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REVIEW

Biology and conservation of marine turtles in the northwestern Indian Ocean: a review

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ABSTRACT: The northwestern Indian Ocean hosts globally crucial marine biodiversity, which is relatively understudied. There has, however, been significant research and conservation effort focused on marine turtles across the region in recent decades. We undertook an exhaustive review of 251 relevant publications to extract and collate the current information concerning marine turtles. To ensure completeness, we received input on a preliminary draft from a large group of experts who have worked extensively in the region. Data presented here are from all 13 countries with significant coastlines in the region (Bahrain, Djibouti, Egypt, Eritrea, Iran, Kuwait, Oman, Qatar, Saudi Arabia, Somalia, Sudan, United Arab Emirates, and Yemen) on occurrence, nesting biology, morphology, foraging areas, population status, threats, and relevant national legislation and international conservation strategies. The experts independently provided details on what they felt were the (1) most significant threats to marine turtles, (2) most critical knowledge gaps for marine turtle ecology, (3) impediments to practical conservation, and (4) essential strengths and opportunities in the region.

KEY WORDS: Northwestern Indian Ocean · Nesting areas · Conservation · Reproductive parameters · Threats · Impediments · Opportunities

1. INTRODUCTION

1.1. Marine ecosystem and biodiversity in the region

The northwestern Indian Ocean (NWIO) subregion includes countries that overlook the Red Sea, Arabian/Persian Gulf (hereafter called the Gulf), Gulf of Oman, and Gulf of Aden. The Red Sea is recognized as one of the world's hotspots for biodiversity and exhibits a high degree of endemism (DiBattista et al. 2016, Ellis et al. 2017). Similarly, the Gulf supports a variety of coastal and marine ecosystems that contribute to the genetic and biological diversity in the area (Naser 2014). The Red Sea is partially isolated by the Gulf of Aden, where environmental conditions and its relatively shallow nature limit species dispersal from the Indian Ocean (Kemp 2000, Rasul & Stewart 2015, Sonnewald & El-Sherbiny 2017, Carvalho et al. 2019). The region is characterized by extreme environmental conditions (Sheppard et al. 2010, Vaughan et al. 2019) but supports thriving ecosystems (Al-Abdulkader et al. 2019). Sea temperatures fluctuate widely between the winter and summer seasons (15–36°C), and the area has a high level of salinity exceeding 40 parts per thousand (John et

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al. 1990, Smith et al. 2007, Riegl & Purkis 2012, Naser 2014). Despite its importance for biodiversity (Naser 2014), the region is considered to be relatively understudied (Ellis et al. 2017).

1.2. Marine turtles in the region

Five of the 7 species of marine turtles can be found in the region: green turtle *Chelonia mydas*, hawksbill turtle *Eretmochelys imbricata*, loggerhead turtle *Caretta caretta*, olive ridley turtle *Lepidochelys olivacea*, and leatherback turtle *Dermochelys coriacea* (Ross & Barwani 1982, Frazier & Salas 1984, Mancini et al. 2015). Besides being considered flagship species for modern marine conservation, marine turtles have substantial cultural importance in many regions (Eckert & Hemphill 2005). The oldest examples of cultural portrayal and celebration of marine turtles are from the Middle East and the Arabian Peninsula, with cultural artifacts dating back several millennia (Frazier 2005).

To help address the various research and management challenges concerning marine turtles, Wallace et al. (2010) collated all available studies and generated separate georeferenced GIS layers for nesting sites, genetic stocks, and core distributions of population subgroups of all species. This resulted in the development of 58 regional management units (RMUs) globally. Of relevance to the current review, an Indian Ocean northwest RMU has been specified for green, hawksbill, and loggerhead turtles, whereas an Indian Ocean west RMU has been defined for olive ridley turtles (Fig. S1 in the Supplement at www.int-res.com/articles/suppl/n048p067_supp.xlsx). An RMU for leatherbacks in the region was not identified.

1.3. Need for regional reviews

Evidence-based conservation involves collecting and analyzing data regarding conservation activities in the past and applying this knowledge in future decision making (Peričić & Tanveer 2019). Evidence can be collated from research published in peer-reviewed journal articles or grey literature, such as management plans and practices, and from expert opinion. Systematic reviews have emerged as a helpful technique in this domain. A systematic review allows for the focus on a specific research question and identifies and evaluates the relevant research evidence to produce conclusions that can be used to inform conservation decisions (Gopalakrishnan & Ganeshkumar 2013).

The first step towards this approach to conservation is to comprehensively review available data and highlight knowledge gaps using expert opinion. Examples using a similar approach for understanding marine turtle ecology and conservation aspects include a review of global satellite tracking in marine turtles (Jeffers & Godley 2016) that evaluated the conservation benefits gained. Rees et al. (2016) revisited an international review (Hamann et al. 2010) that included a refined list of key research questions and further investigated how research focuses on these questions. Another study asked experts to identify knowledge gaps and the main research barriers regarding the study of immature marine turtles (Wildermann et al. 2018). At the same time, other reviews have investigated specific threats, for example, climate change (Fuentes & Cinner 2010) and seismic surveys (Nelms et al. 2016).

1.4. Aim of study

Given the broad spatiotemporal distribution of marine turtles, research must take a regional or ocean-wide approach to better understand the status, ecology and threats, and to empower the development of effective conservation strategies. For example, a regional review was conducted on the 2 breeding species of turtles in the Mediterranean and found that significant knowledge gaps still existed despite a wealth of information (Casale et al. 2018). Here, we set out to use a similar approach to better understand marine turtle populations in the Arabian region. We aimed to summarize the current knowledge and overall understanding of the ecology and conservation status of marine turtle species in the region as well as to understand the threats and key knowledge gaps and elucidate impediments to and opportunities for effective conservation. We did this through a review of the literature and elicitation of expert opinion to produce a comprehensive synthesis that can be used and built upon across the region.

2. METHODS

2.1. Study area

The current review involves the assessment of 13 countries, most of which are considered to be part of the NWIO subregion, and which we will refer to as 'the region' throughout this review (Fig. 1). Jordan,

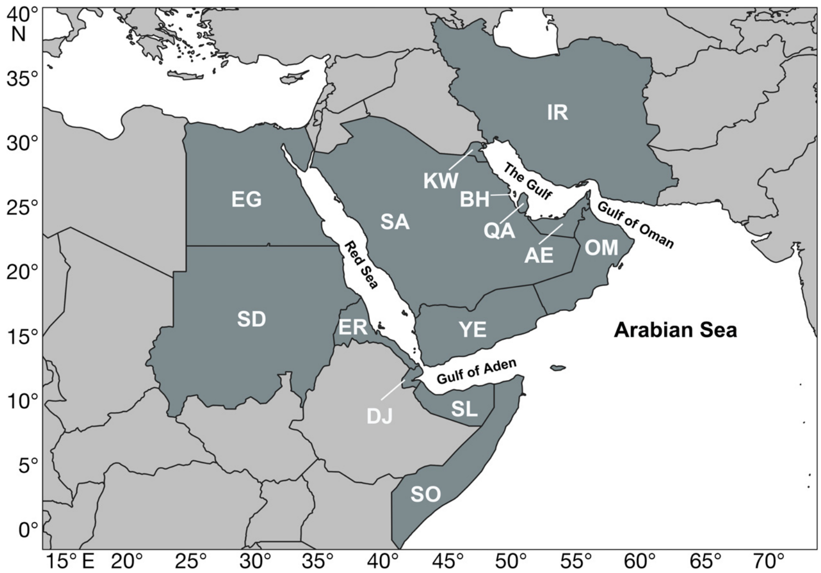

Fig. 1. Countries included in the current review (dark grey): BH: Bahrain; DJ: Djibouti; EG: Egypt; ER: Eritrea; IR: Iran; KW: Kuwait; OM: Oman; QA: Qatar; SA: Saudi Arabia; SO: Somalia; SL: Somaliland; SD: Sudan; AE: United Arab Emirates; YE: Yemen. The Gulf here represents the Arabian/Persian Gulf

Iraq, and Palestine/Israel all possess coastal areas in the region, but these are very limited in extent (27, 58, and 12 km, respectively). Moreover, the Marine Turtle Specialist Group (MTSG) 2020 annual regional report for sea turtles in the Middle East and South Asia region (Phillott & Rees 2020) indicated that no nesting of any marine turtle species had been recorded on these short coastlines; thus, these countries are not included in this review. Somalia and Somaliland are not considered part of the subregion, but we have considered them as part of this review. Furthermore, although the Republic of Somaliland, a self-declared state, is internationally considered to be an autonomous region of the Federal Republic of Somalia, it has not been considered separately from Somalia in this review because of the lack of separate legislation as well as a lack of published research related to marine turtles.

