



# Satellite Tracking of Post-nesting Green Sea Turtles (*Chelonia mydas*) From Ras Baridi, Red Sea

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Identifying migratory pathways and linking nesting sites to foraging areas is essential for effective conservation management of migratory species, such as marine turtles. Post-nesting marine turtles disperse from their nesting sites to multiple foraging areas located from a few to hundreds of kilometers away. Over a six-year period 16 female green turtles (*Chelonia mydas*) were equipped with satellite transmitters between October and December of five nesting seasons to determine their migratory routes from their nesting area at five contiguous beaches at Ras Baridi, Saudi Arabia, to their foraging areas. All foraging areas for these turtles were located in shallow coastal areas or in shallow areas around offshore islands within the Red Sea basin. The majority ( $n = 12$ ) migrated through the shallow (<200 m) water along the coastal margin to reach foraging areas located to the North ( $n = 4$ ) and South ( $n = 12$ ) of the nesting site. Four turtles crossed the deep trough of the Red Sea during their journeys. Ten of the 16 turtles migrated to foraging areas within the territorial waters of Saudi Arabia. The other six turtles migrated to foraging areas in Egypt ( $n = 4$ ) and Eritrea ( $n = 2$ ). These 16 turtles traveled between 130 and 1749 km from their nesting site to foraging areas located in the northern, middle and southern parts of the Red Sea. Because these turtles utilized foraging areas in at least three countries (Saudi Arabia, Egypt, and Eritrea) and one passed through the territorial waters of Sudan, conservation and management of green turtles in the Red Sea requires multinational cooperation to address anthropogenic threats in the region.

**Keywords:** satellite tracking, green turtle, *Chelonia mydas*, Red Sea, Ras Baridi

## INTRODUCTION

The success of conservation efforts for animals that migrate between habitats when they reproduce (e.g., birds: Egevang et al., 2010; fish: Tamario et al., 2019; sea turtles: Russell et al., 2005) depends on understanding their population biology as well as the distribution of important habitats and the connections among these habitats in the context of threatening processes that may be encountered (Martin et al., 2007; Lascelles et al., 2014; Gajdzik et al., 2021). Because migrations for reproduction vary in length depending on the species and the distance between the habitats (Luschi, 2013; Lascelles et al., 2014; Dunn et al., 2019), the routes followed may cross international borders and, as a result, migrating animals may encounter different anthropogenic threats in different jurisdictions (López-Hoffman et al., 2017; Palacios-Abrantes et al., 2020; Gajdzik et al., 2021).

Specific details concerning the distribution and use of important habitats and the connecting migratory routes are needed on an appropriate scale so that regional ecosystem management options can be coordinated and tailored to reduce threatening processes (Rees et al., 2016; Lagabrielle et al., 2018; Hernandez-Avila et al., 2020; Gajdzik et al., 2021). This is particularly important in a marginal sea such as the Red Sea, wherein the majority of the coastal margin is managed by six countries (two other countries border the Gulf of Aqaba) (PERSGA, 2006). The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA) has a prominent role in coordinating the protection of the marine and coastal environments in the region, including developing guidelines for conservation of living marine resources (e.g., Hariri et al., 2002; PERSGA, 2007). However, the existing marine protected areas in the Red Sea do not seem to provide the level of protective conservation management needed by very mobile and migratory species (i.e., dugong, turtles, and sharks, Roupheal et al., 2015). At least part of this situation stems from the lack of information concerning the migratory routes and habitats used by these marine species in the region (Gajdzik et al., 2021). Understanding the connectivity among important habitats (i.e., foraging areas, nesting sites) and the routes used to connect them is essential to development of effective conservation practices (Bolker et al., 2007; Dunn et al., 2019).

Adult marine turtles are bi-directional migratory iteroparous species that spend the majority of their time in their foraging areas where they live and periodically prepare for reproduction (Miller, 1997; Plotkin, 2003). Reproducing female sea turtles migrate to breeding areas and specific nesting beaches where they oviposit several clutches of eggs at intervals of about 2 weeks, and then return to their foraging areas (Meylan et al., 1990; Miller, 1997; Godley et al., 2008). Marine turtles show high fidelity to both their nesting and foraging areas (Limpus et al., 1992; Pilcher et al., 2020; Shimada et al., 2020). During their reproductive migrations green turtles (*Chelonia mydas*) may utilize coastal and open water corridors (Pendoley et al., 2014; Stokes et al., 2015; Mettler et al., 2019) and/or pass through the territorial waters of one or more nations (Blanco et al., 2012; Rees et al., 2012, 2018; Hart et al., 2018; Pilcher et al., 2021a,b). They may transit areas used for artisanal and/or commercial fishing (Gladstone, 2002; PERSGA, 2003, 2004, 2006, 2007). Although fishing is regulated in every country that borders the Red Sea, the impact of bycatch on the turtle populations is poorly defined (PERSGA, 2003; Mancini et al., 2015).

