2022].

GG. (2019). *Wild Animal Reservation and Protection Act B.E. 2562*. Bangkok, Thailand: Royal Thai Government Gazette, The Secretariat of the Cabinet. http://www.ratchakitcha.soc.go.th/DATA/PDF/2562/A/071/T_0104.PDF [Accessed 27 February 2022].

Hamer, D. & Minton, G. (2020). *Guidelines for the safe and humane handling and release of bycaught small cetaceans from fishing gear*. Bonn, Germany: UNEP/CMS Secretariat. https://www.cms.int/sites/default/files/publication/TS43_Safe_Handling_Release_Guidelines.pdf

Healy, T., Hill, N., Chin, A. & Barnett, A. (2020). A global review of elasmobranch tourism activities, management and risk. *Marine Policy*, 118, 103964. https://doi.org/10.1016/j.marpol.2020.103964

Heithaus, M.R., Frid, A., Wirsing, A.J. & Worm, B. (2008). Predicting ecological consequences of marine top predator declines. *Trends in Ecology & Evolution*, 23(4), 202–210. https://doi.org/10.1016/j.tree.2008.01.003

Hines, E., Strindberg, S., Junchompoo, C., Ponnampalam, L., Ilangakoon, A., Jackson-Ricketts, J. et al. (2015). Line transect estimates of Irrawaddy dolphin abundance along the eastern Gulf Coast of Thailand [original research]. *Frontiers in Marine Science*, 2(63). https://doi.org/10.3389/fmars.2015.00063

Huber, P.J. (1967). The behavior of maximum likelihood estimates under nonstandard conditions. In: *Proceedings of the fifth Berkeley symposium on mathematical statistics and probability*. Berkeley, CA. 1(Statistics): University of California Press, pp. 221–233.

Jaroensutasinee, M., Jutapruet, S. & Jaroensutasinee, K. (2010). Population size of indo-Pacific humpback dolphins (*Sousa chinensis*) at Khanom, Thailand. *Walailak Journal of Science and Technology (WJST)*, 7(2), 115–126. https://doi.org/10.2004/wjst.v7i2.35

Jefferson, T. A., Smith, B. D., Braulik, G. T. & Perrin, W. (2017). *Indo-Pacific Humpback Dolphin (Sousa chinensis)*. Available at: https://doi.org/10.2305/IUCN.UK.2017-3.RLTS.T82031425A50372332.en [Accessed 27th February 2022].

Jutapruet, S., Huang, A.S.L., Li, S., Lin, M., Kittiwattanawong, K. & Pradit, S. (2015). Population size and habitat characteristics of the indo-Pacific humpback dolphin (*Sousa chinensis*) off Donsak, Surat Thani, Thailand. *Aquatic Mammals*, 41(2), 129–142. https://doi.org/10.1578/AM.41.2.2015.129

Karczmarski, L., Huang, S.-L., Wong, W.-H., Chang, W.-L., Chan, S.C., Keith, M.J.E. et al. (2017). Distribution of a coastal delphinid under the impact of long-term habitat loss: indo-Pacific humpback dolphins off Taiwan's west coast. *Estuaries and Coasts*, 40(2), 594–603. https://doi.org/10.1007/s12237-016-0146-5

Kiszka, J., Muir, C., Poonian, C., Cox, T.M., Amir, O.A., Bourjea, J. et al. (2009). Marine mammal bycatch in the Southwest Indian Ocean: review and need for a comprehensive status assessment. *Western Indian Ocean Journal of Marine Science*, 7(2), 119–136.

Kiszka, J.J., Heithaus, M.R. & Wirsing, A.J. (2015). Behavioural drivers of the ecological roles and importance of marine mammals. *Marine Ecology Progress Series*, 523, 267–281. https://doi.org/10.3354/meps11180

Krajangdara, T. (2014). *Sharks and rays in Thailand*. Thailand: D. o. F. Andaman Sea Fisheries Research and Development Center (Phuket).