2.2. Literature review

An initial literature search was conducted in Web of Science (WoS), SCOPUS, and Google Scholar. The key words used were the same for all 3 search engines:

1. (Marine turtle OR Sea turtle) AND (Bahrain OR Djibouti OR Egypt OR Eritrea OR Iran OR Kuwait OR Oman OR Qatar OR Saudi Arabia OR Somalia OR Somaliland OR Sudan OR United Arab Emirates OR Yemen).

2. (Marine turtle OR Sea turtle) AND (Red Sea OR Persian Gulf OR Arabian Gulf OR Western Indian Ocean) AND (Bahrain OR Djibouti OR Egypt OR Eritrea OR Iran OR Kuwait OR Oman OR Qatar OR Saudi Arabia OR Somalia OR Somaliland OR Sudan OR United Arab Emirates OR Yemen).

We first ran the 2 sets of key words through WoS. The results were filtered for irrelevant material, and a final list from WoS was created. The same set of key words were run through SCOPUS, filtered, and consolidated, creating a final SCOPUS list. This was then compared with the final list from WoS, and any repeated results found on SCOPUS were removed. Google Scholar was the last web search, in which the filtered and the consolidated lists were compared, with repeated entries again discarded. Further details on how references were extracted from each source are reflected in Fig. S2. Additional searches were conducted through other search engines (ScienceDirect, ResearchGate, and BioOne) as well as the Marine Turtle Newsletter (MTN), Indian Ocean Turtle Newsletter (IOTN), and African Sea Turtle Newsletter (ASTN).

Materials were examined systematically, and data were collated regarding (1) species presence/absence; (2) nesting data; (3) biometrics of eggs, hatchlings, and adults; (4) reproductive parameters; (5) foraging and migration; (6) threats and conservation status; (7) knowledge and capacity gaps; and (8) laws, international treaties, and conventions. The literature review was last updated in November 2020. Any references discovered after this date were integrated into the narrative but not the bibliometric analyses.

2.3. Invitation of regional experts

Once data were collated and summarized (by H.M.A., B.J.G., A.F.R.), invitations for input were sent to regional experts and subject matter experts who either have worked in the study area or have a good knowledge of the region. The invitation was sent to 26 experts, and an agreement to participate and provide input was received from 18 (69%). The review received input from experts with experience of marine turtles in 9 of the 13 countries (no expert input was received regarding Bahrain, Djibouti, Eritrea, and Sudan). Experts were independently asked to check and add to data consolidated thus far and to independently provide details on what they considered, for the region, were the 5 (1) most significant threats to marine turtles, (2) most important knowledge gaps in marine turtle ecology, (3) most significant impediments to practical conservation, and (4) most important strengths and opportunities in the region that may facilitate effective conservation. Engaged experts were also invited to be co-authors of the manuscript and comment and contribute to final drafts. All agreed.

3. RESULTS

3.1. Summary of publications

Until our cutoff date (November 2020), we had collated 262 relevant publications. Since the mid-1990s, the number of publications and reports concerning marine turtles in the region has dramatically increased (Fig. 2a), perhaps leveling off in more recent years. The search from WoS resulted in 103 relevant publications, SCOPUS yielded 54 relevant publications (of which 7 were previously undetected and were thus added to the list), and the search on Google Scholar yielded 66 relevant publications (of which 36 were previously undetected). Searching ScienceDirect, ResearchGate, BioOne, MTN, IOTN, and ASTN resulted in an additional 75 relevant articles. An additional 41 articles were added during expert elicitation, 11 in Farsi, only 8 of which had an English abstract. No copies could be obtained of another 8; thus, the number of publications included in the review totalled 251 (Table S1a). When looking at the number of publications per country, marine turtles in Oman were the most represented, followed by Iran and the United Arab Emirates (UAE) (Fig. 2b), with turtles in Djibouti featured the least. The complete list of publications per country is presented in Table S1b. An additional manuscript was made available in December 2020, which we include in this review. This regional report under the IUCN's Species Survival Commission MTSG (Phillott & Rees 2020) summarizes data for every country in the region (11 of the 13 from this study).

3.2. Species presence

The presence of nesting and/or foraging turtles across the region is summarized in Table 1 and in Table S2.

The hawksbill turtle is the most widely distributed in the region, recorded nesting in 12 of the 13 countries (absent in Bahrain). This species is confirmed to forage in the waters of all the countries of this study (Table S2) (Ross & Barwani 1982, Hillman & Gebremariam 1996, Hanafy 2012, Mobaraki 2004a, Al-Mohanna et al. 2014, Mancini et al. 2015).

Green turtles nest in 11 countries in the region, excluding Bahrain and Qatar (Pilcher 1999, 2000, Al Kiyumi et al. 2002, Mobaraki 2004c, Al-Ghais 2009, Chatting et al. 2018, Mobaraki et al. 2019) and forage in the waters of all 13 countries (Table S2). Loggerheads nest in Oman and Yemen, with occasional nesting in Somalia and Sudan. This species forages in most countries and is occasionally sighted in Bahrain, Djibouti, Egypt, Qatar, Somalia, Sudan, and the UAE (Table S2). Olive ridleys nest annually in Oman, with infrequent nesting in 3 other countries (Eritrea, Iran, and the UAE), and are recorded as regularly foraging in the waters of 5 countries (Eritrea, Iran, Oman, Saudi Arabia, and Somalia; Table S2). Leatherbacks are the least observed in the study region, with no nesting locations, but the species is recorded as foraging in 4 countries (Eritrea, Kuwait, Oman, and Somalia) and is reported to occur occasionally in the remaining countries except Qatar (Table S2).

Oman is the most species-rich location for marine turtle nesting (Ross & Barwani 1982, Al Kiyumi et al. 2002, Alkindi et al. 2003, Baldwin et al. 2003). In contrast, Bahrain has no nesting reported, despite substantial efforts to detect nesting turtles (Miller & Abdulqader 2009, Abdulqader 2010, Naser 2016).