In recent years, satellite tracking of marine turtle movements between their nesting sites and foraging areas has elucidated much of the previously unknown biology and habitat use (Godley et al., 2002, 2008; Luschi et al., 2003; Blumenthal et al., 2006; Hart et al., 2013, 2017; Luschi and Casale, 2014; Pilcher et al., 2014, 2021a,b; Rees et al., 2016; Ferreira et al., 2020), including bi-directional movements (Limpus and Limpus, 2001; Pilcher et al., 2020). It is now well established that post-nesting turtles which used a particular nesting location return to several different foraging areas (Luschi et al., 1996; Bjorndal et al., 2005; Blumenthal et al., 2006; Bolker et al., 2007; Bradshaw et al., 2017; Shimada et al., 2020). Conversely, turtles foraging in one general

habitat disperse to several different nesting locations (i.e., mixed stock) (Limpus et al., 1992; Dethmers et al., 2010; Carreras et al., 2011; Jensen et al., 2013; Read et al., 2015; Dutton et al., 2018). In combination with other methods (e.g., genetics), satellite tracking of marine turtles can be used to better define the uniqueness of nesting populations and shared use of habitat (Godley et al., 2010; Hart et al., 2012, 2020; Bourjea et al., 2015; Jensen et al., 2019). In addition, satellite tracking of marine species has contributed to identifying important foraging areas (Pilcher et al., 2014; Stokes et al., 2015, 2019), threatening processes (Hays et al., 2003; Hart et al., 2018), and helped with development of conservation and management options (Hays et al., 2014, 2019, 2021; Pendoley et al., 2014; Hays and Hawkes, 2018).

However, a better understanding of the migration patterns of marine species is necessary to support conservation efforts and to identify potential areas of threatening processes in the Red Sea (Gajdzik et al., 2021), particularly for species that are globally or regionally at risk. Of the five species of sea turtles that occur in the Red Sea, at least infrequently (Mancini et al., 2015), the green turtle (*Chelonia mydas*) and the hawksbill (*Eretmochelys imbricata*) are regularly observed. The loggerhead (*Caretta caretta*), the olive-ridley (*Lepidochelys olivacea*), and the leatherback (*Dermochelys coriacea*) are less commonly seen (Ross and Barwani, 1982; Frazier et al., 1987; Pilcher et al., 2006; PERSGA, 2010; Mancini et al., 2015; Miller, 2020). In the northern Indian Ocean region, the herbivorous green turtle (Bjorndal, 1997; Stokes et al., 2019; Esteban et al., 2020) is classified as *Vulnerable* (Mancini et al., 2019) and is listed in Appendix 1 of the Convention on International Trade of Endangered Species (CITES, 2021).

Although the information concerning the routes used by green turtles as they migrate between nesting sites and foraging areas in the Arabian region is increasing (Pilcher et al., 2020, 2021a,b) much remains to be determined. Currently, little is known about the connectivity between nesting sites and foraging areas for green turtles (Mancini et al., 2015, 2018; Pilcher et al., 2021b) or about foraging area inclusion in existing Marine Protected Areas (MPAs) in the Red Sea because a relatively low number of green turtles have been tracked to foraging areas (Roupheal et al., 2015; Gajdzik et al., 2021). In 2010 satellite transmitters were used to identify the migratory pathways of four green turtles that had nested at Zabargad Island (off shore of Egypt) (Attum et al., 2014). This study provided evidence of the locations of foraging areas associated with nesting in the northern Red Sea (Attum et al., 2014). Recently, three green turtles were followed using satellite transmitters to foraging areas in the southern portion of the Red Sea from nesting areas located in Oman (Rees et al., 2012, 2018; Pilcher et al., 2021b). Although, the migrations to foraging areas by sea turtles that nest at sites in the northern Red Sea have received little attention (Attum et al., 2014; Mancini et al., 2015, 2018), their use of nesting sites and internesting habitat has recently been described in detail (Shimada et al., 2021a,b).

Surveys of the biology of green turtles nesting at Ras Baridi began in 1987 (Miller, 1989). In 1989 the National Center for Wildlife (NCW) [formerly the National Commission for Wildlife Conservation and Development] initiated detailed studies of multiple aspects of the nesting turtles, including their

morphology and their nesting success (Al-Merghani et al., 2000; Pilcher and Al-Merghani, 2000; Al-Mansi et al., 2003; Al-Mansi, 2016). In addition to studies concerning the turtles, physical characteristics of the beach and environmental factors were studied to determine their impact on the hatching success of eggs (Al-Mansi et al., 1991; Pilcher, 1999; Tanabe et al., 2020). Jensen et al. (2019) defined a unique genetic allele from the green turtles nesting at Ras Baridi. Recently, an assessment of the nesting population and the use of interesting habitat in the vicinity of the Ras Baridi nesting beaches was described (Shimada et al., 2021a).

In late 2009 the NCW began a research program with the goal of identifying the migratory routes and the foraging areas used by green turtles nesting at Ras Baridi. Herein we present the results of satellite tracking of 16 post-nesting green turtles from Ras Baridi on the Red Sea Coast of the Kingdom of Saudi Arabia between 2009 to 2014.