Krajangdara, T. (2017). *The cartilaginous fishes (sharks, rays, and chimeras) found in Thai waters and the adjacent areas*. Phuket, Thailand: Department of Fisheries, The Ministry of Agriculture and Cooperatives.

Lewison, R.L., Crowder, L.B., Wallace, B.P., Moore, J.E., Cox, T., Zydelis, R. et al. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proceedings of the National Academy of Sciences of the United States of America*, 111(14), 5271–5276. https://doi.org/10.1073/pnas.1318960111

Lucas, S. & Berggren, P. (2022). A systematic review of sensory deterrents for bycatch mitigation of marine megafauna. *Reviews in Fish Biology and Fisheries*, 33, 1–33. https://doi.org/10.1007/s11160-022-09736-5

Lymer, D., Funge-Smith, S., Khemakorn, P., Naruepon, S. & Ubolratana, S. (2008). *A review and synthesis of capture fisheries data in Thailand. Large versus small-scale fisheries*. Available at: https://www.fao.org/3/i0573e/i0573e.pdf [Accessed 3th March 2022].

Marsh, H. & Sobtzick, S. (2015). *Dugong (Dugong dugon)*. Available at: https://doi.org/10.2305/IUCN.UK.2015-4.RLTS.T6909A43792211.en [Accessed 27th February 2022].

Minton, G., Smith, B. D., Braulik, G. T., Kreb, D., Sutaria, D. & Reeves, R. (2017). *Irrawaddy Dolphin (Orcaella brevirostris)*. Available at: https://doi.org/10.2305/IUCN.UK.2017-3.RLTS.T15419A50367860.en [Accessed 27th February 2022].

Moore, J.E., Cox, T.M., Lewison, R.L., Read, A.J., Bjorkland, R., McDonald, S.L. et al. (2010). An interview-based approach to assess marine mammal and sea turtle captures in artisanal fisheries. *Biological Conservation*, 143(3), 795–805. https://doi.org/10.1016/j.biocon.2009.12.023

Mortimer, J. A. & Donnelly, M. (2008). *Hawksbill Turtle (Eretmochelys imbricata)*. Available at: https://doi.org/10.2305/IUCN.UK.2008.RLTS.T8005A12881238.en [Accessed 27th February 2022].

Muir, C., Sallema, A., Abdallah, O., Luca, D. & Davenport, T. (2003). The dugong (*Dugong dugon*) in Tanzania: a national assessment of status, distribution and threat. *Wildlife Conservation Society (WCS)*, 31.

Mustika, P.L.K., Wonneberger, E., Erzini, K. & Pasisingi, N. (2021). Marine megafauna bycatch in artisanal fisheries in Gorontalo, northern Sulawesi (Indonesia): an assessment based on fisher interviews. *Ocean & Coastal Management*, 208, 105606. https://doi.org/10.1016/j.ocecoaman.2021.105606

Peckham, S.H., Diaz, D.M., Walli, A., Ruiz, G., Crowder, L.B. & Nichols, W.J. (2007). Small-scale fisheries bycatch jeopardizes endangered Pacific loggerhead turtles. *PLoS ONE*, 2(10), e1041. https://doi.org/10.1371/journal.pone.0001041

Pimoljinda, J. (2002). Small-scale fisheries management in Thailand. In: Hew, S. (Ed.) *Interactive mechanisms for small-scale fisheries management: report of the regional consultation*. Bangkok, Thailand: FAO Regional Office for Asia and the Pacific, RAP Publication, pp. 80–91.