3.3. Nesting seasons

The nesting season of each turtle species varies geographically (Table S3). Green turtles mostly nest between May and September, generally peaking in July and August, depending on location (Hillman & Gebremariam 1996, PERSGA/GEF 2003). A few exceptions have been reported in Djibouti, where green turtles have been found to nest early in the year from January to April, peaking between February and March. Ras Al Hadd, Oman, has almost year-round green turtle nesting, with peak nesting in September and October and significant nesting in November and December (Ross & Barwani 1982). Another exception can be seen in the Saudi Arabian Red Sea, where green turtles nest up to November (Shimada et al. 2021a). Hawksbill turtles nest earlier in the year than other species, mainly between March and July, peaking during the summer (May to

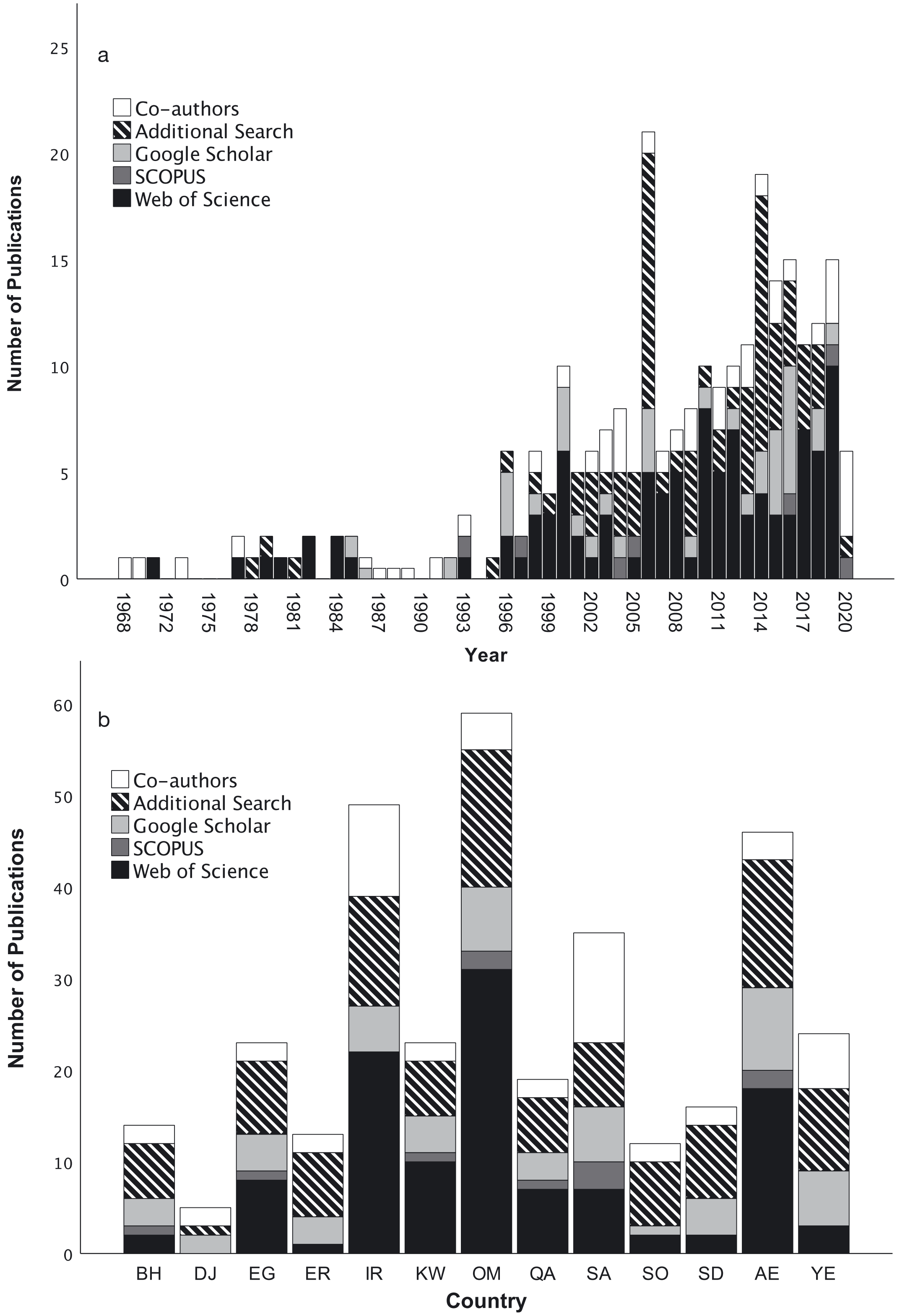

Fig. 2. Number of scientific publications on marine turtles from the study region. (a) Per year from the period 1968 to November 2020 indexed by the Web of Science (n = 103), SCOPUS (n = 7), Google Scholar (n = 36), additional search (n = 75), and input from co-authors (n = 40). A detailed list of publications by year can be found in Table S1a. (b) Per country (see Fig. 1 for country abbreviations). If a publication included multiple countries, it was included for each one. A detailed list of publications by country can be found in Table S1b. Note different scales on *y*-axes

Table 1. Presence and absence of nesting and foraging marine turtle species from all countries in the study derived from the collated references. Cm: green turtle *Chelonia mydas*; Ei: hawksbill turtle *Eretmochelys imbricata*; Cc: loggerhead turtle *Caretta caretta*; Lo: olive ridley turtle *Lepidochelys olivacea*; Dc: leatherback turtle *Dermochelys coriacea*; ✓: present; ✗: absent; ND: no data; –: single/few/rare occasions; UAE: United Arab Emirates. Sources listed in Table S2

Country	Species									
	Cm		Ei		Cc		Lo		Dc	
	Nest	Forage	Nest	Forage	Nest	Forage	Nest	Forage	Nest	Forage
Bahrain	✗	✓	✗	✓	✗	–	✗	–	✗	–
Djibouti	✓	✓	✓	✓	✗	–	✗	ND	✗	–
Egypt	✓	✓	✓	✓	✗	–	✗	–	✗	–
Eritrea	✓	✓	✓	✓	✗	✓	–	✓	✗	✓
Iran	✓	✓	✓	✓	✗	✓	–	✓	✗	–
Kuwait	✓	✓	✓	✓	✗	✓	✗	–	✗	–
Oman	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Qatar	✗	✓	✓	✓	✗	✓	✗	ND	✗	✗
Saudi Arabia	✓	✓	✓	✓	✗	✓	✗	✓	✗	–
Somalia	✓	✓	✓	✓	–	–	ND	✓	✗	✓
Sudan	✓	✓	✓	✓	–	–	✗	–	✗	–
UAE	–	✓	✓	✓	✗	–	–	–	✗	–
Yemen	✓	✓	✓	✓	✓	✓	✗	–	✗	–

July) in the Gulf (Ross & Barwani 1982, Pilcher 1999, Mobaraki 2004a, 2004c, Al-Ghais 2009, Al-Mohanna et al. 2014, Chatting et al. 2018). In the Red Sea, hawksbill turtle nesting commences in October in Eritrea (Hillman & Gebremariam 1996) and February in Saudi Arabia (Al Merghani et al. 2000, Mendonca & Abi-Anoun 2009), mostly peaking in May and June (Shimada et al. 2021b). Loggerheads nest from April to September in Oman and Yemen, peaking in June and July in Oman (Ross & Barwani 1982). Olive ridley turtles nest in Oman from February to May, peaking in March and April (Ross & Barwani 1982).

3.4. Estimated magnitude of nesting

We collated the magnitude of nesting in terms of an estimate number of nesting females in a given year. The number of green turtles nesting annually was highest in Oman (20 000) (Indian Ocean and Southeast Asia [IOSEA] 2014), followed by Yemen (6000) (PERSGA 2006). Medium levels of nesting green turtles have been recorded on the Gulf side of Saudi Arabia (800) (Pilcher 2000, Pilcher & Al Merghani 2000) and the Red Sea coast (400) (Shimada et al. 2021b). Lower levels of nesting have been reported from Djibouti, Egypt, Somalia, and Sudan (40–250) (PERSGA/GEF 2003, PERSGA 2006, El-Sadek et al. 2016, Nasr 2015, Herghada Environmental Protection & Conservation Association [HEPCA] unpubl. data). There are also low levels of nesting individuals in Iran (<10) (Mobaraki 2004b, Mohammadizadeh & Soltanpour 2014, Sinaei et al. 2018) and Kuwait (2–3) (Rees et al. 2013a), and nesting levels have not been quantified in Eritrea. Isolated nesting was reported in the UAE (Al Suweidi et al. 2012) (Fig. 3a, Table S4). It is important to note that the numbers listed are the most recent estimates published for each study site; thus, care must be taken when comparing among sites.

