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Viewpoint

Using species connectivity to achieve coordinated large-scale marine conservation efforts in the Red Sea

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ABSTRACT

In the face of increasing anthropogenic threats, coastal nations need to reach common ground for effective marine conservation. Understanding species' connectivity can reveal how nations share resources, demonstrating the need for cooperative protection efforts. Unfortunately, connectivity information is rarely integrated into the design of marine protected areas (MPAs). This is exemplified in the Red Sea where biodiversity is only nominally protected by a non-cohesive network of small-sized MPAs, most of which are barely implemented. Here, we showcase the potential of using connectivity patterns of flagship species to consolidate conservation efforts in the Red Sea. We argue that a large-scale MPA (LSMPA) would more effectively preserve Red Sea species' multinational migration routes. A connectivity-informed LSMPA approach provides thus one avenue to unite coastal nations toward acting for the common good of conservation and reverse the global decline in marine biodiversity.

1. Main text

The upcoming decade (2021–2030) will play a pivotal role for the protection of our oceans. The United Nations (UN) has urged the development of concerted conservation actions among ocean stakeholders to arrest the decline in ocean health and attain social equity and sustainability (Frazão Santos et al., 2020; Österblom et al., 2020). Global climate change and local anthropogenic activities are rapidly deteriorating environmental conditions, causing habitat-forming species to disappear worldwide. One prime example is the loss of coral reefs due to massive bleaching events that are generally triggered by heat stress (Hughes et al., 2018). Halting these declines will require science-informed policies to preserve marine ecosystems, especially those in critical regions of the world.

Hosting more than 1,100 fish and ~390 coral species, the Red Sea is a marine biodiversity hotspot with a relatively high endemism (Bogorodsky and Randall, 2019; DiBattista et al., 2016; Roberts, 2002) that covers an area of 480,385 km^2 (One Shared Ocean, 2015). Due to its semi-enclosed basin and limited exchange with the Indian Ocean, the Red Sea is home to sharp latitudinal gradients in salinity, temperature, and primary productivity (Churchill et al., 2019; Raitsos et al., 2013). Attempts to protect the Red Sea's biodiversity started in the 1980's and early 1990's with various national entities (*e.g.*, the Meteorology and Environmental Protection Administration in Saudi Arabia) and international organizations (*e.g.*, the World Conservation Union) that identified coastal sites of great conservation interest (Child and Grainger, 1990; Jungius, 1988; Ormond et al., 1984). In 1998, the Regional Organization for the Conservation of the Environment of the Red Sea and the Gulf of Aden (PERSGA) recommended 75 marine protected areas (MPAs) to primarily conserve biodiversity and manage human activities while supporting the economy and the sustainable use of marine resources (Pearson and Shehata, 1998; PERSGA/GEF, 1998). Yet, due to the lack of enforcement and establishment of most MPAs (Gladstone, 2000; PERSGA/GEF, 1998), this number was revised in 2003 and reduced to 12 MPAs spread over six countries bordering the Red Sea (Fig. 1). PERSGA and other national initiatives that followed (mainly in Egypt and Saudi Arabia) resulted in a substantial increase in MPA coverage from ~2 km^2 (prior to 1983) to >16,600 km^2 (in 2014) (One Shared Ocean, 2015).

However, almost three decades later, the majority of MPAs in the Red Sea remain only proposed with no implementation, management, or legal enforcement (UNEP-WCMC and IUCN, 2020). This is particularly

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alarming because the population growth rate around the Red Sea is expected to double in the next 20–30 years (Fine et al., 2019; United Nations DoEaSAPD, 2017). For example, some areas along the Saudi Arabian coastline are projected to dramatically increase in human population size due the development of a city (NEOM) and two large resorts (AMAALA and The Red Sea Project – TRSP) (Fig. 1). Despite commitment to environmental protection and sustainability (*e.g.*, Chalastani et al., 2020), these projects are intended to accommodate more than two million people by 2030 (Berumen et al., 2019; Daye, 2019) who may exert additional pressures on the Red Sea's marine ecosystems. Local anthropogenic activities (*e.g.*, pollution, overfishing, and the use of destructive fishing gears including commercial trawling and purse seining) are already estimated to affect half of the coral reefs in this region (Burke et al., 2011; One Shared Ocean, 2015).