## MATERIALS AND METHODS

### Study Area

Ras Baridi (N 24° 16' 24.33"; E 37° 37'35.30") is located 60 km north of Yanbu on the eastern coast of Saudi Arabia, facing the north-central Red Sea (**Figure 1**) (for regional context see: Head, 1987; Tesfamichael and Pauly, 2016; Carvalho et al., 2019; **Supplementary Material**). Green turtles are the main species nesting at Ras Baridi, where the nesting season extends from August through November/December (Pilcher and Al-Merghani, 2000; Shimada et al., 2021b). An estimated 178 to 330 green turtles nest on the five well-developed pocket beaches (Shimada et al., 2021b; **Figure 1**). The beaches range from 50 to 1500 m long and are about 50 m wide. The other species that nests at Ras Baridi, at least infrequently, is the hawksbill (*Eretmochelys imbricata*) (Shimada et al., 2021b), which nests in low numbers throughout the region (Miller, 2020).

### Transmitter Attachment and Data Processing

During the study period (December 2009 through October 2014), 16 female green turtles were selected to carry satellite transmitters. After oviposition had been completed, each turtle was corralled in a wooden-sided frame that prevented it from returning to the sea. A titanium tag (Stockbrands Co., Pty Ltd.) was attached to the trailing edge of the left front flipper of each turtle (Balazs, 1999). The curved carapace length (CCL) of each nesting female was measured using a flexible tape measure over the curve of the carapace along the midline from the anterior point at the midline of the nuchal scute to the posterior tip of the supra caudal scutes (CCLn-t, Bolten, 1999). The curved carapace width (CCW) was measured over the curve of the carapace from margin to margin at the widest part, perpendicular to the midline of the carapace (**Supplementary Table 1**).

Transmitter attachment was accomplished by washing the anterior carapace with disinfectant and rinsing the area with water. The second vertebral scute of the carapace (transmitter location) was gently rubbed with sandpaper and washed with

acetone (Coyne et al., 2009). The transmitter was attached to the carapace with epoxy (PC-11 epoxy glue, Protective Coating Company), according to the manufacturer's instructions and established procedures (Coyne et al., 2009). The turtle was released after the epoxy had dried (approximately 90 min) to return to the sea.

Turtles were tracked with Kiwisat 101 PTTs (Sirtrack Ltd.), programmed for a duty cycle of 8 h on/16 h off, and synchronized to operate during daylight hours to prolong battery life. Saltwater switches restricted transmission to periods when the unit was at the surface.

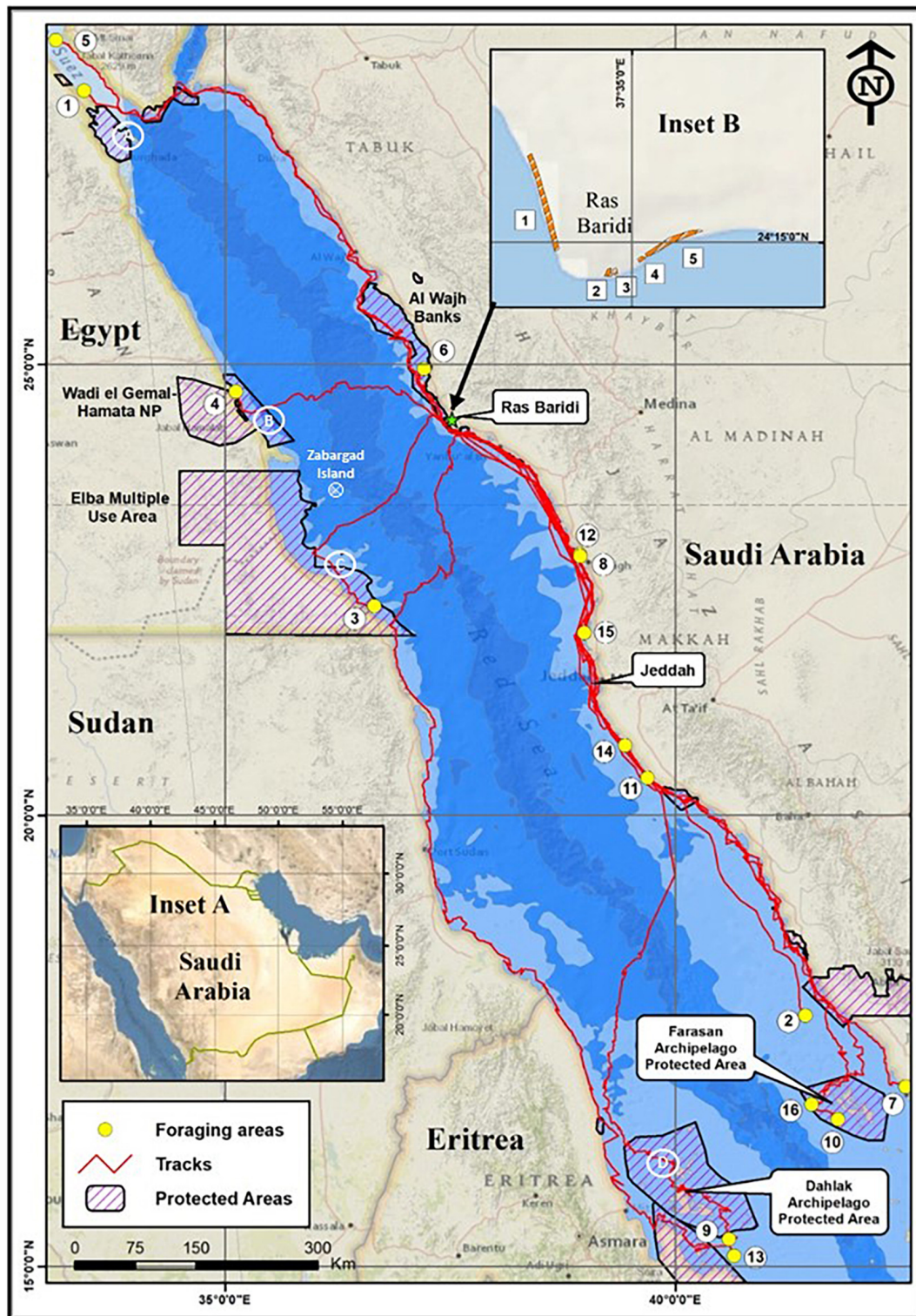
Filtering of the data from Argos used standard doppler-based geolocation technology. Locations were assigned an estimate of accuracy by the Argos system: class 0 = > 1,500 m, class 1 = > 1,000 m, class 2 = > 500 m, and class 3 = > 150 m, plus class A and B using Kalman filtering. Only data points from ARGOS estimated accuracy location classes 3, 2, 1, and A were included in the analysis (Hays et al., 2001). In addition, data points greater than 100 km from the previous location or that indicated a turtle speed greater than 5 km/h (Troëng et al., 2005; Broderick et al., 2007) were omitted from the data set before analysis. Also, data points that were greater than 2 m above sea level or that were over land were omitted from the analysis (Attum et al., 2014).

