

# Satellite tracking of hawksbill turtles *Eretmochelys imbricata* nesting in northern Bahia, Brazil: turtle movements and foraging destinations

Maria Ângela Marcovaldi\*, Gustave G. Lopez, Luciano S. Soares,  
Milagros López-Mendilaharsu

Fundação Pró-TAMAR, Rubens Guelli 134 sl. 307, CEP. 41815-135, Salvador, BA, Brazil

**ABSTRACT:** Data on hawksbill *Eretmochelys imbricata* migratory patterns are virtually unknown for nesting populations in the South Atlantic Ocean. The most significant nesting ground for hawksbills in the South Atlantic is located in Brazil, specifically in the northern state of Bahia. From February to March 2005, 15 adult female hawksbills were equipped with satellite transmitters on beaches of northern Bahia. During the internesting period, satellite-tracked hawksbills remained in the coastal waters of northern Bahia for 12 to 60 d before embarking on their postnesting migrations. Internesting areas occupied by the turtles varied between 43.1 and 447.9 km<sup>2</sup>. Turtles' postnesting migrations were performed mostly over the continental shelf: 5 headed south, and 8, north. Results from genetic analyses of tracked turtles showed that 6 of the individuals, characterized morphologically as hawksbills, were actually hawksbill-loggerhead hybrids. Foraging destinations of hawksbills were situated along the eastern coast of Brazil (9 to 17.5°S). Conversely, except for 1 hybrid that stayed along the eastern coast, hybrid turtles migrated to distant foraging areas located on the northern coast of Brazil (0 to 5°S). Foraging home range areas of satellite-tracked turtles ranged from 225.7 to 2192.3 km<sup>2</sup>, and there were no significant differences in size between areas used by hawksbills and those used by hybrids. The location of hawksbill foraging areas partially overlapped with established marine protected areas (MPAs) distributed along the main reef areas in Brazil. These results underscore the importance of strengthening MPA monitoring and enforcement to protect critical hawksbill habitats in Brazil.

**KEY WORDS:** Satellite tracking · *Eretmochelys imbricata* · Internesting · Postnesting · Migration · Hybrids · Brazil

— Resale or republication not permitted without written consent of the publisher —

## INTRODUCTION

Hawksbill turtles *Eretmochelys imbricata* are widely distributed throughout the tropics and are currently listed as Critically Endangered by the International Union for the Conservation of Nature (IUCN) Redbook (Mortimer & Donnelly 2008) and by the Brazilian Red List of Threatened Species (Marcovaldi et al. 2011). One of the principal reasons for the species' decline is the collection of its elaborate shell (i.e. tortoiseshell or bekko) for fabrication of decora-

tive items and jewellery (Mortimer & Donnelly 2008). Fishery-related mortality, the impact of unregulated tourism and the deleterious effects of debris in the marine environment may also have contributed to its reduction in numbers (Dayton et al. 1995).

The species is commonly associated with coral reefs and thought to exert a positive indirect effect on maintaining coral biodiversity due to its highly specialized diet of marine sponges (Meylan 1988, León & Bjørndal 2002). Hawksbills exhibit a complex life cycle in which they inhabit different ecosystems,

\*Email: neca@tamar.org.br

from pelagic waters to coastal waters, reef systems and terrestrial beaches (Mortimer & Donnelly 2008). Genetic studies have shown, for instance, that juvenile aggregations on foraging grounds are composed of mixed stock populations (Bowen et al. 1996, Blumenthal et al. 2009). During their life cycle, the turtles disperse and migrate—traveling long distances and habitually moving between the open sea and the territorial waters of many nations (Meylan et al. 2011). The migratory routes are usually associated with movements to different foraging habitats and/or from foraging grounds to breeding areas. Females, for example, migrate from foraging areas to nesting sites every 2 or 3 yr (Witzell 1983). Satellite-tracking studies of hawksbills from different rookeries have shown that some females migrate longer distances towards foraging grounds, while others remain close to their nesting beaches (Mortimer & Balazs 2000, Horrocks et al. 2001, Troëng et al. 2005, Cuevas et al. 2008, Van Dam et al. 2008, Parker et al. 2009). It has been suggested that the different migratory patterns observed in adult sea turtles could be the result of the extent of passive dispersion experienced by hatchlings during the extended (2 to 3 yr) pelagic stage (Bass et al. 2006, Hays et al. 2010).

Knowledge of population size and postnesting movements of hawksbill turtles has been obtained mostly from flipper-tag recoveries (Meylan 1999, Troëng et al. 2005, Van Dam et al. 2008, Horrocks et al. 2011). However, the advent of satellite telemetry has allowed researchers to study marine turtle migratory, distributional and behavioural patterns at sea (Troëng et al. 2005, Godley et al. 2008). Data on hawksbill migratory patterns are scarce and mostly restricted to a few regions around the world, e.g. Caribbean (Starbird et al. 1999, Horrocks et al. 2001, Troëng et al. 2005, Cuevas et al. 2008, Van Dam et al. 2008), Seychelles (Mortimer & Balazs 2000), Hawaii (Parker et al. 2009) and Australia (Miller et al. 1998), and virtually unknown for nesting populations in the South Atlantic Ocean (Wallace et al. 2010).

The Brazilian coastline is a vast area extending for >8000 km and known as an important habitat for sea turtle populations (Marcovaldi & Marcovaldi 1999). Of the 7 sea turtle species existing in the world, 5 can be found in Brazil: loggerhead *Caretta caretta*, green *Chelonia mydas*, leatherback *Dermochelys coriacea*, hawksbill *Eretmochelys imbricata* and olive ridley *Lepidochelys olivacea* (Marcovaldi & Marcovaldi 1999). The main sea turtle nesting sites and foraging grounds in the country have been protected since 1980 by TAMAR (Brazilian Sea Turtle Conservation Program), a federal government initiative (ICMBio—

Chico Mendes Institute of Biodiversity) co-managed by Fundação Pró-TAMAR, a non-governmental organization (Marcovaldi et al. 2005).