The imminent pressure from coastal development highlights the urgency for multinational cooperation in protecting marine resources of the Red Sea. Although challenging, such protection efforts can be achieved through connectivity-informed MPAs. The benefits of considering

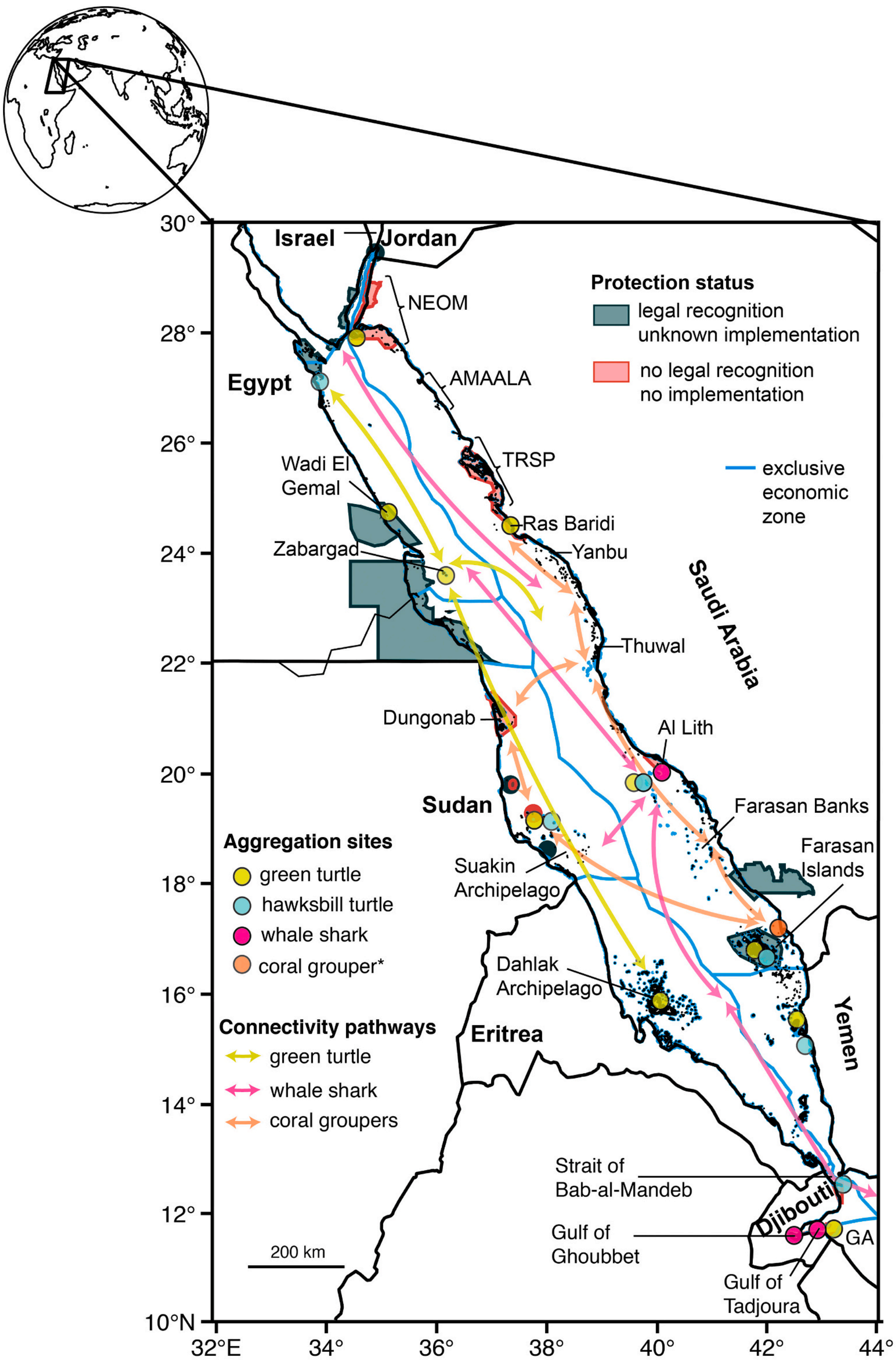

Fig. 1. Protected areas and connectivity of flagship species in the Red Sea. The dark-green protected areas are designated and legally recognized but their implementation and management are unknown (UNEP-WCMC and IUCN, 2020). The red protected areas (*i.e.*, proposed, established, or inscribed to the World Heritage Convention) vary in their designation status but are not recognized by any legal means and not implemented (UNEP-WCMC and IUCN, 2020). NEOM, AMAALA, and "The Red Sea Project" (TRSP) are three large-scale coastal development projects in Saudi Arabia that are presently under development. The exclusive economic zone (Flanders Marine Institute, 2018) of each nation bordering the Red Sea and Djibouti in the Gulf of Aden (GA) are represented by blue lines. Different types of aggregation sites are also indicated: green dots for nesting sites of the green sea turtle (*Chelonia mydas*), turquoise dots for nesting sites of the hawksbill turtle (*Eretmochelys imbricata*) (Mancini et al., 2015; Scott, 2020; Tanabe et al., 2020), pink dots for foraging sitesof juvenile whale sharks (*Rhincodon typus*) (Berumen et al., 2014; Boldrocchi et al., 2020; Cochran et al., 2019; Rowat et al., 2007), and an orange dot for a potential (*) spawning site for a coral grouper (*Plectropomus areolatus*) (DesRosiers, 2011). The known connectivity pathways within and outside the Red Sea are represented for the flagship species: green arrows for green turtle migrations (Attum et al., 2014), orange arrows for genetic connectivity of two coral groupers (*P. areolatus* and *P. pessuliferus marisrubri*) (Wilson, 2017), and pink arrows for whale shark migrations (Berumen et al., 2014; Cochran et al., 2019; Rowat et al., 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