The Satellite Tracking and Analysis Tool "STAT" (Coyne and Godley, 2005) was used to organize and analyze the data. Geographic information system software (ESRI ArcGIS 10.14) was used to map turtle movements. Cumulative distance traveled was calculated as the sum of the distances between contiguous locations measured using the geometry calculation in ArcGIS assuming straight-line movements between fixes. The speed for each turtle was calculated based on the sum of time intervals and the sum of distances measured between contiguous locations in each of three habitats: open water, coastal water, and foraging area. Turtles were deemed to have left the nesting beach when the signal locations indicated directional movement away from the nesting area (Pilcher et al., 2014). The 200 m depth contour was used to determine whether turtles moved into open water or remained along the coast because it is beyond the depth of seagrass growth (Duarte, 1991) and green turtle foraging dives (Lutcavage and Lutz, 1997). Turtles were deemed to have arrived at foraging areas when the rate of travel was consistently below 1 km/h and signal positions indicated short distance, multidirectional movements separated by sharp acute angles (i.e., <30°) (Schofield et al., 2010; Foley et al., 2013). In all cases, the boundaries between habitats were determined visually from the plotted points.

## RESULTS

### Signals Received and Filtered

The mean number of location signals received from the satellite transmitters affixed to the post-nesting turtles during their migrations to foraging habitats was 194.8 (Range: 45–666,  $n = 16$ ) (**Table 1**). The mean number of locations removed before analysis was 12.4 (Range: 4–24,  $n = 16$ ), the majority of which were removed because the location was "over land" during the coastal



**FIGURE 1 |** Map of the Red Sea showing the distribution of foraging areas of 16 green turtles that nested at Ras Baridi on the eastern coast of Saudi Arabia. Inset A provides regional orientation. Inset B shows the distribution of beaches at Ras Baridi. Circled numbers = identification of foraging areas used by 16 post-nesting green turtles in the present study. Green Star = Ras Baridi. White circled X = Zabargad Island; white circled letters = general location of foraging areas used by the green turtles tracked by Attum et al. (2014). Depth contours: light blue = coastal shelf < 200 m, medium blue = > 200 m, dark blue > 1000 m. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, IPC, and Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community by ESRI software 10.4.

**TABLE 1** | Summary of the numbers of locations used in the study, daily means in the open water and coastal habitats, and the reasons for removal of points.