In Brazil, the most significant nesting grounds for hawksbills are located in the states of Bahia and Rio Grande do Norte (see Marcovaldi et al. 2007). Brazilian waters also host 2 known important feeding grounds for immature hawksbills: the Rocas atoll and the Fernando de Noronha archipelago (Marcovaldi et al. 1998, Sanches & Bellini 1999). However, there is no information regarding foraging habitats of adult individuals in Brazil. Genetic analyses of mitochondrial DNA from Bahia nesting grounds indicate that hawksbills nesting in Brazil are genetically distinct from other populations in the western Atlantic, thus representing a separate stock (Bass 1999, Bowen & Karl 2007). This distinctiveness and the fact that long-lived, late-maturing species such as the hawksbill require long-term conservation efforts, make the species a top conservation priority. Due to the scattered nature of hawksbill nesting and the species' long history of overexploitation, hawksbill protection is considered a challenge on an international level (Mortimer & Donnelly 2008, Gaos et al. 2010, Marcovaldi et al. 2011).

The aim of the present paper is to elucidate the interesting and postnesting movements and behaviour of female hawksbills nesting in Bahia, Brazil, in order to expand data on the species' regional spatial ecology and thus guide conservation actions.

## MATERIALS AND METHODS

From February to March 2005, 15 adult female hawksbills *Eretmochelys imbricata* were equipped with satellite transmitters (KiwiSat 101; Sirtrack) after they had nested on beaches along the northern coast of Bahia, Brazil.

After oviposition was completed, turtles were measured (curved carapace length, CCL, taken from the nuchal notch to the posterior-most marginal scute tip) tagged with inconel tags in both front flippers and sampled for genetic analysis. To attach the units, a portable wooden corral was placed around each turtle following nesting. The carapace of each turtle was prepared by scrubbing to remove epibionts, and cleaned with sandpaper and alcohol. Platform transmitter terminals (PTTs) were attached using a 2-part epoxy resin (Tubolit MEP-301) and covered with a layer of antifouling paint. For a summary of deployment information, biometrics and satellite transmitter performance for all individuals see Table 1.

Instrumented turtles were released at their capture sites <4 h later. We tracked the turtles through the Argos system (<http://www.argosinc.com>) with geo-locations being categorized into 7 location classes (LCs 3, 2, 1, 0, A, B and Z). Location classes 3, 2 and 1 are categorized to lie within 150, 150 to 350, or 350 to 1000 m, respectively, of the tag's true position, while LCs 0, A, B and Z have no location error estimate (Hays et al. 2001). Routes were reconstructed using filtered Argos positions LC 3, 2, 1, 0 and A, based on a maximum rate of travel of 5 km h<sup>-1</sup>.

Data were downloaded and analyzed in the Satellite Tracking and Analysis Tool (STAT; Coyne & Godley 2005), including data on bathymetry associated with the turtle's positions.

Geographic information systems software (ArcGis 9.1, ESRI) was used to map turtle movements and calculate high-use areas. Minimum convex polygons (MCP) were calculated to determine individual interesting and foraging home range areas. We used MCPs because they are simple to generate and understand and because they enabled comparisons between our results and previous studies. Nonetheless, being sensitive to sample size and biased by outliers, they typically overestimate home ranges (Burgman & Fox 2003). At foraging grounds, core areas (e.g. regions of more concentrated activity) were defined using 50 % kernel-estimated utilization distributions (UD). We used the 50 % polygon for our analyses, since it is the least influenced by outliers (Yasuda & Arai 2005). Individual kernel contours

were delineated using an *h* factor of 0.05 calculated following Silverman (1986).

We assumed turtles were interesting when we observed nesting or location data indicating that nesting occurred after release. To identify presumed emergences from Argos data we utilized the following criteria: turtle movements directed onshore for nesting followed by an immediate offshore departure, location quality improvement (e.g. LC 3 or 2) within a short time span and an elapsed time span which corresponded to the expected interesting intervals for hawksbills.

Postnesting migrations were deemed to have begun once movement away from the nesting beach was directional and protracted and were considered complete when movement no longer appeared to be directed for at least 3 consecutive days (Zbinden et al. 2008). Foraging areas were identified as those areas where turtles showed restricted movements (multi-directional and backtracked over previous tracks) following postnesting migrations which continued until the transmitters ceased or turtles engaged in new return migrations (Troëng et al. 2005).

## RESULTS

Five of the 15 transmitters attached to hawksbill *Eretmochelys imbricata* females emitted signals for <2 mo (range: 15 to 57 d), the other 10 individuals were tracked for 486 ± 279 d (range: 238 to 804 d; all data are mean ± SD). Total travelled distance during the tracking period varied from 65 to 6903 km (Table 1, Fig. 1).

Tracked hawksbills (n = 15) were sampled for genetic analysis. Results showed that 6 individuals, although characterized morphologically as hawksbills, were actually hawksbill-loggerhead hybrids (hereafter referred to as hybrids) (Lara-Ruiz et al. 2006). The mean CCL of the turtles tracked (Turtles a to o) ranged from 86.0 to 106.5 cm; interestingly, the CCL of the hybrid turtles was larger than that of the hawksbill turtles (*t* = 5.6, *p* < 0.01).

### Interesting period

Of the 15 female hawksbills satellite-tracked, 2 immediately departed coastal waters (Turtles f and j). The

Table 1. *Eretmochelys imbricata*. Summary information for hawksbill turtles (n = 15) equipped with platform transmitter terminals along the northern coast of the state of Bahia, Brazil. CCL: curved carapace length (cm)

Turtle ID	CCL (cm)	Release location	Date deployed (dd/mm/yy)	Date last location (dd/mm/yy)	Days tracked	Total distance covered (km)
a	99.0	Praia do Forte	05/02/05	02/02/06	362	1479
b	91.5	Jacuipe	05/02/05	27/02/05	22	65
c <sup>a</sup>	106.5	Busca Vida	06/02/05	20/10/05	256	3338
d <sup>a</sup>	100.0	Busca Vida	07/02/05	03/10/05	238	1749
e	92.5	Guarajuba	09/02/05	13/12/05	307	2028
f <sup>a</sup>	100	Santa Maria	09/02/05	28/02/05	19	760
g	91.5	Jacuipe	11/02/05	20/03/05	37	70
h	86.0	Guarajuba	11/02/05	06/03/07	753	2977
i	92.0	Busca Vida	11/02/05	17/01/07	705	1811
j <sup>a</sup>	99.0	Santa Maria	12/02/05	24/07/06	527	4936
k	93.0	Guarajuba	21/02/05	19/04/05	57	1353
l	94.5	Santa Maria	25/02/05	12/03/05	15	278
m <sup>a</sup>	105.0	Santa Maria	26/02/05	07/07/06	516	3893
n <sup>a</sup>	101.5	Santa Maria	27/02/05	12/05/07	804	6903
o	90.5	Guarajuba	28/03/05	19/04/05	387	1338