connectivity in the core design of MPAs are numerous. From an ecological and evolutionary point of view, connectivity-informed MPAs can promote species' persistence and their adaptive capacity while maintaining ecosystem functioning (Carr et al., 2017; Walsworth et al., 2019). From a cultural standpoint, they have great potential to reconcile nations' conservation goals because patterns of species' connectivity (*e.g.*, through the exchange of larvae and/or genetic material) and movement of individuals to key areas (*e.g.*, spawning, feeding grounds) often cross multiple administrative boundaries (Lewis et al., 2017). Some of the best management tools that include such benefits are large-scale MPAs (LSMPAs).

LSMPAs encompass wide-ranging patterns and processes of ecological connectivity from various species over areas of at least 150,000 km^2, and empower connections among human populations from diverse cultural and socio-economic backgrounds (Koldewey et al., 2010; Lewis et al., 2017; O'Leary et al., 2018; Toonen et al., 2011; Wilhelm et al., 2014) by building on common heritage (*e.g.*, Pacific LSMPAs; Friedlander et al., 2016). LSMPAs are economically advantageous because they are less expensive to manage per unit area than smaller-scaled MPAs (Balmford et al., 2004). Crucially, LSMPAs were suggested to represent the best avenue to reach the 2020-Aichi biodiversity targets of protecting 10% of global marine habitats (Toonen et al., 2013). Key examples of multinational LSMPAs are the Micronesia Challenge for marine and terrestrial resource management spread over five jurisdictions in the South Pacific (http://www.micronesiachallenge.org/), the Caribbean Challenge initiative that includes eight countries (https://www.caribbeanchallengeinitiative.org/), and the Coral Triangle Initiative on Corals Reefs, Fisheries, and Food Security, a partnership among six nations in southeastern Asia and western Pacific Ocean (http://www.coraltriangleinitiative.org/). In particular, the role of connectivity in the Coral Triangle example revealed the necessity to establish a multinational network of MPAs to effectively preserve sea turtles, groupers, and sea cucumbers that routinely crossed or exchange larvae among nations' borders (Beger et al., 2015; Walton et al., 2014).