Iran hosts the largest estimated number of nesting hawksbills (500–1000) (Mortimer & Donnelly 2008), followed by Egypt (611) (Hanafy 2012). Closely following Egypt is Oman, with 600 annual nesters reported (IOSEA 2014). Medium levels of nesting individuals occur in Qatar (90) (Tayab & Quiton 2003, Chatting et al. 2018), the Saudi Arabian Gulf coast (175–265) (Mortimer & Donnelly 2008), the Saudi Arabian Red Sea (100–200) (Mortimer & Donnelly 2008), Sudan (300–350) (Mortimer & Donnelly 2008), the UAE (278) (Al Ameri et al. 2020), and Yemen (500) (PERSGA 2006). Low levels of nesting are reported in Kuwait (<20) (Mortimer & Donnelly 2008) and Somalia (<50) (PERSGA 2006). While there are limited surveys on Mojedi Island, Eritrea, they suggest hundreds of hawksbill female turtles nest per year (Mebrahtu 2015). The annual number of nesters in Djibouti has not been quantified (Fig. 3b, Table S4).

Nesting by loggerhead turtles is only documented in Oman and Yemen, with the former including 10 223 to 11 500 annual nesters (Willson et al. 2020) (Table S4) and the latter 50 to 100 annual nesters documented on Jabal Aziz island (PERSGA 2006) (Table S4). Oman is estimated to have 150 to 400 olive ridley nesters annually (IOSEA 2014), with sporadic nesting in Eritrea, Iran, and the UAE (Mebrahtu 2013, Tollab et al. 2015, Yaghmour & Rodríguez-Zárate 2021) (Table S4).

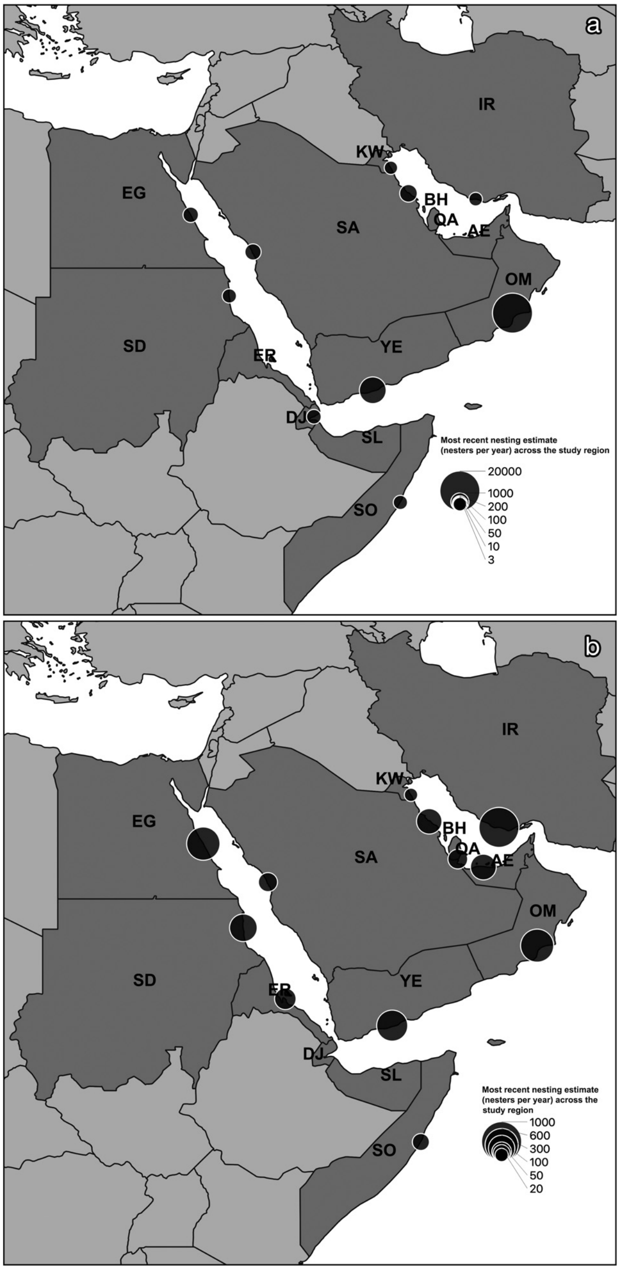

Fig. 3. Most recent estimated annual nesting populations from the study region for (a) *Chelonia mydas* and (b) *Eretmochelys imbricata*. *Caretta caretta* and *Lepidochelys olivacea* nesting is only in Oman and/or Yemen. There is no nesting of *Dermochelys coriacea*. Symbols are associated with the country, not the location within the country. Details of most recent estimated nesting populations are available in Table S4. See Fig. 1 for country abbreviations

3.5. Spatial distribution patterns

Understanding and managing nesting sites is complicated in the region. Although the region does have several large, high-density aggregations of nesting turtles at several locations (e.g. green turtles at Ras al Hadd, Oman, and Zabargad Island, Egypt), much of the nesting is widespread at low density.

For example, the Red Sea coast of Saudi Arabia has numerous islands along its 1760 km coast, many of which are used by small numbers of hawksbill turtles (Miller 2020). Similarly, the Suakin (Sudan) and Dahlak (Eritrea) archipelagos are comprised of numerous islands, many of which host low-density nesting by hawksbill turtles, the total of which means these areas may contain large yet unquantified nesting populations.

Furthermore, in the Gulf, low-density nesting by hawksbill turtles occurs at several locations along the Iranian coast. Although the highest-density nesting by hawksbill turtles in the northern Gulf is at Jana Island in Saudi Arabia, the sum of nesting along the Iranian coast equals or exceeds it.

3.6. Biometrics and reproductive parameters

A summary of the range of sizes recorded for nesting females of each species is presented in Table 2 (further details in Table S5a–l), together with descriptive statistics for reproductive parameters (Table S5m). The gaps highlight the relative paucity of studies reporting these basic parameters. Although the curved carapace length of most species falls in the range of world populations (Dodd 1988, Hirth 1997), the hawksbill turtles of the Gulf are notably among the smallest (Miller 1989, Pilcher et al. 2014b, Chatting et al. 2018). The cause(s) and consequence(s) of this size difference are unknown but are likely linked to nutrient limitations or the environmental conditions experienced in climate-challenged foraging habitats. The other reproductive parameters are less remarkable when compared to populations elsewhere.

3.7. Migration

Several studies on marine turtle migration have been conducted in our study region. These have included flipper tagging studies from Iran, Oman, Qatar, and Saudi Arabia (hawksbill, green, and loggerhead turtles) and 16 satellite tracking studies in 7 countries (Egypt, Iran, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE). However, these studies have demonstrated connectivity with another 6 countries, underlining the need for a coordinated regional approach for conservation actions as is summarized in Table 3 and fully detailed in Table S6.