<sup>a</sup>Hybrids

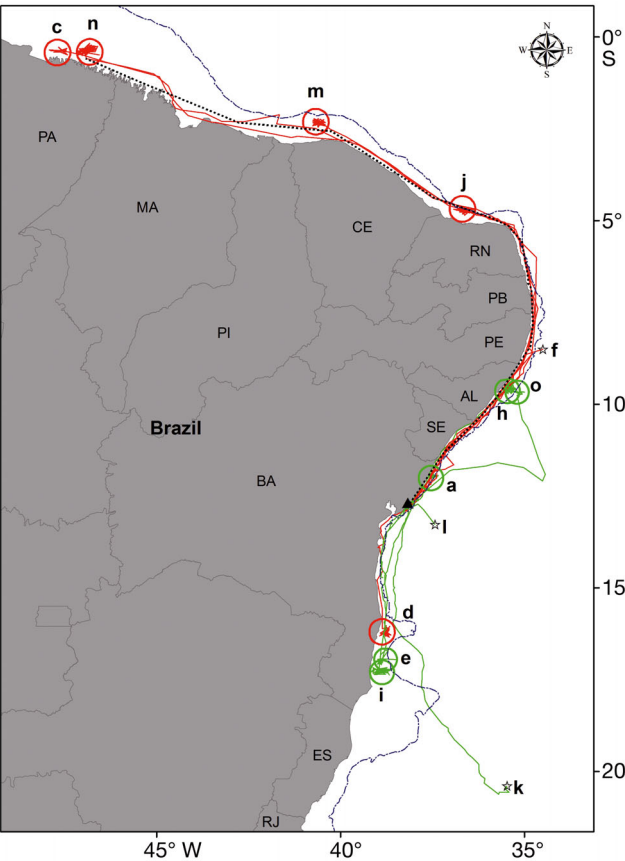


Fig. 1. *Eretmochelys imbricata*. Migratory paths and foraging areas of hawksbill turtles satellite-tracked from nesting grounds in northern Bahia, Brazil (n = 15). Lower case letters: individual turtles; circles: foraging areas (green: hawksbills; red: hawksbill-loggerhead hybrids); stars: turtles that stopped transmitting during migration; black dotted line: return migration path of Turtle n; dashed line: 200 m bathymetry contour; black triangle: satellite transmitter deployment site. Abbreviations for foraging areas, see Table 2 legend

others remained between 12 and 60 d in coastal waters; however, 2 of them (Turtles b and g) stopped sending signals during this period. Internesting areas were calculated for 10 turtles (a, b, c, d, e, g, i, k, m and n); poor signal reception provided a small number of location fixes for 2 turtles (h and o), which were excluded from the analysis (Table 2). Nesting events and number of internesting intervals identified for each turtle are summarized in Table 2.

During the internesting period turtles remained mostly over the continental shelf (<200 m), in a few cases (e.g. Turtles a, c and e) also making small excursions beyond it (e.g. 1000 m isobath), with movements of no further than 24 km from the coast (Fig. 2). MCP analyses revealed that individual at-

Table 2. *Eretmochelys imbricata*. Data collected at internesting and foraging areas and during migration of hawksbill turtles satellite-tracked from nesting beaches in northern Bahia, Brazil. Data for foraging grounds include no. of days residency, size of home range and core areas, seafloor depth and distance from shore. BA: Bahia; PA: Pará; AL: Alagoas; RN: Rio Grande do Norte; CE: Ceará; MCP: minimum convex polygon; KHR: kernel-estimated home range contour

Turtle ID	Inter-nesting (d)	No. of nesting events	MCP inter-nesting (km <sup>2</sup> )	Max. distance from shore (km)	Post-nesting migration (d)	Distance nesting-foraging (km)	Foraging grounds (location)	Residency (d)	MCP Foraging (km <sup>2</sup> )	Depth range (m)	Core area 50% KHR (km <sup>2</sup> )	Depth range (m)	Distance from shore (mean ± SD; km)
a	51	4	345.5	24	3	98	BA; 11.9° S, 37.5° W	308	225.7	2–50	91.8	8–20	6.4 ± 6.4
b	22	2	187.5	16	–	–	–	–	–	–	–	–	–
c <sup>a</sup>	60	4	190.1	13	49	2550	PA; 0.4° S, 47.9° W	116	493.8	9–21	113.6	15–20	23.5 ± 3.9
d <sup>a</sup>	44	4	43.1	5	10	420	BA; 16.1° S, 38.7° W	186	952.8	19–40	145.7	25–30	22.5 ± 7.8
e	20	2	447.9	20	12	514	BA; 16.9° S, 38.5° W	279	1117.3	10–61	190.8	25–35	23.5 ± 8.8
f <sup>a,b</sup>	–	–	–	–	19	–	–	–	–	–	–	–	–
g	37	3	83.3	10	–	–	–	–	–	–	–	–	–
h	19 <sup>c</sup>	–	–	–	11	450	AL; 9.6° S, 35.4° W	722	2192.3	6–2089	143.2	25–35	17.1 ± 9
i	48	4	196.1	16	17	530	BA; 17.4° S, 38.7° W	637	1098.3	6–47	220.5	20–30	29.0 ± 11
j <sup>a</sup>	–	–	–	–	27	1155	RN; 4.6° S, 36.6° W	500	1154.3	6–1473	158.67	20–75	35.5 ± 6.1
k	34	3	202.3	14	23	–	–	–	–	–	–	–	–
l	12	2	48.2	13	3	–	–	–	–	–	–	–	–
m <sup>a</sup>	29	3	97.3	6	25	1680	CE; 2.4° S, 40.4° W	443	1742.8	15–64	286.9	25–35	49 ± 8.5
n <sup>a,b</sup>	38	4	123.2	10	58	2400	PA; 0.4° S, 47.1° W	565	1731.5	11–23	257.7	15–20	40 ± 11.7
o	22 <sup>c</sup>	–	–	–	21	740	AL; 9.6° S, 35.4° W	161	1358.1	11–2370	421.1	25–60	27 ± 13.7

<sup>a</sup>Hybrids; <sup>b</sup>returned to the nesting beaches in Bahia after 2 yr; <sup>c</sup>poor signal reception during internesting period resulted in small number of location fixes to calculate internesting areas