Turtle No.	Total number of Locations	Number of Locations Used	Number in Open water	Daily Mean in Open water	Number in Coastal water	Daily Mean in Coastal water	Number of Locations Removed	Reasons for Removal
1	155	141			141	8.29	14	5,2,1
2	163	144			144	9.6	19	5,4,1
3	172	167	49	26.59	118	15.23	5	5,1
4	93	89	45	17.3	44	6.98	4	4,1
5	147	137			137	7.86	10	5,3,4,1
6	95	71			71	24.66	24	5,1
7	258	244			244	9.76	14	5,2,1
8	126	117			117	23	9	5,1
9	109	100			100	16.67	9	5,1
10	459	444	62	19.81	382	10.85	15	5,4,3
11	177	169			169	11.27	8	5,1
12	100	94			94	18.8	6	5,2,1
13	666	649	74	19.7	575	12.83	17	5,3,1
14	140	118			118	12.16	22	5,1
15	45	33			33	6.6	12	5,3,1
16	213	202			202	8.46	11	5,4,2,1
<b>Mean</b>	<b>194.87</b>	<b>182.44</b>	<b>57.5</b>	<b>20.85</b>	<b>168.06</b>	<b>12.69</b>	<b>12.44</b>	
<b>(Min)</b>	<b>45</b>	<b>33</b>	<b>45</b>	<b>17.3</b>	<b>33</b>	<b>6.6</b>	<b>4</b>	
<b>(Max)</b>	<b>666</b>	<b>649</b>	<b>74</b>	<b>26.59</b>	<b>575</b>	<b>24.66</b>	<b>24</b>	
<b>Count</b>	<b>16</b>	<b>16</b>	<b>4</b>	<b>4</b>	<b>16</b>	<b>16</b>	<b>16</b>	

Turtle numbers are shown on **Figure 1**. Codes for Reasons for Removal: 1. Accuracy of location = B, 2. Data points greater than 100 km from the previous location, 3. Speed between points was greater than 5 km/h, 4. Greater than 2 m above sea level, and 5. Over land.

movement phase of the migration of each turtle. The mean number of usable locations was 182.4 (Range: 33–649,  $n = 16$ ).

## Migration Paths

The destinations of the 16 post-nesting female green turtles tracked by satellite transmitters from Ras Baridi to foraging areas demonstrated that they did not leave the Red Sea basin (**Figure 1**). The majority ( $n = 12$ ) of the turtles used coastal migration routes within the 200 m bathymetry contour but a few ( $n = 4$ ) crossed the deep trough (>1000 m deep, Head, 1987) of the Red Sea. The dispersal pattern shows that in any 1 year the turtles migrated to foraging areas located in different areas of the Red Sea (**Figure 1** and **Supplementary Table 2**). The majority ( $n = 10$ ) remained along the coastal margin of Saudi Arabia while six of the turtles ended their journeys in other countries: Egypt ( $n = 4$ ) and in Eritrea ( $n = 2$ ).

Twelve turtles migrated along the coastal margin. Of these 12, three turtles migrated northward along the coast of Saudi Arabia. One of these stopped in Saudi Arabia and two continued to the Gulf of Suez. Five of the 12 turtles traveled southward along the eastern coast of Saudi Arabia to neritic foraging areas in the vicinity of Jeddah (**Figure 1**). Three turtles stopped along the coast north of Jeddah and two turtles continued southward to coastal feeding areas to the south of Jeddah. Four of the 12 turtles migrated much further south to the vicinity of the Farasan Archipelago (**Figure 1**). One finished its journey in the northern part of the area. One settled in the coastal area in front of the city of Jizan. The other two turtles traveled to the shallow water of the Farasan Archipelago.

The other four turtles of the 16 crossed the deep-water trough (>1000 m, Head, 1987) of the Red Sea during their journeys to foraging areas in Egypt ( $n = 2$ ) and Eritrea ( $n = 2$ ) (**Figure 1**). One of these turtles crossed to the western side of the Red Sea and then traveled slightly northward to Wadi El Gemal-Hamata National Reserve (Egypt). The second turtle crossed the Red Sea in a southwesterly direction and then followed the coast southward to the vicinity of Halayib Island in the Elba Multiple Use Area. The third turtle crossed the Red Sea and continued southward along Sudanese coast to the Dahlak Archipelago in Eritrea. The fourth turtle moved southward along the eastern coast of Saudi Arabia for about half of its journey, then crossed the Red Sea, and continued southward on the western side to the Dahlak Archipelago.

## Post-nesting Migration Distance, Duration, and Rate of Travel

The mean post-nesting migration distance traveled by the 16 turtles in the present study was 784.9 km ( $\pm$ Standard Deviation of the Sample = 505.78 km) (**Table 2**). The shortest distance traveled was to the vicinity of Umm Sihr Island located 130 km to the North of Ras Baridi. The longest journey covered a distance of 1749 km, ending in the Dahlak Archipelago of Eritrea. The duration of migrations between the nesting site at Ras Baridi and the foraging areas ranged from 3 to 47.1 days (mean =  $17.1 \pm 12.6$  days,  $n = 16$ , **Table 2**). The turtle that traveled the shortest distance did so in 3 days and the turtle that traveled the longest distance required 38 days to complete its journey. The turtle that traveled the longest time covered a distance of

**TABLE 2** | Summary of data for each of the 16 green turtles followed by satellite tags from nesting at Ras Baridi, Saudi Arabia, including duration of signal reception, total migration distance, travel days, speed and distance traveled in open water and along the coast, residence time in foraging area before loss of signal, and speed in foraging area.