Pinnegar, J.K., Polunin, N.V.C., Francour, P., Badalamenti, F., Chemello, R., Harmelin-Vivien, M.L. et al. (2000). Trophic cascades in benthic marine ecosystems: lessons for fisheries and protected-area management. *Environmental Conservation*, 27(2), 179–200. https://doi.org/10.1017/S0376892900000205

Pusineri, C., Kiszka, J., Quillard, M. & Caceres, S. (2013). The endangered status of dugongs *Dugong dugon* around Mayotte (East Africa, Mozambique Channel) assessed through interview surveys. *African Journal of Marine Science*, 35(1), 111–116. https://doi.org/10.2989/1814232X.2013.783234

Ramírez-Amaro, S., Cartamil, D., Galván-Magaña, F., Gonzalez Barba, G., Graham, J., Carrera Fernández, M. et al. (2013). The artisanal elasmobranch fishery of the Pacific coast of Baja California Sur, Mexico, management implications. *Scientia Marina*, 77(3). https://doi.org/10.3989/scimar.03817.05A

Read, A.J., Drinker, P. & Northridge, S. (2006). Bycatch of marine mammals in US and global fisheries. *Conservation Biology*, 20(1), 163–169. https://doi.org/10.1111/j.1523-1739.2006.00338.x

Reeves, R.R., McClellan, K. & Werner, T.B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, 20(1), 71–97. https://doi.org/10.3354/esr00481

Rigby, C. L., Barreto, R., Carlson, J., Fernando, D., Fordham, S., Francis, M. P. et al. (2019). *Great Hammerhead (Sphyrna mokarran)*. Available at: https://doi.org/10.2305/IUCN.UK.2019-3.RLTS.T39386A2920499.en [Accessed 27th February 2022].

Rigby, C. L., Bin Ali, A., Chen, X., Derrick, D., Dharmadi Ebert, D. A. et al. (2020). *Mottled Eagle Ray (Aetomylaeus maculatus)*. Available at: https://doi.org/10.2305/IUCN.UK.2020-3.RLTS.T60120A124440727.en [Accessed 27th February 2022].

Rigby, C. L., Carlson, J., Chin, A., Derrick, D., Dicken, M. & Pacoureau, N. (2021). *Blacktip Shark (Carcharhinus limbatus)*. Available at: https://doi.org/10.2305/IUCN.UK.2021-2.RLTS.T3851A2870736.en [Accessed 27th February 2022].

Schofield, G., Scott, R., Katselidis, K.A., Mazaris, A.D. & Hays, G.C. (2015). Quantifying wildlife-watching ecotourism intensity on an endangered marine vertebrate. *Animal Conservation*, 18(6), 517–528. https://doi.org/10.1111/acv.12202

Seminoff, J. A. (2004). *Green Turtle (Chelonia mydas)*. Available at: https://doi.org/10.2305/IUCN.UK.2004.RLTS.T4615A11037468.en [Accessed 27th February 2022].

Sherman, C. S., Bin Ali, A., Bineesh, K. K., Derrick, D., Dharmadi, Fahmi et al. (2021). *Zonetail Butterfly Ray (Gymnura zonura)*. Available at: https://doi.org/10.2305/IUCN.UK.2021-1.RLTS.T60113A124439689.en [Accessed 27th February 2022].

Shiraishi, T., Sugiura, H. & Matsuda, S. (2019). *Pairwise multiple comparisons: theory and computation*. Singapore: Springer Singapore Pte. Limited. https://doi.org/10.1017/10.1007/978-981-15-0066-4

Simpfendorfer, C., Derrick, D., Bin Ali, A., Fahmi, V.Q., V., Tanay, D. et al. (2021). *Tawny Nurse Shark (Nebrius ferrugineus)*. Available at: https://doi.org/10.2305/IUCN.UK.2021-2.RLTS.T41835A173437098.en [Accessed 27th February 2022].

Simpfendorfer, C., Fahmi, B., Ali, A., Utzurrum, J. A. T., Seyha, L., Maung, A. et al. (2020). *Grey Reef Shark (Carcharhinus amblyrhynchos)*. Available at: https://doi.org/10.2305/IUCN.UK.2020-3.RLTS.T39365A173433550.en [Accessed 27th February 2022].

Tavares, D.C., Moura, J.F., Acevedo-Trejos, E. & Merico, A. (2019). Traits shared by marine megafauna and their relationships with ecosystem functions and services. *Frontiers in Marine Science*, 6, 262. https://doi.org/10.3389/fmars.2019.00262

Teh, L., Zeller, D. & Pauly, D. (2015). *Preliminary reconstruction of Thailand's fisheries catches: 1950–2010*. Fisheries Centre: University of British Columbia.