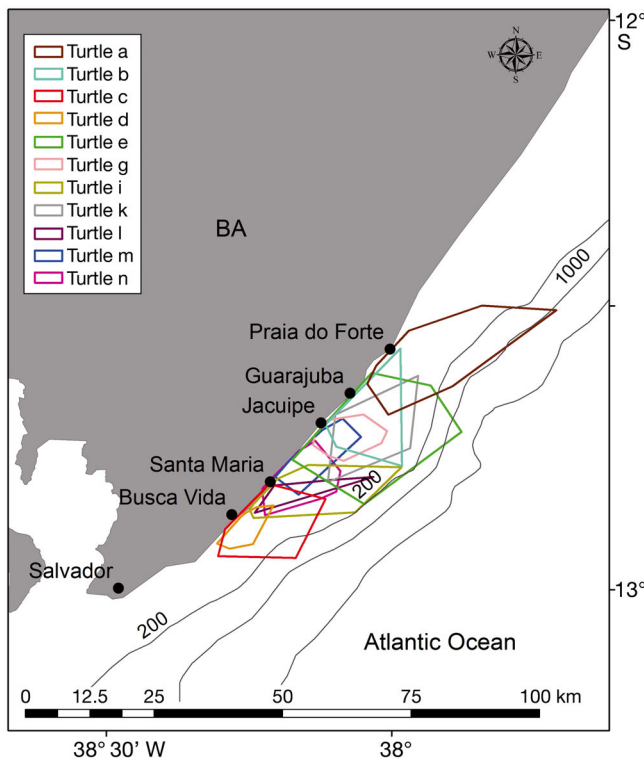


Fig. 2. *Eretmochelys imbricata*. Individual internesting areas (indicated by minimum convex polygons) of 10 hawksbill turtles satellite-tracked along the northern coast of Bahia, Brazil. The figure shows the deployment sites at 5 different nesting beaches

sea areas occupied by the turtles varied between 43.1 and 447.9 km<sup>2</sup> (Table 2). No significant correlation was found between the size of the internesting area and (1) the number of internesting intervals included in the analysis for each turtle ( $r = 0.15$ ,  $p = 0.70$ ), (2) their CCL ( $r = -0.10$ ,  $p = 0.77$ ) or (3) the 'species' (i.e. hybrid or hawksbill) ( $r = -0.41$ ,  $p = 0.21$ ).

Two females (Turtles n and f) returned to the breeding grounds in Bahia after 2 yr for a subsequent nesting season. One of the females (Turtle n) was tracked during migration back to the nesting beach; however, transmission ceased a couple of days after arrival. The turtle followed the same migratory route displayed during her migration towards the foraging ground (Fig. 1). Turtle f, which stopped sending signals within the first month after deployment, was observed nesting on the beach of Busca Vida (<10 km away from the beach where she was first tagged) 2 yr later during nightly patrols. The transmitter was still attached to the carapace of the turtle and was removed successfully. The carapace of the turtles was in very good condition after being equipped with a PTT tag for almost 2 yr.

## Postnesting migrations

During postnesting migrations 5 females migrated southward, and 8 northward. Three of the turtles (f, k and l) stopped sending signals before reaching their final destination, including 1 female (Turtle k) that moved away from the coast toward oceanic waters, along the Vitória-Trindade seamount chain; these individuals (Turtles f, k and l) travelled  $623 \pm 382$  km (range: 243 to 1006 km) (Fig. 1).

Five hybrids migrated northward, one stopped its transmissions during migration off the state of Pernambuco (Turtle k) and the other 4 reached foraging grounds located along the northern coast of Brazil, specifically off the states of Rio Grande do Norte (Turtle j), Ceará (Turtle m) and Pará (Turtles c and n). Only 1 hybrid migrated south, reaching neritic habitats off the southern coast of Bahia (Turtle d) (Table 2, Fig. 1).

Amongst the 9 hawksbills, 2 stopped transmitting before leaving the nesting areas (Turtles b and c, see results in 'Internesting period'), 4 moved southward and 3 moved northward; however, they all remained along the eastern coast of Brazil (see Fig. 1). Individuals reached foraging grounds located off the southern coast of Bahia (Turtles e and i), northern coast of Bahia (Turtle a) and Alagoas (Turtle h, and Turtle o after displaying an offshore migratory movement) (Table 2, Fig. 1).

Postnesting migrations were completed after reaching foraging grounds and lasted between 3 and 58 d. The direct distance between the nesting beach and the foraging areas ranged from 98 to 2550 km (mean  $\pm$  SD,  $1050 \pm 871$  km) (Table 2). Hawksbills migrated shorter distances than hybrids ( $458 \pm 222$  and  $1641 \pm 885$  km respectively;  $t = 2.9$ ,  $p = 0.02$ ) before reaching foraging grounds.

## Foraging areas

Upon arrival at foraging areas turtles remained resident for a period ranging between 116 and 722 d, and the mean distance from shore ranged from  $6.4 \pm 6.4$  to  $49 \pm 8.5$  km (Table 2). Foraging areas of hawksbills (i.e. 'true' hawksbills) were located along the eastern coast of Brazil within coastal reef ecosystems (9 to 17.5°S). In contrast, all hybrid turtles, except Turtle d, migrated to foraging areas along the northern coast of Brazil (0 to 5°S) (Figs. 3 & 4). Only 2 of the hybrids (Turtles d and j) remained associated (at least partially) with reef habitats (Fig. 4C,F).



Home range areas of both hawksbill and hybrid turtles at foraging grounds ranged from 225.7 to 2192.3 km<sup>2</sup>, with no differences in size among the 2 groups ( $t = -0.04$ ,  $p = 0.9$ ). Core activity areas (50% UD) varied from 91.8 to 286.9 km<sup>2</sup> and were characterized by relatively shallow waters, usually between 20 and 35 m depth (Table 2, Fig. 4). There were no significant correlations between the core area size and (1) the number of days the turtles spent in foraging areas ( $r = -0.05$ ,  $p = 0.89$ ), (2) their CCL ( $r = -0.20$ ,  $p = 0.57$ ), and (3) the 'species' (i.e. hybrid or hawksbill) ( $r = -0.11$ ,  $p = 0.76$ ). At foraging destinations a large proportion (55%) of hawksbill location points fell within marine protected areas which encompass important coral reef ecosystems in Brazil. Even though some hybrids foraged at or near coral reef habitats, none of these areas overlapped with established coral reef protected areas.