Turtle No.	Signal Reception Duration (Days)	Total Migration Distance (km)	Total Travel Days	Open Water Migration Distance	Open Water Travel Days	Open Water Speed (km/h)	Coastal water Migration Distance	Travel Days in Coastal Water	Coastal Speed (km/h)	Foraging Area Residence Days	Foraging Area Speed (km/h)
1	283	795	17				795	17	1.95	251	0.051
2	157	913	15				913	15	2.54	56	0.43
3	709	380	8.9	210	2.6	3.31	170	6.3	1.12	672	0.38
4	1118	344	7	251	3.4	3.07	93	2.7	1.44	1111	0.42
5	285	935	22				935	22	1.77	248	0.55
6	280	130	3				130	3	1.81	635	0.69
7	127	1230	25				1230	25	2.05	92	0.49
8	188	290	6				290	6	2.01	171	0.39
9	142	1749	38	245	3.1	3.31	1504	34.9	1.79	110	0.57
10	129	1304	26				1304	26	2.09	100	0.44
11	173	634	15				634	15	1.76	155	0.59
12	322	271	5				271	5	2.26	275	0.41
13	166	1542	47.1	305	3.9	3.28	1237	43.2	1.19	112	0.77
14	218	480	10				480	10	2	178	0.4
15	108	325	5				325	5	2.71	101	0.61
16	229	1237	24				1237	24	2.15	195	0.58
<b>Mean</b>	<b>289.6</b>	<b>784.9</b>	<b>17.1</b>	<b>252.8</b>	<b>3.3</b>	<b>3.2</b>	<b>721.8</b>	<b>16.3</b>	<b>1.9</b>	<b>278.9</b>	<b>0.5</b>
<b>StDev.s*</b>	<b>262.80</b>	<b>505.78</b>	<b>12.63</b>	<b>39.25</b>	<b>0.54</b>	<b>0.12</b>	<b>482.40</b>	<b>12.11</b>	<b>0.43</b>	<b>285.70</b>	<b>0.16</b>
<b>Min</b>	<b>108</b>	<b>130</b>	<b>3</b>	<b>210</b>	<b>2.6</b>	<b>3.07</b>	<b>93</b>	<b>2.7</b>	<b>1.12</b>	<b>56</b>	<b>0.051</b>
<b>Max</b>	<b>1118</b>	<b>1749</b>	<b>47.1</b>	<b>305</b>	<b>3.9</b>	<b>3.31</b>	<b>1504</b>	<b>43.2</b>	<b>2.71</b>	<b>1111</b>	<b>0.77</b>
<b>Count</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>4</b>	<b>4</b>	<b>4</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>

\*Stdev.s = Standard Deviation of the Sample.

Turtle numbers are shown on **Figure 1**.

1542 km. The mean rate of travel of turtles while moving along the coast was  $1.9 \pm 0.426$  km/h ( $n = 16$ , **Table 2**). The mean speed of four turtles while crossing the deep water of the Red Sea was  $3.24 \pm 0.116$  km/h ( $n = 4$ , **Table 2**). The mean speed dropped to  $0.49 \pm 0.163$  km/h ( $n = 16$ , **Table 2**) in the foraging areas. The rate of travel suggests that the turtles did not stop for any length of time during their migrations.

The mean reception period for a satellite signal was  $289.6 \pm 262.8$  days. The longest reception period was 1118 days after the initial tagging, and the shortest reception period was 108 days (**Table 2**). Transmitters remained active for an average of  $278.9 \pm 285.7$  days ( $n = 16$ ) after the behavior of the turtles indicated they were foraging rather than traveling (**Table 2**).

### Managed and/or Protected Areas

The destinations of the migrations were inside ( $n = 5$ ) and outside ( $n = 11$ ) managed and/or protected areas. Two turtles (#10, #16) concluded their migrations in the Farasan Islands Resource Use Reserve, and one turtle (#6) was tracked to the Al Wajh Bank Resource Use Reserve in Saudi Arabia (**Figure 1**). The remaining two turtles (#4, #3) crossed the Red Sea to reach foraging areas in Wadi el Gemal-Hamata National Park, which is a multiple use management area, and to the Elba Multiple Use Management Area situated along the central and southern coast of Egypt, respectively. The other 11 turtles were tracked to foraging locations outside protected areas. Six turtles

settled within 30 km of a protected area and five stopped in foraging areas without nearby protected areas (i.e., >30 km) along the narrow coastal margin to the North and South of Jeddah (**Figure 1**).

### DISCUSSION

Satellite tracking of marine turtle movements between their foraging and nesting areas has begun to fill in much of the missing information on migratory movements and habitat use in the region of the Arabian Peninsula (Rees et al., 2012, 2018; Pilcher et al., 2020, 2021a,b). However, very little information is known about green turtle migrations or the locations of their foraging areas in the Red Sea basin (Attum et al., 2014; Mancini et al., 2015, 2018; Shimada et al., 2021a,b).