Table 2. Ranges of means of reproductive morphometric parameters from all countries in this study. CCL: curved carapace length; CCW: curved carapace width; SCL: straight carapace length; SCW: straight carapace width; ND: no data. See species legend in Table 1. Further details and sources are listed in Table S5a–m

Data	Species			
	Cm	Ei	Cc	Lo
Adult				
CCL (cm)	93.2–106.3[a]	63.54–81.8[a]	98.9–101.0	67.5–74.1
CCW (cm)	63.3–99.0	52.1–68.5	ND	73[b]
Weight (kg)	104.9–160.0	37.7–55.75	118[b]	ND
Reproduction				
Clutch size (eggs)	41.4–111.0	58.6–129.5	97.0–107.0	105.0–118.0
Clutch frequency	1.9–4.0	1.4–2.2	5.4[b]	1.0–3.0[c]
Incubation duration (d)	59.7–61.8	49.4–61.1	50.2–51.2	ND
Hatching success (%)	65.7–87.2	36.6–96.0	53.1–67.8	0[d]
Egg				
Egg diameter (mm)	38.3–57.0	35.4–40.0	43.0[b]	ND
Egg weight (g)	32.4–52.9	24.3–33.6	44.0[b]	ND
Hatchling				
SCL (mm)	43.4–48.7	36.2–41.6	ND	ND
SCW (mm)	35.1–37.9	28.2–29.6	ND	ND
Weight (g)	21.98–28.2	11.0–15.1	ND	ND

[a]Records from Djibouti were removed from this range, as reported adult CCL was too low; [b]Only 1 record; [c]Range only listed without mean; [d]One record was predated upon

3.8. Threats

The literature review highlighted 7 significant threats to marine turtles in the region (Fig. 4a, Table S7), and these were broadly concordant with those identified through expert elicitation (Fig. 4b).

3.8.1. Coastal development. This was documented as a threat in all the countries. It was either listed as a general form, or in some cases, publications were more specific, outlining, for example, beach reclamation (Papathanasopoulou 2009, Hanafy 2012), modification of the coastline for urban expansion (Al-Mohanna et al. 2014), and beach erosion (Rees & Baker 2006). The region (particularly in Qatar, Saudi Arabia, and the UAE) has undergone extensive coastal development in the past 30 yr, especially for land reclamation and mega infrastructure projects. Coastal developments contributed to the significant disturbance and/or loss of nesting and for-

Table 3. Summary of migration studies conducted in the region. N: number of turtles; UAE: United Arab Emirates; ND: no data. See species legend in Table 1. Further tagging studies can be found in Table S6

Species	Origin	N	Type	Status	End location	Source
Cm	Kuwait	2	Satellite	Post-nesting females	Saudi Arabia	Rees et al. (2013a)
	Kuwait	4	Satellite	Rehabilitated females	Kuwait and UAE	Rees et al. (2018)
	Oman	2	Satellite	Post-nesting females	Saudi Arabia and Eritrea	Rees et al. (2012a)
	Oman	ND	Flipper tag	ND	Eritrea, Iran, Pakistan, Qatar, Saudi Arabia, Somalia, UAE, Yemen, and Maldives	Al Saady et al. (2005)
	UAE	8	Satellite	Rehabilitated; 3 adult females and 5 subadults (unknown sex)	UAE, Pakistan, and Andaman Sea	Robinson et al. (2017)
	UAE	45	Satellite	Foraging	Oman and UAE	Pilcher et al. (2021)
	Oman	8	Satellite	Post-nesting females	UAE, India, Oman, and Eritrea	Pilcher et al. (2021)
	Egypt	4	Satellite	Post-nesting females	Remained in the Red Sea (Djibouti, Egypt, Eritrea, and Saudi Arabia)	Attum et al. (2014)
Ei	Kuwait	4	Satellite	Post-nesting females	Kuwait and Saudi Arabia	Rees et al. (2019)
	Iran, Qatar, and UAE	90	Satellite	Post-nesting females	Qatar, UAE, Bahrain, Kuwait, and Saudi Arabia	Pilcher et al. (2014a,b)
Cc	Oman	10	Satellite and flipper tag	Post-nesting females	Oman, Eritrea, Iran Pakistan, Qatar, Saudi Arabia, Somalia, UAE, and Yemen	Rees et al. (2010), Al Saady et al. (2005)
	Reunion Island	18	Satellite	Juveniles (sex not defined)	Oman, Somalia, and Yemen	Dalleau et al. (2014)
Lo	Oman	9	Satellite	Post-nesting females	Oman, Gulf, and Pakistan	Rees et al. (2012b)

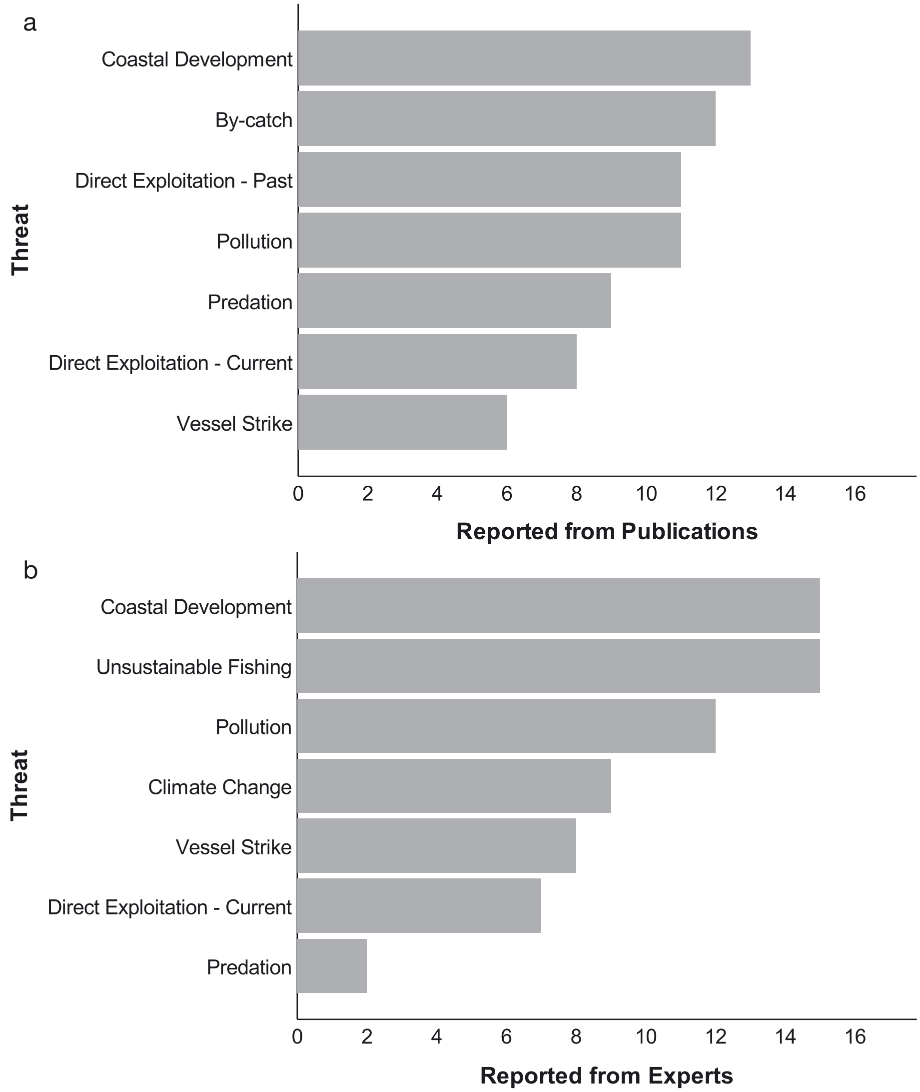

Fig. 4. Threats reported (a) from collated studies and (b) through expert elicitation. Bycatch has been included in unsustainable fishing in Fig. 5b. Detailed information on threats from collated studies is available in Table S7

aging marine turtles, as this has been documented for all countries, with the exception of Qatar, Somalia, and Yemen. The development of the region's coast has also led to erosion and sand extraction, which is evident in Bahrain, Djibouti, Egypt, Oman, Qatar, Saudi Arabia, Somalia, Sudan, and Yemen (Table S7).