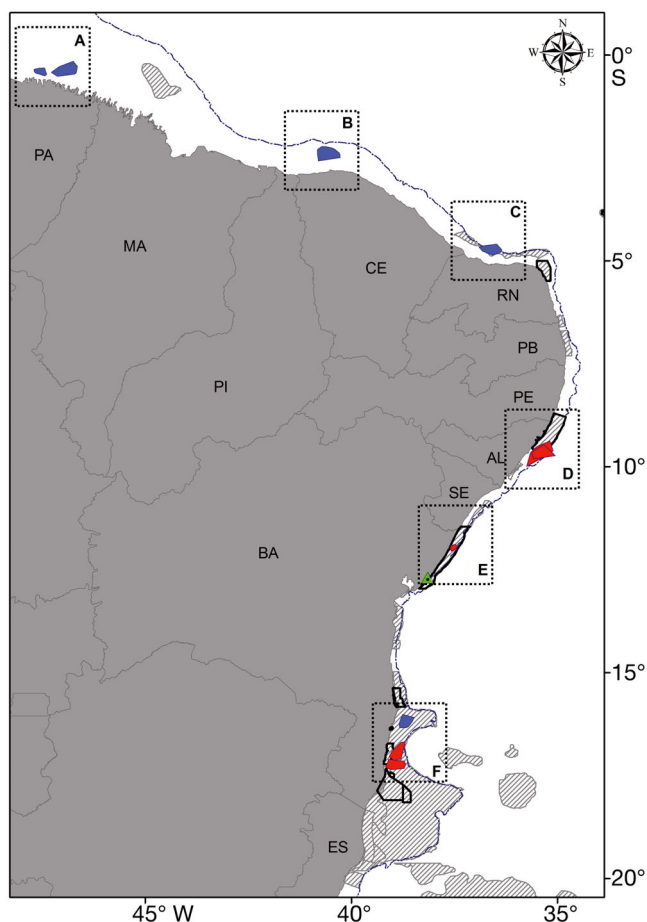


Fig. 3. *Eretmochelys imbricata*. Foraging areas of postnesting *E. imbricata* (red: hawksbills; blue: hybrids) in relation to coral reef ecosystems (hatched areas) and established marine protected areas (black outlining). Green triangle: transmitter deployment site. Box enclosures (A to F) show foraging destinations; these areas are shown in detail in Fig. 4

## DISCUSSION

The data collected from satellite-tracked *Eretmochelys imbricata* females (i.e. hawksbills and hybrids) indicate that they remained in the vicinity of the nesting beaches during the internesting period, although some moved longer distances from shore than internesting females from St. Croix, US Virgin Islands, and Yucatan nesting colonies (no further than 2.5 and 13 km offshore, respectively; Starbird et al. 1999, Cuevas et al. 2008).

Interesting home ranges of hawksbills from Bahia were similar to those reported by Cuevas et al. (2008) for hawksbills nesting on the Yucatan Peninsula (range: 87.6 to 282.1 km<sup>2</sup>). However, interesting home range sizes were much larger compared with hawksbills from St. Croix, US Virgin Islands (Starbird et al. 1999). Interesting habitats reported by Starbird et al. (2009) were identified by radio telemetry, which can be more accurate than satellite telemetry, resulting in more precise home range estimations and thus not entirely comparable with our study.

Though foraging behaviour (i.e. analysis of dive depth and duration patterns) could not be determined in the present study, several studies have suggested that extended movements during the internesting period may be associated with a search for food (Hochscheid et al. 1999, Georges et al. 2007). The northern coast of Bahia encompasses discontinuous bank reefs, including continental shelf-edge reef formations (Olavo et al. 2011); thus, it is possible that opportunist foraging may occur during the breeding period.

Postnesting females that migrated north ( $n = 6$ ), towards foraging grounds in north and northeast Brazil, shared a migration corridor located over the continental shelf and break. In a previous study, 10 postnesting loggerheads satellite-tracked from northern Bahia used the same migratory corridor (Marcovaldi et al. 2010), highlighting the importance of this area. Likewise, hawksbill turtles tracked in other studies (Balazs et al. 2000, Mortimer & Balazs 2000, Troëng et al. 2005, Cuevas et al. 2008) displayed migratory trajectories close to the shore.

Telemetry studies in the Atlantic have revealed that hawksbills can travel hundreds to thousands of kilometres between nesting and foraging areas (Horrocks et al. 2001, Troëng et al. 2005, Cuevas et al. 2008, Van Dam et al. 2008). Satellite-tracked hawksbills from other ocean basins, such as Seychelles in the Indian Ocean and Hawaii in the Pacific, showed postnesting movements limited to a few hundred kilometres (35 to 175 km and 90 to 345 km, respec-