The destinations of these 16 post-nesting green turtles showed they remained within the Red Sea basin (**Figure 1**). Their destinations indicate that turtles nesting at Ras Baridi originated from at least 11 foraging areas located in three countries (Saudi Arabia, Egypt, Eritrea), with most foraging in neritic habitat in Saudi Arabia (**Figure 1** and **Supplementary Table 2**). The majority followed routes along the coastal margin within the 200 m bathymetry contour but a few crossed the deep trough (>1000 m deep) of the Red Sea. The migration routes illustrate that turtles which migrated to the same destination

did not necessarily follow the same migratory route and that turtles which did follow the same general migratory route did not necessarily stop at the same foraging area. While in route along the coast and over deep-water areas, they swam at speeds comparable to those reported by others, with migration speeds over deep-water being faster (e.g., Papi et al., 1995; Cheng, 2000 and citations therein; Godley et al., 2002; Ferreira et al., 2020).

The green turtles tracked from Ras Baridi showed the Type A1 migratory behavior (Godley et al., 2008) described for green turtles in the Mediterranean (Godley et al., 2002). Although the green turtles from Ras Baridi behaved in a similar manner to those in the western Mediterranean (Godley et al., 2002; Stokes et al., 2015), there were differences. Only four of the turtles from Ras Baridi crossed deep water of the Red Sea, whereas all of the turtles tracked from Cyprus crossed deep water during part of their migrations. All the turtles from Ras Baridi and Cyprus utilized neritic habitat during part of their migrations to reach foraging areas. However, the migratory routes of the turtles from Ras Baridi were shorter (mean, range: 784.9, 130–1749 km vs. 1363.7, 322.6–2199.6 km, Godley et al., 2002; 1283, 181 to 2641 km, Stokes et al., 2015) and, as a consequence, required shorter travel times (mean, range: 17.1, 3–47 days vs. 27.6, 8.2–43.8 days, Godley et al., 2002, 2008, and 36, 6–80 days, Stokes et al., 2015) to reach their destinations.

The migration distances of green turtles vary widely throughout their global range, mostly as the result of the relative locations of nesting and foraging habitats in the context of the physiography of the regional environment (Godley et al., 2002; Blanco et al., 2012; Read et al., 2014; Stokes et al., 2015; Mettler et al., 2019). Within the long narrow Red Sea (Head, 1987; Carvalho et al., 2019), green turtles behave in a similar manner and likely for the same reasons because some migrated relatively short distances and others moved more than 1000 km (i.e., Zabargad Island: 140–940 km, Attum et al., 2014; Ras Baridi: 130–1749 km, present study).

The four post-nesting green turtles tracked from Zabargad Island provided the initial view of habitat areas used by green turtles that nested in the northern Red Sea region (Attum et al., 2014; **Figure 1**). The locations of their destinations and those of the current study indicate that turtles using these separate nesting locations share some general foraging areas. The proximity of the destinations identifies four general areas that are important to the foraging aggregations of green turtles in the western Red Sea [i.e., Gamsha Archipelago (Egypt), the Wadi el Gemal-Hamata NP and Elba Multiple use Area (Egypt), and the Dahlak Archipelago (Eritrea)] (**Figure 1**). In addition, the turtles from Ras Baridi identified new foraging habitats on the eastern side of the Red Sea (i.e., coastal margin in the vicinity of Jeddah and in the Farasan Archipelago) that are connected to the turtles nesting at Ras Baridi.

The distribution of the foraging areas used by these northern nesting turtles corroborates the genetic difference (allele cmP71.1, Jensen et al., 2019) reported from 16 tissue samples collected in 1993 because all tracked turtles remained within the Red Sea. The genetic difference and the ancestral link to the

green turtles nesting in Oman (Jensen et al., 2019) are further supported because both metal flipper tags and satellite tags applied in Oman have been carried to the southern Archipelagos of the Red Sea (Ross and Barwani, 1982; Salm et al., 1993; Rees et al., 2012, 2018; Pilcher et al., 2021b) indicating that these foraging areas support mixed foraging stock. Although the combination of these independent methods (i.e., genetics, satellite tracking) differentiates the nesting population at Ras Baridi as being unique, additional sampling of the genetic composition of turtles from other nesting locations in the Red Sea basin is needed to define the linkages among the nesting aggregations and foraging habitats of green turtles. This information has direct implications on the development of multinational conservation management of marine turtles and their habitats in the northern Red Sea.