3.8.2. Bycatch. This was listed as a threat in all the countries in the region. This includes illegal, unreported, and unregulated fishing (Gladstone et al. 2003, Teclemariam et al. 2009). Both commercial (Fig. 4a) (Abdulqader & Miller 2012, Mebrahtu 2013, Rees et al. 2013a, M. Rezaie-Atagholipour pers. comm.) and artisanal (Van de Elst 2006, Rees et al. 2012a, Ghassemi-Khademi 2014, Abdulqader et al. 2017) fishing operations are present in the region, and these are generally net-based fisheries (Table S7).

3.8.3. Pollution. Pollution of key concern includes light and oil pollution, lost and abandoned fishing gear, and marine debris that includes microplastics. Light pollution is considered significant across the region (Pilcher & Al-Merghani 2000, Pilcher 2005, Hanafy 2012, Ghassemi-Khademi 2014) but has not been listed explicitly from Eritrea and Yemen. Moreover, oil pollution has been recorded in Djibouti, Egypt, Eritrea, Iran, Kuwait, and Saudi Arabia (Al-Mohanna & Meakins 2000, Teclemariam et al. 2009, Ghassemi-Khademi 2014). Publications detail marine debris, where plastic is the most common form, either floating in the water or washed up onshore, occurring in Djibouti, Egypt, Iran, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE (Pilcher 2005, Rees & Baker 2006, Rees et al. 2013a,b, Yaghmour et al. 2018a, Mancini et al. 2019, Al Ameri et al. 2020, Miller 2020, Phillott et al. 2020) (Fig. 4a, Table S7). More specifically, recent publications have found marine debris inside the digestive tracts of marine turtles in Oman (Ferreira et al. 2006) and the UAE (Yaghmour et al. 2018a,b) and mortalities due to debris entanglement (EAD 2016, Yaghmour et al. 2018b, Yaghmour 2020). Furthermore, oil pollution in the UAE has been examined and detected to be related to marine turtle mortalities (Yaghmour 2019). Exposure to oil spills has also been reported based on polycyclic aromatic hydrocarbon levels in marine turtles in Iran (Sinaei & Zare 2019) and the UAE (Yaghmour et al. 2020). There has also been a reporting of alarming levels of harmful pesticides, including DDTs, in green turtles (Yaghmour et al. 2020).

3.8.4. Direct exploitation. In the past, typically before the 1980s, direct exploitation was marked across the region, as it occurred in all countries except Kuwait (Hirth & Abdel Latif 1980, Aspinall 1995, Baldwin 1995, Firouz 2005, Hassan 2014) and was mainly in the form of direct take of adult marine turtles and their eggs (Fig. 4a).

Current direct exploitation of turtle eggs, meat, and carapace was reported in Bahrain, Djibouti, Egypt, Eritrea, Iran, Oman, Qatar, Saudi Arabia, Somalia Sudan, and Yemen (Pilcher & Al-Merghani 2000, Gladstone et al. 2003, PERSGA 2006, Pilcher & Saad 2006, Rees & Baker 2006, Van de Elst 2006, Ficetola 2008, Mebrahtu 2013, Saeed 2015, Awadh et al. 2017, Al Ameri et al. 2020), although there is a downward trend across the region (Table S7).

3.8.5. Vessel strikes. Vessel strikes and disturbance that can result from increased maritime traffic are also a consequence of coastal development. This often leads to mortality, which was also reported as a common occurrence by experts in tourist areas and along shipping routes (Wilson et al. 2003, Pilcher & Saad 2006, Mendonca & Abi-Anoun 2009, Rees et al. 2012b, Ghassemi-Khademi 2014, EAD 2016) (Fig. 4b, Table S7).

3.8.6. Predation. Predation, particularly on land, is another noted threat reported in publications and by experts. This is principally in the form of predation of eggs and hatchlings (Mobaraki 2004a, Pilcher 2005, Rees & Baker 2006, Ficetola 2008, Mendonca et al. 2010, Hebbelmann et al. 2016) (Table S7).

3.8.7. Climate change. Climate change effects are considered, by experts, to be a primary threat for marine turtles in the region, although this was not well reflected in regional publications. This includes the increasing occurrence of storms, associated flooding, erosion leading to loss of habitat, and increased overall temperature affecting sex ratio and/or reduced hatching success (Patrício et al. 2021). Although not considered one of the top 3 threats, experts perceived that this would change in the future, mandating an increase in understanding the impacts of climate change-related threats (Fig. 4b). A recent publication attempted to forecast the primary sex ratio in hatchlings until the end of the 21st century in Qatar. The study found a significant increase in female biases by 2100. Hindcasting of sex ratios (1993–2018) gave approximately 73% female hatchling production and increasing to >95% from 2075 to 2100 (Chatting et al. 2021). Tanabe et al. (2020) calculated the expected sex ratio of both green and hawksbill turtles in the Red Sea and showed that sites could already be exceeding thermal maximums and may be vulnerable to rising temperatures. On the contrary, findings from Pilcher at al. (2015) do not indicate any feminization of populations with warming climates and warming sea temperatures. It has been suggested that while it is important to assimilate climate change variables into conservation models and predictions, research suggests that animals are able to physiologically adapt to climate change. Marine turtles may possess the ability to adapt to climate change; however, they might not be in a position to adapt to the current rate of climate change.

3.9. Knowledge gaps

The subtopics below summarize input received from expert elicitation as to the main knowledge gaps identified (Fig. 5a).

3.9.1. In-water ecology. This included research on the identification of critical habitats and foraging population structure. More specifically, detailed information on crucial demographic parameters derived from long-term and high-quality monitoring programs (such as abundance, local population size, mortality, and survival rates) is needed. Although some countries have conducted research to identify connectivity between nesting and feeding areas, further research is required to identify metapopulation dynamics to underpin regional conservation frameworks (Fig. 5a).

3.9.2. Threat assessment. It was felt that knowledge in this regard was underdeveloped. Specifically, the impact of fishing practices that result in bycatch and entanglement was lacking. There is also minimal knowledge on the magnitude of illegal take, pollution, predation, and threats on the high seas (Fig. 5a).

3.9.3. Nesting evaluation. Experts highlighted the lack of consistent monitoring and scattered data on abundance. This includes the location and assessment of all key nesting sites and knowledge of vital demographic features, such as annual clutch frequency and remigration intervals, that would greatly empower rigorous assessment of nesting population sizes and trends (Fig. 5a).