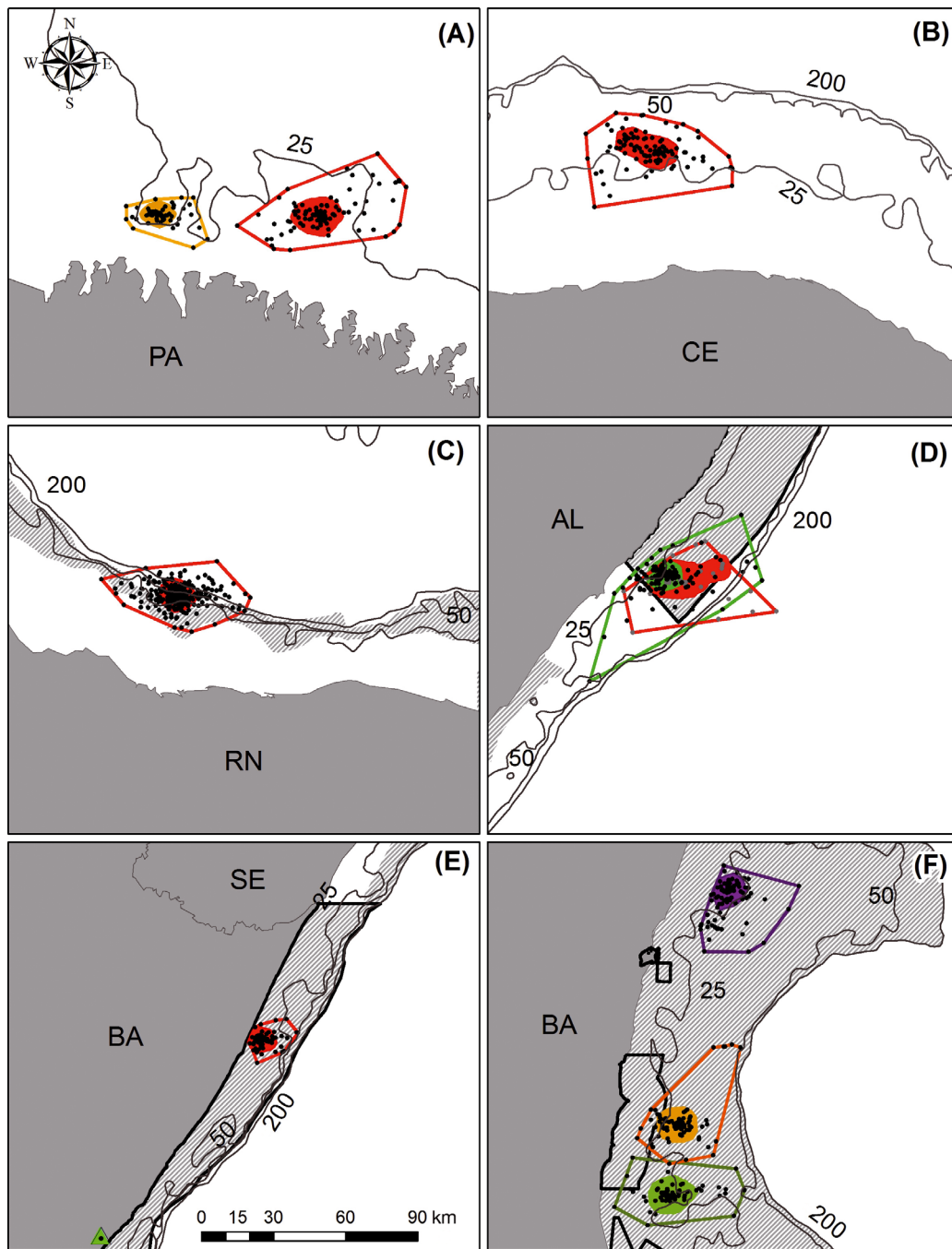


Fig. 4. *Eretmochelys imbricata*. Hawksbill turtle foraging areas along the north/north-eastern coast of Brazil. Overall foraging areas were delineated by minimum convex polygons, and core-use areas were identified using 50 % kernel density contours. (A) Turtles c (yellow) and n (red); (B) Turtle m; (C) Turtle j; (D) Turtles o (red) and h (green); (E) Turtle a; and (F) Turtles d (purple), e (orange) and j (green). Coral reef ecosystems are indicated by hatched areas and marine protected areas by thick black lines. Green triangle in (E) indicates the deployment site

tively; Mortimer & Balazs 2000, Parker et al. 2009). This contrasting pattern between ocean basins may be related to the fact that in the latter studies the satellite-tracked females nested on isolated islands

(Hawaii and Seychelles) and which were situated thousands of kilometres from major landmasses and also characterized by coral reef ecosystems (Mortimer & Balazs 2000, Houghton et al. 2003, Parker et

al. 2009). Probably food availability is not a limiting factor for turtles foraging along those areas, allowing postnesting turtles to remain resident in close proximity of the breeding grounds without exceeding carrying capacity.

Flipper tag recoveries of adult females have shown that they are capable of travelling long distances (e.g. 1400 to 2400 km) between nesting and breeding grounds and vice versa (Bell et al. 2000, Hillis-Starr et al. 2000); however, relatively few studies have documented complete long-distance hawksbill migrations (Van Dam et al. 2008).

Hawksbill foraging destinations were located up to 530 km from breeding grounds, while foraging areas of hybrids (except for Turtle d) were located between 1150 and 2550 km away, along the northern coast of Brazil, in areas previously reported as loggerhead foraging grounds (Marcovaldi et al. 2010). It has been suggested that the selection of a permanent foraging site may be influenced by the broad geographic area that individuals previously encountered in the pelagic drift phase, and that during this initial early life phase individuals may imprint on potential predictable foraging sites (Hays et al. 2010).

The fact that loggerheads and hawksbills have specific foraging grounds and that their hybrids have migration patterns similar to one or another may indicate that migration behaviour may be influenced by genetic traits in sea turtles. Although hybrid turtles were characterized morphologically as hawksbills, we do not know their feeding behaviour, and further studies are needed to verify if they can actually exploit uncommon environments for hawksbill turtles as identified in this work. Studies of hybridization in cyprinid fishes have shown that the intermediate phenotype of hybrids might play a role in their feeding abilities, resulting in the utilization of a broader trophic spectrum than the parental species (Toscano et al. 2010). Consequently, we have started a study to verify the diet of turtle hybrids and compare it to the parental species to better understand how it could influence the reproductive output of this population.

MCPs and 50 % kernel estimated foraging areas of both hawksbills and hybrids were much larger than those reported along the Caribbean for this species (Cuevas et al. 2008). For example, estimated core activity areas in the present study ranged from 91.8 to 421.1 km<sup>2</sup>; in contrast, postnesting hawksbills in the Caribbean (Cuevas et al. 2008) showed much smaller core foraging ranges, from 10.4 to 26.7 km<sup>2</sup>. The apparent differences between this and other sites may relate to the patchy distribution of food and shelter resources. Smaller foraging areas in the

Caribbean might indicate a higher quality of food to satisfy nutritional needs (Cuevas et al. 2008), but this could also be a density-dependent phenomenon, i.e. a higher density of individuals in a restricted area may result in a smaller individual foraging area. It is possible that the intra-species competition is higher in the Caribbean than along the Brazilian coasts.

The Brazilian coastline stretches over >8000 km; however, only a small number of MPAs have been established. Conservation units that encompass reef communities are already distributed in practically all the main reef areas in Brazil and are divided into 2 main categories: (1) full protection, where no use of natural resources is allowed; and (2) sustainable use, which allows the sustainable use of part of their resources. Along the northern coast of Bahia a sustainable use MPA extends to 15 km offshore from the coast; thus, most of the interesting habitats utilized by the nesting turtles (i.e. hawksbills and hybrids) fell within the protected area. Therefore, the spatial extent of the established MPA offers a good opportunity to enhance the protection of these critical breeding grounds. In hawksbill (i.e. not hybrid) foraging areas a large proportion of locations (55 %) fell within MPAs declared by the state and federal government to be for sustainable use only. However, due to resource limitations, many of these sites lack monitoring and enforcement, which prevents an effective protection of these critical habitats. It is recognized that satellite telemetry can be a useful tool in determining the effectiveness of current MPA boundaries and where additional protected areas should be considered (Witt et al. 2008, Shillinger et al. 2010). Our results underscore the importance of strengthening MPA monitoring and enforcement as well as paying increased attention to issues concerning fisheries management, in order to guarantee the protection of key foraging areas of hawksbill turtles in Brazil.