Temple, A.J., Kiszka, J.J., Stead, S.M., Wambiji, N., Brito, A., Poonian, C.N.S. et al. (2018). Marine megafauna interactions with small-scale fisheries in the southwestern Indian Ocean: a review of status and challenges for research and management. *Reviews in Fish Biology and Fisheries*, 28(1), 89–115. https://doi.org/10.1007/s11160-017-9494-x

Temple, A.J., Stead, S.M., Hind-Ozan, E., Jiddawi, N. & Berggren, P. (2020). Comparison of local knowledge and researcher-led observations for wildlife exploitation assessment and management. *Environmental Conservation*, 47(4), 304–309. https://doi.org/10.1017/S0376892920000296

Temple, A.J., Westmerland, E. & Berggren, P. (2021). By-catch risk for toothed whales in global small-scale fisheries. *Fish and Fisheries*, 22(6), 1155–1159. https://doi.org/10.1111/faf.12581

VanderWright, W. J., Bin Ali, A., Bineesh, K. K., Derrick, D., Haque, A. B., Krajangdara, T. et al. (2020a). *Grey Bamboo Shark (Chiloscyllium griseum)*. Available at: https://doi.org/10.2305/IUCN.UK.2020-3.RLTS.T41792A124416752.en [Accessed 27th February 2022].

VanderWright, W. J., Bin Ali, A., Derrick, D., Dharmadi, Fahmi, Haque, A. B. et al. (2020b). *Indonesian Bamboo Shark (Chiloscyllium hasselti)*. Available at: https://doi.org/10.2305/IUCN.UK.2020-3.RLTS.T161557A124506268.en [Accessed 27th February 2022].

Wade, P.R., Long, K.J., Francis, T.B., Punt, A.E., Hammond, P.S., Heinemann, D. et al. (2021). Best practices for assessing and managing bycatch of marine mammals [policy and practice reviews]. *Frontiers in Marine Science*, 8. https://doi.org/10.3389/fmars.2021.757330

Wallace, B.P., Kot, C.Y., DiMatteo, A.D., Lee, T., Crowder, L.B. & Lewison, R.L. (2013). Impacts of fisheries bycatch on marine turtle populations worldwide: toward conservation and research priorities. *Ecosphere*, 4(3), 1–49. https://doi.org/10.1890/ES12-00388.1

Wang, J. Y. & Reeves, R. (2017). *Indo-Pacific Finless Porpoise (Neophocaena phocaenoides)*. Available at: https://doi.org/10.2305/IUCN.UK.2017-3.RLTS.T198920A50386795.en [Accessed 27th February 2022].

White, H. (1980). A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica: Journal of the Econometric Society*, 817–838. https://doi.org/10.2307/1912934

Willems, T., Depestele, J., De Backer, A. & Hostens, K. (2016). Ray bycatch in a tropical shrimp fishery: do bycatch reduction devices and turtle excluder devices effectively exclude rays? *Fisheries Research*, 175, 35–42. https://doi.org/10.1016/j.fishres.2015.11.009

WWF. (2017). *Remote Electronic Monitoring in UK Fisheries Management*. Available at: https://www.wwf.org.uk/sites/default/files/2017-10/RemoteElectronicMonitoringinUKFisheriesManagement_WWF.pdf [Accessed 9th March 2022].

Zollett, E.A. & Swimmer, Y. (2019). Safe handling practices to increase post-capture survival of cetaceans, sea turtles, seabirds, sharks, and billfish in tuna fisheries. *Endangered Species Research*, 38, 115–125. https://doi.org/10.3354/esr00940

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Svarachorn, T., Temple, A.J. & Berggren, P. (2023). Marine megafauna catch in Thai small-scale fisheries. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 33(11), 1245–1262. https://doi.org/10.1002/aqc.3989