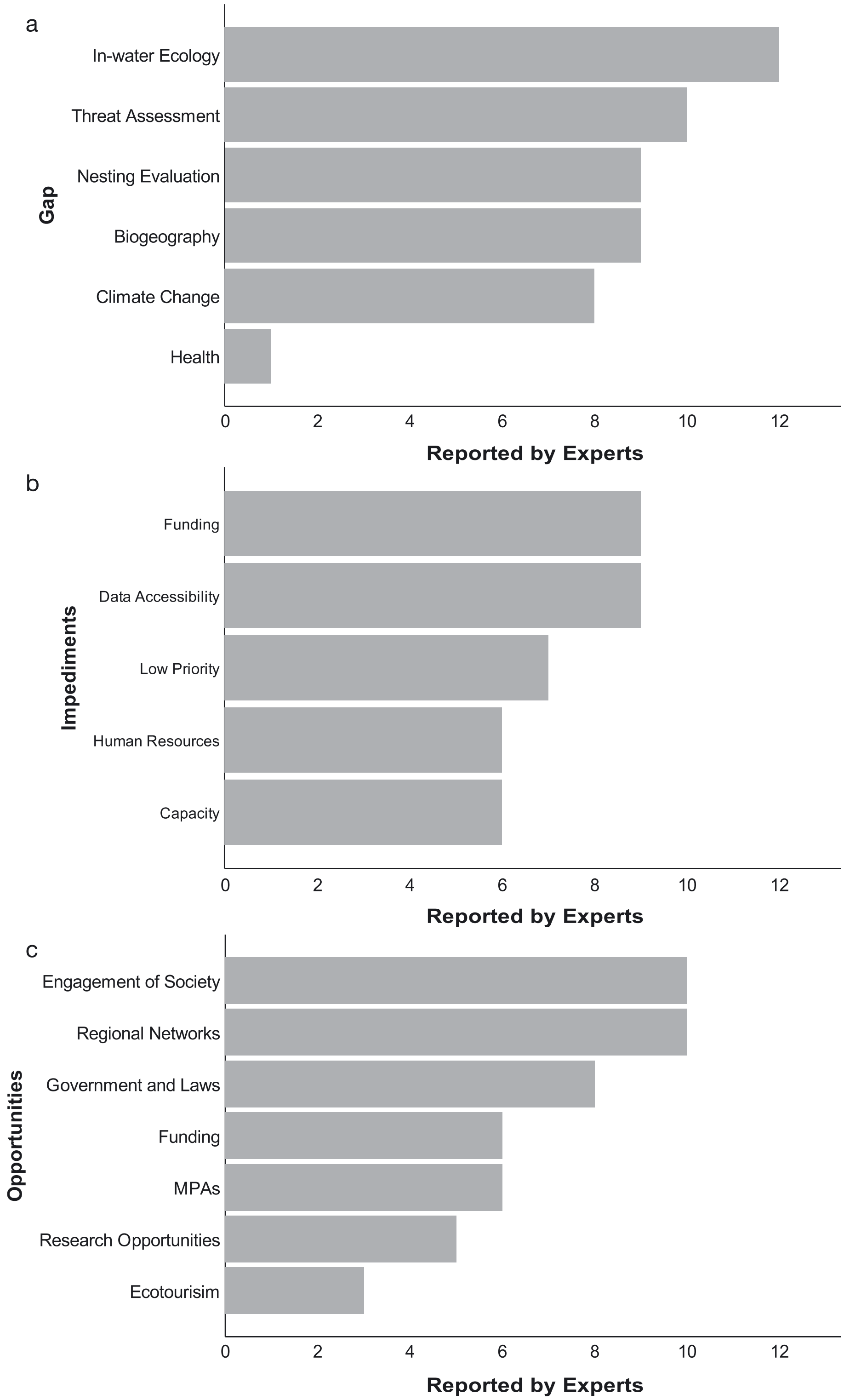

Fig. 5. Results of expert elicitation on (a) knowledge gaps, (b) impediments towards conservation, and (c) opportunities for conservation in the study region. MPAs: marine protected areas

3.9.4. Biogeography. This includes migration routes and the genetic linkages among nesting populations and genetic structure across the region. Comprehensive long-term flipper tagging, satellite tracking, and genetic studies are needed at the nesting sites; as of yet, no work has been carried out on the patterns of dispersal of hatchling and juvenile turtles, and there has been minimal research on adult males (Fig. 5a). We note here that although information on hatchlings and juvenile turtles is listed as a gap, this is not unique to the region but of global concern.

3.9.5. Climate change. As well as being highlighted as a significant threat, despite recent work (Chatting et al. 2021), this was considered a significant knowledge gap. Temperature-dependent sex determination mechanisms and the prevailing sex ratios of hatchlings and other life stages have yet to be determined, much less the impact of increasing temperatures, sea-level rise, or increasing storminess (Fig. 5a).

3.9.6. Health. Experts highlighted the need to assess anthropogenic influences such as pollution on marine turtle health in the region (Fig. 5a).

To help highlight the biological gaps, we present a table that elaborates the relative completeness of biological knowledge by country that may help steer researchers, policymakers, and donors (Table 4).

3.10. Challenges and opportunities

An analysis of expert opinion revealed some of the clear systematic impediments to conservation in the study region (Fig. 5b) and some of the opportunities to augment conservation going forward (Fig. 5c). We discuss these 2 points together, as they are often intimately linked as problem and solution.

3.10.1. Government and laws. The political situation in the region is complicated, and experts noted that this could hinder cross-border collaboration and information exchange between scientists, environmental managers, and conservationists. Nevertheless, a range of regional networks as outlined below reflects the existing regional networks as an opportunity for enhanced collaboration. The active presence of international initiatives and regional networks could support future monitoring, conservation, and capacity-building programs. They could be better utilized to enhance collaboration, particularly around widespread threats.

International policy instruments could also aid in accelerating efforts towards recognizing essential at-sea areas for marine turtles. The number of international instruments (Table 5) addressing environmental protection, in general, has increased (Hykle 2002). Most of these instruments are binding for the parties and, therefore, need to be implemented through the adoption of adequate legislation (FAO 2004). However, the effectiveness of the tools regarding marine turtle conservation has been debated (Hykle 2002, Tiwari 2002). Of the 13 countries involved in the study area, only 7 have laws that explicitly protect marine turtles (Bahrain, Djibouti, Iran, Oman, Qatar, the UAE, Yemen). The other 6 countries have laws

Table 4. Data availability on nesting marine turtles in the study area. UAE: United Arab Emirates; ✓: data available; ✗: data unavailable. See species legend in Table 1. Only species known to nest are included for each country. Bahrain is not included due to no nesting being recorded

Data details	Djibouti			Egypt		Eritrea			Iran		Kuwait		Oman				Qatar
	Cm	Ei	Lo	Cm	Ei	Cm	Ei	Cc	Cm	Ei	Cm	Ei	Cm	Ei	Cc	Lo	Ei
Nester population estimate	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annual nesting counts	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✓
Emergence/hatching success	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✓	✗	✗	✗	✓	✗	✓
Nester curved carapace length	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Clutch counts	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓
Incubation duration	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✓	✗	✓
Nest season start	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Nest season end	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Peak season identified	✓	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓	✗	✓	✓	✗	✗	✗
Egg size	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✗	✗	✓	✗	✓	✗	✓
Egg weight	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✗	✗	✓	✗	✓	✗	✓
Hatchling size	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓
Hatchling weight	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✓	✗	✓
Sex ratio of hatchlings	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Nest success estimates (nest/false)	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

Data details	Saudi Arabia		Somalia			Sudan				UAE		Yemen		
	Cm	Ei	Cm	Ei	Cc	Cm	Ei	Cc	Lo	Cm	Ei	Cm	Ei	Cc
Nester population estimate	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓
Annual nesting counts	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Emergence/hatching success	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓
Nester curved carapace length	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗
Clutch counts	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Incubation duration	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Nest season start	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓
Nest season end	✓	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓
Peak season identified	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗
Egg size	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗
Egg weight	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Hatchling size	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Hatchling weight	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Sex ratio of hatchlings	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Nest success estimates (nest/false)	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗

Table 5. International conventions and national laws protecting marine turtles in the study area. CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora; CMS: Convention on the Conservation of Migratory Species of Wild Animals; CBD: Convention on Biological Diversity; IOSEA: Indian Ocean and Southeast Asia; MoU: Memorandum of Understanding; ROPME: Regional Organization for the Protection of the Marine Environment; PERSGA: Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden; Ramsar: Ramsar Convention on Wetlands; ✓: direct protection; ✗: indirect protection; RS: range state; NP: non-party; N/A: not applicable; UAE: United Arab Emirates. Year represents date of signing. Sources listed in Table S8

Country	National law	Regional/international conventions and treaties						
		CITES	CMS	CMS: IOSEA Marine Turtle MoU	CBD	ROPME	PERSGA	Ramsar
Bahrain	✓	2012	NP	2007	1992	Yes	N/A	1998
Djibouti	✓	1992	2004	RS	1992	N/A	Yes	2003
Egypt	✗	1978	1983	2014	1992	N/A	Yes	1988
Eritrea	✗	1994	2005	2006	1996	N/A	No	NP
Iran	✓	1976	2008	2001	1992	Yes	N/A	1975
Kuwait	✗	2002	NP	RS	1992	Yes	N/A	2015
Oman	✓	2008	NP	2004	1992	Yes	N/A	2013
Qatar	✓	2001	NP	RS	1992	Yes	N/A	NP
Saudi Arabia	✗	1996	1991	2005	2001	Yes	Yes	NP
Somalia	✗	1985	1986	RS	2009	N/A	Yes	NP
Sudan	✗	1982	NP	2015	1992	N/A	Yes	2005
UAE	✓	1990	2016	2007	1992	Yes	N/A	2007
Yemen	✓	1997	2006	2008	1992	N/A	Yes	2008

that protect marine turtles in a more general form (e.g. environmental or fishery laws that describe marine turtles as part of the marine wildlife, marine organisms, migratory animals, or endangered species) (Table 5). Exclusive regional instruments such as the Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats of IOSEA(IOSEA Marine Turtle MoU) aim to promote recovery of marine turtle populations through the promotion of intergovernmental cooperation (CMS 2020).