The transboundary routes of migrating marine turtles expose them to various anthropogenic threats, including becoming bycatch in fishing operations (PERSGA, 2007; Stokes et al., 2015; Gajdzik et al., 2021). In the Red Sea basin marine turtles are not typically the target of fishing activities and they are protected both inside and outside of National Parks and other protected areas throughout the region by a mixture of national laws and international agreements (PERSGA, 2003; Mancini et al., 2015; Shepherd, 2015; Phillott and Rees, 2020). However, because most migrate by means of the coastal shelf where much of the fishing activity occurs, they are subject to incidental capture. In addition, they reside and forage in areas where seagrasses and alga grow, which are also areas of intense fishing activity, thus making them vulnerable to being caught in artisanal and commercial fishing operations. Studies conducted elsewhere have demonstrated that the likelihood of bycatch increases when fishing grounds overlap with turtle high-use areas (Stokes et al., 2015; Monteiro et al., 2016) which can have severe impacts on turtle populations (Lucchetti et al., 2019). Within the Red Sea marine turtles are caught in both artisanal and commercial fisheries throughout the region (Hariri et al., 2002; Tecleremariam et al., 2009; Mebrahtu, 2013, 2015; Mancini et al., 2015; Roupheal et al., 2015; Pilcher et al., 2021b) but there is very little published information concerning this impact on the turtle populations. Additional information on the habitats (i.e., foraging habitat, migratory routes, and internesting habitat) used by the turtles and details of fishing operations is required to develop plans that protect habitat and reduce bycatch (Casale, 2008; Wallace et al., 2013; Casale et al., 2018).

Studies conducted elsewhere have shown positive benefit for sea turtles in marine protected areas (Scott et al., 2012; Hart et al., 2013; Revuelta et al., 2015; Doherty et al., 2020). For green turtles, this results from the protection of seagrass and algal habitats over large areas along with the management of fishing and other anthropogenic activities to benefit the marine fauna, including marine turtles (PERSGA, 2007; Read et al., 2014). Because marine turtles demonstrate high fidelity to foraging areas (Schofield et al., 2010, 2013; Pilcher et al., 2020; Shimada et al., 2020), following turtles via satellite telemetry can be used to identify important foraging habitat and contribute to identifying locations for the creation of new

protected areas (Maxwell et al., 2011; Pilcher et al., 2014, 2021a; Esteban et al., 2018; Roberts et al., 2021). In the present study about two-thirds of the destinations of the turtles from Ras Baridi were within or close to (<30 km) protected or managed areas (Figure 1). The selection of these areas by the turtles is associated with the distribution and growth of seagrass (Duarte, 1991; Bjørndal, 1997; Serrano et al., 2018; Qurban et al., 2019; Stokes et al., 2019; Esteban et al., 2020). However, the current designated protected areas alone will not provide protection for all members of the foraging aggregations because marine turtles display complex movements within and among large and/or disjunct foraging areas throughout the year (Hawkes et al., 2006; Shimada et al., 2016; Dujon et al., 2018). The designation of additional smaller protected areas that contain a range of habitats would benefit foraging turtles of different age/size classes as well as other marine species (Hays et al., 2021), particularly along the narrow coastal foraging areas located to the North and South of Jeddah. Because the destinations of the 16 post-nesting green turtles indicate that these turtles are using more areas than are currently within the designated management areas of the Red Sea, a review of existing and proposed management areas with a view to assess their effectiveness in protecting at-risk species and to provide habitat for multiple marine species is warranted (Rouphael et al., 2015; Gajdzik et al., 2021).

## CONCLUSION

The satellite tracking of 16 post-nesting female green turtles (*Chelonia mydas*) to foraging areas located within the Red Sea basin enhances the knowledge-base of the regional ecology of green turtles because it provides both confirming and new information about marine turtles in the region. As would be expected, the majority of the turtles migrated along the shallow coastal corridor to reach wide-spread foraging areas; however, four traversed the deep trough of the Red Sea during their journeys. The dispersal of these turtles establishes connectivity for turtles nesting at Ras Baridi with multiple foraging habitats throughout the Red Sea, which is essential information for research and conservation management. Previously, a connection was shown for turtles in the southern part of the Red Sea to the nesting sites in Oman. However, the turtles nesting in the northern part of the Red Sea at Ras Baridi have now been shown to remain within the Red Sea basin. These turtles have a unique allele which confirms their separation from nesting turtles in Oman. In combination, this information will aid future mixed stock analysis and will contribute to better regional conservation management.

Some of the turtles used different migratory pathways to reach the same destination area and passed through the territorial waters of different countries that border the Red Sea. It follows that during their migration the turtles were exposed to different unquantified threatening processes depending on their route and the fishing operations occurring along the way. The identification of connecting corridors along the coast may be used to assist

in the revision and standardization of fishery management guidelines to reduce bycatch of green sea turtles, especially in trawl and gillnet fisheries, and to support the development of additional marine protected areas. The identification of connectivity between nesting sites and transboundary foraging areas reinforces the need for multi-national cooperation to ensure that research and conservation management efforts are effective in the Red Sea. Our study demonstrates that regional and local studies contribute important information concerning marine turtle migrations and provides context for cooperative conservation decision-making within the region.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## ETHICS STATEMENT

The animal study was reviewed and approved by Saudi Wildlife Authority Projects Committee.

## AUTHOR CONTRIBUTIONS

AA-M designed the study. AA-M, AS, BA, AHA, AAA, and RA conducted the field work. AA-M and JM wrote the manuscript. All authors contributed to the editing of the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2021.758592/full#supplementary-material>



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