*Acknowledgements.* We thank CENPES/PETROBRAS (Centro de Pesquisas da PETROBRAS) for supporting the 'Mamíferos e Quelônios Marinhos' project, which included the present study. We thank Tamar's technical team for their hard work during field activities. Special thanks go to Guilherme Maurutto for his valuable help with maps. Projeto TAMAR is a conservation program of the Brazilian Ministry of the Environment, affiliated with ICMBio and co-managed by Fundação Pró-TAMAR, and officially sponsored by Petrobras.

#### LITERATURE CITED

Balazs GH, Katahira LK, Denise ME (2000) Satellite tracking of hawksbill turtles nesting in the Hawaiian Islands. In:



- Abreu-Grobois FA, Briseno-Duenas R, Marquez R, Sarti L (eds) Proc 18th Annu Symp Sea Turtle Biol Conserv Pt. 3: 16th Annu Symp Sea Turtle Biol Conserv Addendum, US Dept. of Commerce, Miami, FL. NOAA Tech Memo NMFS-SEFSC 436:279–281
- Bass AL (1999) Genetic analysis to elucidate the natural history and behavior of hawksbill turtles (*Eretmochelys imbricata*) in the wider Caribbean: a review and re-analysis. *Chelonian Conserv Biol* 3:195–199
- Bass AL, Epperly SP, Braun-McNeill J (2006) Green turtle (*Chelonia mydas*) foraging and nesting aggregations in the Caribbean and Atlantic: impact of currents and behavior on dispersal. *J Hered* 97:346–354
- Bell I, Miller JD, Dobbs KA, Limpus CJ (2000) Hawksbill turtle movements in the Coral Sea. In: Abreu-Grobois FA, Briseño R, Márquez R, Sarti L (eds) Proc 18th Annu Symp Sea Turtle Biol Conserv. NOAA Tech Memo NMFS-SEFSC 436:95
- Blumenthal JM, Abreu-Grobois FA, Austin TI, Broderick AC and others (2009) Turtle groups or turtle soup: dispersal patterns of hawksbill turtles in the Caribbean. *Mol Ecol* 18:4841–4853
- Bowen BW, Karl SA (2007) Population genetics and phylogeography of sea turtles. *Mol Ecol* 16:4886–4907
- Bowen B, Bass AL, Garcia-Rodriguez A, Diez CE and others (1996) Origin of hawksbill turtles in a Caribbean feeding area as indicated by genetic markers. *Ecol Appl* 6: 566–572
- Burgman MA, Fox JC (2003) Bias in species range estimates from minimum convex polygons: implications for conservation and options for improved planning. *Anim Conserv* 6:19–28
- Coyne MS, Godley BJ (2005) Satellite Tracking and Analysis Tool (STAT): an integrated system for archiving, analyzing and mapping animal tracking data. *Mar Ecol Prog Ser* 301:1–7
- Cuevas E, Abreu-Grobois FA, Guzmán-Hernández V, Liceaga-Correa MA, Van Dam RP (2008) Post-nesting migratory movements of hawksbill turtles *Eretmochelys imbricata* in waters adjacent to the Yucatan Peninsula, Mexico. *Endang Species Res* 10:123–133
- Dayton PK, Simon F, Thrush M, Agardy T, Hofman RJ (1995) Environmental effects of marine fishing. *Aquatic Conserv* 5:205–232
- Gaas A, Abreu-Grobois F, Alfaro-Shigueto J, Amorcho D and others (2010) Signs of hope in the eastern Pacific: international collaboration reveals encouraging status for the severely depleted population of hawksbill turtles *Eretmochelys imbricata*. *Oryx* 44:595–601
- Georges JY, Fossette S, Billes A, Ferraroli S and others (2007) Meta-analysis of movements in Atlantic leatherback turtles during the nesting season: conservation implications. *Mar Ecol Prog Ser* 338:225–232
- Godley BJ, Blumenthal JM, Broderick AC, Coyne MS, Godfrey MH, Hawkes LA, Witt MJ (2008) Satellite tracking of sea turtles: Where have we been and where do we go next? *Endang Species Res* 4:3–22
- Hays GC, Åkesson S, Godley BJ, Luschi P, Santidrian P (2001) The implications of location accuracy for the interpretation of satellite tracking data. *Anim Behav* 61: 1035–1040
- Hays GC, Fossette S, Katselidis KA, Mariani P, Schofield G (2010) Ontogenetic development of migration: Lagrangian drift trajectories suggest a new paradigm for sea turtles. *J R Soc Interface* 7:1319–1327
- Hillis-Starr Z, Coyne M, Monaco M (2000) Buck Island and back-hawksbill turtles make their move. In: Kalb HJ, Wibbels T (eds) Proc 19th Annu Symp Sea Turtle Biol Conserv. NOAA Tech Memo NMFS-SEFSC 443:159
- Hochscheid S, Godley BJ, Broderick AC, Wilson RP (1999) Reptilian diving: highly variable dive patterns in the green turtle *Chelonia mydas*. *Mar Ecol Prog Ser* 185: 101–112
- Horrocks JA, Krueger BH, Fastigi M, Pemberton EL, Eckert KL (2011) International movements of adult female hawksbill turtles (*Eretmochelys imbricata*): first results from the Caribbean's Marine Turtle Tagging Centre. *Chelonian Conserv Biol* 10:18–25
- Horrocks JA, Vermeer LA, Krueger B, Coyne M, Schroeder BA, Balazs GH (2001) Migration routes and destination characteristics of post-nesting hawksbill turtles satellite-tracked from Barbados, West Indies. *Chelonian Conserv Biol* 4:107–114
- Houghton JDR, Callow MJ, Hays GC (2003) Habitat utilization by juvenile hawksbill turtles (*Eretmochelys imbricata* Linnaeus, 1766) around a shallow water coral reef. *J Nat Hist* 37:1269–1280
- Lara-Ruiz P, Lopez GG, Santos FR, Soares LS (2006) Extensive hybridization in hawksbill turtles (*Eretmochelys imbricata*) nesting in Brazil revealed by mtDNA analyses. *Conserv Genet* 7:773–781
- León YM, Bjørndal KA (2002) Selective feeding in the hawksbill turtle, an important predator in coral reef ecosystems. *Mar Ecol Prog Ser* 245:249–258
- Marcovaldi MA, Marcovaldi GG (1999) Marine turtles of Brazil: the history and structure of Projeto TAMAR IBAMA. *Biol Conserv* 91:35–41
- Marcovaldi MA, Silva ACCD, Gallo BMG, Baptistotte C and others (1998) Sea turtle feeding grounds of Brazil. In: Abreu-Grobois FA, Briseño R, Márquez R, Sarti L (eds) Proc 18th Annu Symp Sea Turtle Biol Conserv. NOAA Tech Memo NMFS-SEFSC 436:150–152
- Marcovaldi MA, Patiri V, Thomé JC (2005) Projeto tamaribama: twenty-five years protecting Brazilian sea turtles through a community-based conservation programme. *Mast* 3/4:39:62
- Marcovaldi MA, Lopez GG, Soares LS, Santos AJB, Bellini C, Barata PCR (2007) Fifteen years of hawksbill sea turtle (*Eretmochelys imbricata*) nesting in northern Brazil. *Chelonian Conserv Biol* 6:223–228
- Marcovaldi MA, Lopez GG, Soares LS, Lima EHSM, Thomé JCA, Almeida AP (2010) Satellite-tracking of female loggerhead turtles highlights fidelity behavior in northeastern Brazil. *Endang Species Res* 12:263–272
- Marcovaldi MA, Lopez GG, Soares LS, Santos AJB, Bellini C, Santos AS, Lopez M (2011) Avaliação do estado de conservação da tartaruga marinha *Eretmochelys imbricata* (Linnaeus, 1766) no Brasil. *Biodiversidade Brasileira* 1:20–27
- Meylan A (1988) Spongivory in hawksbill turtles: a diet of glass. *Science* 239:393–395
- Meylan AB (1999) International movements of immature and adult hawksbill turtles (*Eretmochelys imbricata*) in the Caribbean region. *Chelonian Conserv Biol* 3:189–194
- Meylan PA, Meylan AB, Gray JA (2011) The ecology and migrations of sea turtles. 8. Tests of the developmental habitat hypothesis. *Bull Am Mus Nat Hist* 357:1–70
- Miller JD, Dobbs KA, Limpus CJ, Mattocks N, Landry AM (1998) Long-distance migrations by the hawksbill turtle,