Building on these examples, we propose a change of course for conservation efforts in the Red Sea. The basin, spanning 12° in latitude, could be better preserved if the Red Sea was considered as a LSMPA. Currently, the Red Sea is protected by relatively small-sized MPAs, between <900 km^2 and 5,400 km^2 (UNEP-WCMC and IUCN, 2020) with no cohesive scientific design or shared best practices for management. In addition, the majority of conservation initiatives only mention principles of connectivity (DeVantier et al., 2000; Gladstone et al., 2003; PERSGA/GEF, 1998) and did not include connectivity data of focal species into the design of MPAs. Yet, on-the-ground data are necessary to protect migratory routes and critical areas to provide a continuous supply of larvae that can disperse and recruit in marine habitats from different jurisdictions (Beger et al., 2015; Hamilton et al., 2011). To further highlight the potential of a connectivity-informed LSMPA for the Red Sea, we herein present some potential "flagship" species that are either emblematic and highly migratory or of great commercial value.

Green (*Chelonia mydas*) and hawksbill (*Eretmochelys imbricata*) sea turtles are commonly found throughout the Red Sea (Fig. 1). Nine green turtle nesting sites (*e.g.*, the Dahlak Archipelago in Eritrea, the Farasan Banks in Saudi Arabia) and five hawksbill turtle nesting sites (*e.g.*, Al Hudaydah in Yemen) have been identified within the basin, although additional sites are expected to be found as research continues (Mancini et al., 2015; Scott, 2020; Tanabe et al., 2020). Some of the largest aggregations with >150 females are located in Ras Baridi in northern Saudi Arabia, in the Zabargad Islands off Egypt, and in the Suakin Archipelago in Sudan (Mancini et al., 2015) (Fig. 1). Other nesting sites for both species are located near the Strait of Bab-el-Mandeb in the Gulf of Aden and the Gulf of Tadjoura along the Djibouti coastline (Mancini et al., 2015). Additionally, post-nesting migration routes of green turtles females tagged on the Egyptian Zabargad Islands indicated that they foraged further north but also in waters of Saudi Arabia and Eritrea, while passing through Sudan (Attum et al., 2014) (Fig. 1). However, none of PERSGA's conservation guidelines or plans of action (PERSGA, 2004) that specifically address the protection of sea turtles have been implemented. Thus, turtle nesting sites and their migration routes receive virtually no protection, except two sites in Egypt that are protected (Wadi El Gemal and Zabargad Islands) but not necessarily enforced (Fig. 1). Both green and hawksbill turtles remain largely imperiled by direct poaching for their meat and eggs, pollution (*e.g.*, oil spill, plastics, cement dust pollution), and as fisheries bycatch (Mancini et al., 2015; PERSGA, 2004; Pilcher, 1999). Likewise, the increase in water temperatures (Jensen et al., 2018) and sea level threaten their nests (*e.g.*, Pike et al., 2015). As a result, green turtles are considered as endangered by the IUCN Red List of Threatened Species (Seminoff, 2004), while hawksbill turtles are critically endangered (Mortimer and Donnelly, 2008); further urging a call to action to protect their basin-wide movements and critical habitats.