Similar regional agreements include the Regional Organization for the Protection of the Marine Environment (ROPME; covering the Gulf) and the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA). Their main objective is to coordinate the member states' efforts against marine pollution and developmental activities that may harm or stress the coastal environment within their respective regions (ROPME 2018, PERSGA 2019). A breakdown of the different strategies initiated by the countries involved can be found in Table 5 and in Table S8. The authors felt that much more could be achieved through these initiatives than is currently the case.

The protection of marine turtles specific to threats is also being considered under sectoral policy arrangements. An example of this is the Indian Ocean Tuna Commission (IOTC), which recognizes that fishing operations in the Indian Ocean adversely impact marine turtles and their associated habitats. This resulted in the adoption of a resolution that requires all interactions with marine turtles in the IOTC area to be reported and mitigation measures taken. Countries under the IOTC from the region are Eritrea, Iran, Oman, Somalia, Sudan, and Yemen (IOTC 2012).

Furthermore, there is a federal-level commitment and ongoing support from both civil and military authorities towards effective implementation of existing legislation. Examples include the establishment of rescue facilities and the prohibition of nesting beach access during the nesting season. Additionally, there are specific policy advancements at a national level. For example, the UAE underwent a country-wide Red Listing Assessment according to IUCN guidelines to locally assess marine turtle populations and developed a National Plan of Action for Marine Turtles that identifies core research areas until 2021 (MoCCaE 2019). Further opportunities for governments in the region include developing bycatch mitigation programs for both industrial and artisanal fisheries and the utilization of environmental impact assessment guidelines when developing new areas that impact marine turtles.

3.10.2. Funding. There is a general lack of funding and financial support for long-term conservation programs and filling the previously mentioned knowledge gaps. However, numerous opportunities in the region could be further explored that would enable the acquirement of funds. In a broader sense, there is a growing interest from stakeholders in conservation. In some countries (such as Iran, Qatar, Saudi Arabia, and the UAE), the petrochemical sector is becoming more involved in environmental research and thus is providing funding to some ongoing projects. Furthermore, several new development projects (namely in Saudi Arabia and the UAE) are underway and have established research stations, laboratories, and rehabilitation facilities for marine species. In turn, such facilities could support studies on turtles in the region and perhaps act as hubs for facilitating collaborative region-wide studies, funding bids, and intraregional exchange and capacity building.

3.10.3. Regional environmental priorities. Unfortunately, there is a variable level of environmental commitment among the region's governments. Marine turtle conservation and allied issues are low priority in many countries. Although marine protected areas (MPAs) are well established in several countries, enforcement is lacking. The study region's development and economic growth agenda do not reflect, and in some cases are not aligned with, sustainability. As a result, the region is not generating sufficiently robust baseline scientific information quickly enough to support policy changes that help address crucial and widespread threats to marine turtles. Furthermore, even if data were acquired quickly, governments often do not have effective mechanisms to take these data onboard to effect policy change.

3.10.4. Capacity. Some sites have limited access due to the remoteness of the location or to them being in a military or sensitive industrial area. There is also a general lack of technical capacity and skills particular to marine turtle research within governmental organizations in the region that have environmental research as their mandate. These organizations are understaffed when it comes to direct involvement in monitoring and management. Furthermore, there is a prevailing lack of awareness and few educational programs dedicated to marine turtle conservation or a structured approach towards the involvement of local communities in work that would complement current scientific research and monitoring. We feel, however, that there are various opportunities in this domain and rapid gains that can be made. There is a groundswell of interest from students to participate in environmental conservation. Younger generations appear to be highly passionate about protecting endangered species and could thus be trained to do so from a young age. There are also universities in the region that could play a significant role in leading collaborative studies, and citizen science platforms could be further utilized to capture specific data that could address gaps, for example, the quantification of threats or the location of important foraging sites.

3.10.5. Ecotourism and MPAs. There is potential for ecotourism at turtle nesting beaches in uninhabited coastal regions. This could leverage the economic value of these for conservation purposes as well as create work opportunities for local communities. These sites and other MPAs could be further developed into a regional network that would provide management and connectivity across habitats.

4. DISCUSSION AND CONCLUSIONS

The dual aims of this work were to summarize the current knowledge regarding marine turtles and help elaborate pathways forward for conservation and management across the region.

Because marine turtles move widely within the region and come under the jurisdiction of multiple nations, international cooperation is vital for their survival (Tiwari 2002, Blumenthal et al. 2006). Efficient and wide-scale networks and mechanisms for cooperation and data sharing are still challenging and are not yet sufficiently cohesive across the region. A joint regional approach, perhaps facilitated under existing initiatives such as the IOSEA MoU, will more quickly fill the critical data gaps and facilitate more successful fundraising.

Threats and challenges summarized in this review represent the region and are also country specific. To address this, countries could start introducing measures that aid in specific threat reduction, such as using turtle excluder devices and visual deterrents to reduce bycatch, using propeller guards to reduce mortality caused by vessel strikes, covering nests to reduce predation by preventing animals from accessing them, and applying coastal management tools to support the conservation of marine turtle nesting grounds.

Furthermore, the global momentum around climate change, biodiversity loss, and habitat protection is a clear opportunity for action and ties in well with governments' international responsibilities. This provides an opportunity to establish strategic partnerships with the private sector that would support and expand conservation efforts, reverse current trends of devastating biodiversity loss, and help safeguard the future. Diverse alliances will allow the possibility for innovation, accessibility to technology that can facilitate monitoring and conservation actions, and a wider reach for awareness campaigns.

In addition to protected areas, countries could also explore other effective area-based conservation measures (OECMs), a new conservation policy tool that ensures equitable conservation in alliance with indigenous people, local communities, or other private initiatives. OECMs are different from protected areas, as they recognize managed areas to sustain biodiversity regardless of their objective.

Although there has been a strong and increasing effort to study marine turtles across the region, this is highly variable across countries and species. The work published, although increasing, does not fully represent data gathered or ongoing work, with a possibility of species misidentification in earlier years of published research, mainly due to a lack of resources to facilitate publication. This can impede understanding conservation status and trends. Some areas have yet to be adequately assessed, and for other essential nesting sites, the most recent census data are more than 2 decades old. Ongoing assessment is vital, as declines can occur within a single generation (Willson et al. 2020).

This study provides a large-scale overview of marine turtles across the NWIO subregion to support integrated decision making for these species. The dataset provided here through this review is a foundation which can be built upon with newly published material. We recommend actors from each country make a dedicated effort to compile grey literature and publish it to become available for others in the region. Also, integrating available spatial data into marine management plans should be considered a priority by nations to which data sets become available. Efforts can then be made to map overlapping threats and identify the most effective conservation measures required.

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