- Eretmochelys imbricata*, from north-eastern Australia. Aust Wildl Res 25:89–95
- Mortimer JA, Balazs GH (2000) Post-nesting migrations of hawksbill turtles in the granitic Seychelles and implications for conservation. In: Kalb H, Wibbels T (eds) Proc 19th Ann Symp Sea Turtle Biol Conserv. NOAA Tech Memo NMFS-SEFSC 443:22–25
- Mortimer JA, Donnelly M (2008) *Eretmochelys imbricata*. In: IUCN Red List of Threatened Species V. 2010.1. Available at [www.iucnredlist.org](http://www.iucnredlist.org) (accessed 20 March 2011)
- Olavo G, Costa PAS, Martins AS, Ferreira BP (2011) Shelf-edge reefs as priority areas for conservation of reef fish diversity in the tropical Atlantic. Aquat Conserv 21: 199–209
- Parker DM, Balazs GH, King CS, Katahira L, Gilmartin W (2009) Short range movements of post nesting hawksbill turtles (*Eretmochelys imbricata*) from nesting to foraging areas within the Hawaiian Islands. Pac Sci 63:371–382
- Sanches TM, Bellini C (1999) Juveniles *Eretmochelys imbricata* and *Chelonia mydas* in the Archipelago of Fernando de Noronha, Brazil. Chelonian Conserv Biol 3:308–311
- Shillinger GL, Swithenbank AM, Bograd SJ, Bailey H and others (2010) Identification of high-use internesting habitats for eastern Pacific leatherback turtles: role of the environment and implications for conservation. Endang Species Res 10:215–232
- Silverman BW (1986) Density estimation for statistics and data analysis. Chapman & Hall, London
- Starbird CH, Hillis-Starr Z, Harvey JT, Eckert SA (1999) Internesting movements and behavior of hawksbill turtles (*Eretmochelys imbricata*) around Buck Island Reef National Monument, St. Croix, U.S. Virgin Islands. Chelonian Conserv Biol 3:237–243
- Toscano BJ, Pulcini D, Hayden B, Russo T, Kelly-Quinn M, Mariani S (2010) An ecomorphological framework for the coexistence of two cyprinid fish and their hybrids in a novel environment. Biol J Linn Soc 99:768–783
- Troëng S, Dutton PH, Evans D (2005) Migration of hawksbill turtles *Eretmochelys imbricata* from Tortuguero, Costa Rica. Ecography 28:394–402
- Van Dam RP, Diez CE, Balazs GH, Colón Colón LA, McMillan WO, Schroeder B (2008) Sex-specific migration patterns of hawksbill turtles breeding at Mona Island, Puerto Rico. Endang Species Res 4:85–94
- Wallace BP, DiMatteo AD, Hurley BJ, Finkbeiner EM and others (2010) Regional management units for marine turtles: a novel framework for prioritizing conservation and research across multiple scales. PLoS ONE 5:e15465
- Witt MJ, Broderick AC, Coyne M, Formia A and others (2008) Satellite tracking highlights difficulties in the design of effective protected areas for leatherback turtles during the internesting period. Oryx 42:296–300
- Witzell WN (1983) Synopsis of biological data on the hawksbill turtle, *Eretmochelys imbricata* (Linnaeus, 1766). FAO Fisheries Synopsis, No. 137, FAO, Rome
- Yasuda T, Arai N (2005) Fine-scale tracking of marine turtles using GPS-argos PTTs. Zoolog Sci 22:547–553
- Zbinden JA, Aebischer A, Margaritoulis D, Arlettaz R (2008) Important areas at sea for adult loggerhead sea turtles in the Mediterranean Sea: satellite tracking corroborates findings from potentially biased sources. Mar Biol 153: 899–906

Editorial responsibility: Brendan Godley,  
University of Exeter, Cornwall Campus, UK

Submitted: August 26, 2011; Accepted: January 12, 2012  
Proofs received from author(s): April 19, 2012