Unlike sea turtles, regional management guidelines for the protection of whale sharks (*Rhincodon typus*) are either nonexistent or not made available to the public. Prior to the early 2000's, information about the movement of whale sharks in the Red Sea were anecdotal (Gudger, 1938). After 2008, the movement ecology of whale sharks started to be more thoroughly investigated. Within the basin, whale shark tracked movements are mainly concentrated in the central-southern Red Sea between Saudi Arabia, Sudan, Eritrea, and Yemen (Fig. 1) (Berumen et al., 2014). However, northward tracks are substantially less common (Berumen et al., 2014), probably due to the geographic bias in tagging location. One reef near Al Lith in the Farasan Banks (Saudi Arabia) is a known feeding aggregation site (Fig. 1), where female and male juveniles gather seasonally before dispersing into the wider Red Sea and Indian Ocean (Berumen et al., 2014; Cochran et al., 2016, 2019). Immature whale sharks also aggregate in high numbers in Djibouti, specifically in the Gulf of Tadjoura and Gulf of Ghoubbet (Boldrocchi et al., 2020; Rowat et al., 2007) (Fig. 1). Despite being critical habitats for their survival, none of these locations are included in legally-recognized MPAs and no effective protection measures are implemented. Propeller scars from small outboard motors are commonly reported from whale shark sightings throughout the world (Speed et al., 2008), and have been recorded in both the Red Sea (Cochran et al., 2016) and Gulf of Aden (Rowat et al., 2007). Within the Red Sea, this threat appears to be growing, with the number of fishing vessels having tripled in some jurisdictions (DesRosiers, 2011). Collisions with larger vessels can also be a significant source of cryptic mortality for whale sharks (Stevens, 2007). This is particularly relevant in the Red Sea, which is one of the busiest shipping lanes in the world with >14,000 vessels per year navigating its waters (https://www.suezcanal.gov.eg/). Successfully managing the threat of boat-strikes would benefit whale sharks but also other surface-oriented megafauna, including reef mantas (*Mobula alfredi*) (Braun et al., 2015). In addition to local threats, global climate change can affect whale shark foraging sites by modifying the timing and intensity of the upwelling of cold nutrient-rich waters, such as in 2015 in the Farasan Banks (DeCarlo et al., 2021), potentially resulting in a decreased attractiveness of these sites. Considerable effort should be dedicated toward the conservation of whale shark aggregation sites while affording some levels of protection to their migratory routes within the basin.

Coral groupers provide a third potential flagship species for this region. Both *Plectropomus areolatus* and *Plectropomus pessuliferus marisrubri* are species of fisheries interest in the Red Sea (DesRosiers, 2011; Rouphael et al., 1998; Shellem, 2020; UNIDO, 2017). *Plectropomus pessuliferus marisrubri* is also considered to be endemic to the basin (Heemstra and Randall, 1993; Ma et al., 2016). These groupers are heavily consumed and among the highest-priced species in the fish markets with value estimated to reach USD $25 per kilogram (Shellem et al., 2021). Genetic connectivity—derived from individuals that have dispersed to other locations and contributed genes to the next generation (Ovenden et al., 2016)—revealed that populations of *P. areolatus* and *P. pessuliferus marisrubri* are connected between central and southern Red Sea, and across eastern and western margins. Grouper populations from Dungonab and the Suakin Archipelago in Sudan are linked to populations from northern (Ras Baridi, Yanbu, and Thuwal) and southern Saudi Arabia (south of Farasan Banks and near the Farasan Islands) (Wilson, 2017) (Fig. 1). Although some of these populations fall into proposed MPAs, there is no clear indication of any fishing regulation or enforcement. Regional control and surveillance mechanisms for fisheries management of these coral groupers are either weak or non-existent, resulting in unregulated fishing practices and regional overfishing pressure, such as in Yemen (Rouphael et al., 1998). One exception was a reported seasonal fishing closure that occurred for 10 years during springtime in Saudi Arabia, but it is unclear whether this closure remains in place. In addition, one putative spawning aggregation site has been identified along the southern coast of Saudi Arabia (Fig. 1) due to the presence of older individuals of *P. areolatus* and favorable environmental conditions (DesRosiers, 2011). This site does not fall under any kind of permanent or temporary conservation measures. Although commercially and customarily valuable, coral groupers in the Red Sea are not effectively protected.

These case studies of flagship species demonstrate that coastal nations along the Red Sea are highly connected to one another but also to nations outside the basin, requiring a cohesive conservation plan between the Red Sea and the western side of the Gulf of Aden to maintain the connectivity pathways. Yet, the existing small-scale MPAs do not conserve most of the migratory routes and critical habitats of these flagship species. Therefore, marine reserve design in the Red Sea should be revised and accompanied by alternative management tools to protect all population stocks. These tools could include defining areas with restricted access zones (*e.g.*, seasonal closures of nesting beaches and of reefs where coral groupers spawn), proposing no-take areas with no access (*e.g.*, remote islands that are less accessible, which could include offshore islands in the Farasan Banks in Saudi Arabia), and also adjusting governance activities (*e.g.*, modifying the paths of shipping lanes to avoid whale shark seasonal migration routes) as well as implementing other measures, such as size-catch restrictions (*e.g.*, DesRosiers, 2011; Green et al., 2015). A concerted, multinational effort must also arise to safeguard the flagship species that are almost all vulnerable to local and global threats. If nations unify their conservation goals, the Red Sea's economy may also be boosted by maintaining the current annual revenue of US $230 million for fisheries and US $12 billion for tourism (One Shared Ocean, 2015). Additionally, the development of ecotourism using sea turtles and whale sharks could represent additional incomes for the region. For example, sea turtles are a tourist attraction in the Caribbean with an average of US $1.65 million per year (Troëng and Drews, 2004), while whale shark tourism in the South Ari MPA in the Maldives reached US $9.4 million in 2013 (Cagua et al., 2014).

Overall, we advocate for a connectivity-informed LSMPA for the Red Sea to achieve the political theory of "common good" (Beerbohm and Davis, 2017) where collective decision-making can rise above individual nations' interests, setting aside political positions on other issues, to meet conservation goals whose ecological, cultural, and economic values cannot be ignored. A connectivity-common-good nexus for the Red Sea should thus be actively pursued to coordinate research and scientific programs for the better management of coastal resources as proclaimed by the UN Decade for Ocean Sciences. Following other successfull examples (*e.g.*, the Coral Triangle Initiative; Walton et al., 2014), the proposed nexus could be achieved by organizing a "Red Sea Challenge" where all nations meet, discuss, and collaborate to build a consolidated network of MPAs that would address transboundary issues by focusing on connectivity. Existing government and non-governmental agencies, such as PERSGA, could play a pivotal role by leading, developing, and distributing the connectivity information whose message would be that well-managed areas in one nation would benefit other adjacent nations by supporting biodiversity and fisheries. Therefore, the communication materials should be easily understood by different audiences (*e.g.*, scientists, decision makers, local communities) so that the importance of connectivity to coordinate conservation efforts is widely understood.

2. Data availability statement

The connectivity pathways within and outside the Red Sea for the green turtle (*Chelonia mydas*) can be found in Attum et al. (2014), while their nesting were identified by Mancini et al. (2015), Scott (2020), Tanabe et al. (2020). The Red Sea and Djibouti's nesting sites for the hawksbill sea turtle (*Eretmochelys imbricata*) were recorded by Mancini et al. (2015). The basin-wide larvae exchange for two coral groupers (*P. areolatus* and *P. pessuliferus marisrubri*) were published in DesRosiers (2011) and Wilson (2017), while the whale shark migration and aggregation sites were identified by Berumen et al. (2014), Cochran et al. (2019), Rowat et al. (2007), and Boldrocchi et al. (2020).

CRediT authorship contribution statement

Laura Gajdzik: Conceptualization, Software, Formal analysis, and Writing – Original Draft, and Project administration. **Alison** L. **Green**: Conceptualization and Writing- Reviewing and Editing. **Jesse E. M. Cochran**: Writing- Reviewing and Editing. **Royale S. Hardenstine***:* Writing – Reviewing & Editing. **Lyndsey K. Tanabe**: Writing – Reviewing & Editing**. Michael** L. **Berumen:** Writing- Reviewing & Editing, Funding acquisition.

Declaration of competing interest

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

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