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Identification of key marine areas for conservation based on satellite tracking of post-nesting migrating green turtles (*Chelonia mydas*)

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ABSTRACT

The green turtle (*Chelonia mydas*) is classified as an endangered species on the IUCN Red List since 1986. This species is especially threatened in South America due to bycatch by fisheries along the northeastern coasts. It is particularly crucial to identify specific marine areas for conservation measures to safeguard green turtle rookeries in Suriname and French Guiana. Our study provides valuable information to attain this goal, describing the satellite tracking of post-nesting migration routes used by 16 green turtles fitted with Argos/GPS Fastloc satellite tags at the end of the nesting season. The data we obtained show a single migratory corridor: all the turtles followed a similar eastward route along the Guianan and the Brazilian coast. The GPS signal was lost for two individuals a few weeks after tracking commenced, suggesting that they were caught by fishermen. Thirteen turtles reached the coast of the state of Ceará (Brazil), where they spent at least one month. One turtle continued 700 km further to the coastal regions of Natal and Recife (Brazil), which are known feeding areas of the green turtle populations nesting on Ascension Island. The migratory corridor is essentially narrow, with a width of 22 km for most of the distance covered. It constitutes a major dynamic link between the nesting and feeding areas and crosses three Regional Management Units of the Atlantic basin. Since green turtles face a high risk of being caught in fishing nets, measures of protection should be implemented along this corridor.

1. Introduction

Sea turtles are among the most impressive navigators of the animal kingdom. They follow migratory pathways which sometimes go across entire ocean basins (Lohmann et al., 2008). Juveniles of some species, such as loggerheads (*Caretta caretta*) and green turtles (*Chelonia mydas*), settle in neritic feeding grounds with possible seasonal migration between summer and winter habitats (Musick and Limpus, 1997; Lohmann et al., 2008). The adults of most species may migrate considerable distances from their feeding grounds to specific breeding and nesting areas (Craig et al., 2004; Ferraroli et al., 2004; Hays et al., 2002). With the exception of the breeding season, when the females lay their eggs on nesting beaches, it is however difficult to observe sea turtles in their natural environment. The tracking of individuals through the Argos Satellite system may however provide a very fine-scale analysis of the pelagic movements of this species which regularly comes up at the sea surface to breathe (Kaplan et al., 2010), allowing identification of its feeding and breeding areas and of its migration path (Schofield et al., 2010; Maxwell et al., 2011).

While the green turtle is listed as globally endangered, the state of some populations may be a cause for optimism (Seminoff and Shanker, 2008). However, similar to other marine turtles, the incidental catch of green turtles by marine fisheries leads to mortality, and the degradation of the marine and nesting habitat currently poses a great threat to this species (Seminoff et al., 2002; Wallace et al., 2013). Despite its conservation status and legal protection, poaching is also considered as a current threat (García et al., 2003; Koch et al., 2006). Overall, bycatch, habitat

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degradation, human consumption of turtle meat and eggs and the sale of their shells have led to a 48–66% decrease in green turtle populations throughout the world (Seminoff et al., 2002).

However, the current knowledge on the green turtle movement patterns is still very poor. Understanding how this species moves at sea is crucial if we hope to develop and implement more effective bycatch mitigation measures (Hays, 2008; Wallace et al., 2013).

Wallace et al. (2010) defined Regional Management Units (RMU) for all marine turtle species using multi-scale biogeography data that reflected population connectivity. The north-eastern coast of South America has been focused here because it is a major nesting site for green turtles (Seminoff et al., 2002; Wallace et al., 2010), which are relatively abundant on the beaches of Suriname and French Guiana during the nesting period (Chevalier et al., 1998). Wallace et al. (2013) assessed incidental fishing of marine turtles in RMUs and it appears that bycatch is a persistent and serious issue off the north-eastern coast of South America. For all species combined, a very high Bycatch Per Unit Effort (BPUE) was identified at the mouth of the Amazon – among the five highest percentages of global records for longline and net efforts (Wallace et al., 2013).

In the present study, we analyzed the migration of 16 turtles that were tracked by satellite during their post-nesting migration along the coasts of Suriname, French Guiana and Brazil. We determined their migration route, the distance traveled by each green turtle and their individual characteristics, and identified their migratory stopovers. Our study highlights the importance of identifying and mapping this migration corridor, which links nesting and feeding sites and crosses three RMUs (Wallace et al., 2010). Our data should provide a scientific base for decision-making processes concerning the management and conservation of protected areas for green turtles and the regional mitigation of at-sea threats.

2. Materials and methods

2.1. Tag deployment

The beaches of the east coast of Suriname and western coast of French Guiana are one of the major nesting sites for green turtles in the Atlantic basin (Schulz, 1975). In Suriname, approximately 8000 green turtle nests were counted on the Galibi beaches in 2012 (Pinas, 2013). In French Guiana, the nesting activity of the green turtle has been monitored for around 15 years, and a capture-marking-recapture program started in 2010. In 2012, around 4000 green turtle nests and almost 800 individuals were counted on the beaches of French Guiana, mainly on the Awala-Yalimapo beach (Berzins, 2014). Those two sites are now separately protected within the national nature reserves of Amana and Galibi, respectively. Yet, since some turtles use both Awala-Yalimapo (French Guiana) and Galibi (Suriname) beaches to lay during a single nesting season, those two sites might be considered as a single nesting site over the two countries.

From February 29th to June 2012, sixteen Argos/GPS Fastloc 10-F400 satellite tags (Wildlife computer. Redmond. Washington. USA. http://www.argos-system.org) were deployed on 16 adult female green turtles during the nesting season on both sides of the Maroni River: 8 turtles in Suriname (Galibi Nature Reserve beaches) and 8 turtles in French Guiana (Awala-Yalimapo, Amana Nature Reserve beaches) (53°57′W, 5°45′N). The following methods are summarized in the Fig. 1. The PTT were fixed during nesting at night, using a red light to minimize the disturbance of the turtles. First, the shell of the turtle was cleaned with scrapers, water and acetone into cleaning rags in order to remove epibiotic growth in the attachment area and obtain a clean dry working area. Secondly, the attachment area has been lightly sanded with grit sandpaper then wiped again with acetone and dried. This operation has been repeated until cloth comes up clean (Blumenthal et al., 2006; Broderick et al., 2007; Godley et al., 2002; Hawkes et al., 2007a, 2007b). The tag was then fixed with Epoxy glue as close as possible to the head, in order to secure the satellite connection at sea when the turtle breathes at the surface. As the drying time of the glue (about 2 h) was longer than the duration of nesting (about 30 min), a removable wooden enclosure was installed around the turtle to restrict its movements and delay its return to sea. The raw telemetry data were downloaded daily using the WC-DAP 3.0 software package (Wildlife Computers).

2.2. Data gathered

Data were downloaded daily via the Argos Message Retriever (WC-DAP, Wildlife Computers-Data Analysis Programs, Inc. 2010). In order to provide higher location accuracy and to increase the number of available positions, the tags were programmed to record simultaneously Argos and GPS locations (Costa et al., 2010). GPS sampling interval recorded the position of the turtle every 4 h. To each Argos location was assigned a Location Class (LC): 3, 2, 1, 0, A, B or Z. Each LC was associated to an estimated error based on the number of messages received per satellite pass: from <250 m to >1500 m (LC 3, 2, 1 and 0), no accuracy estimation (LC A and B) and invalid location (LC Z). For this analysis, LC Z were excluded as well as those on land and those separated by

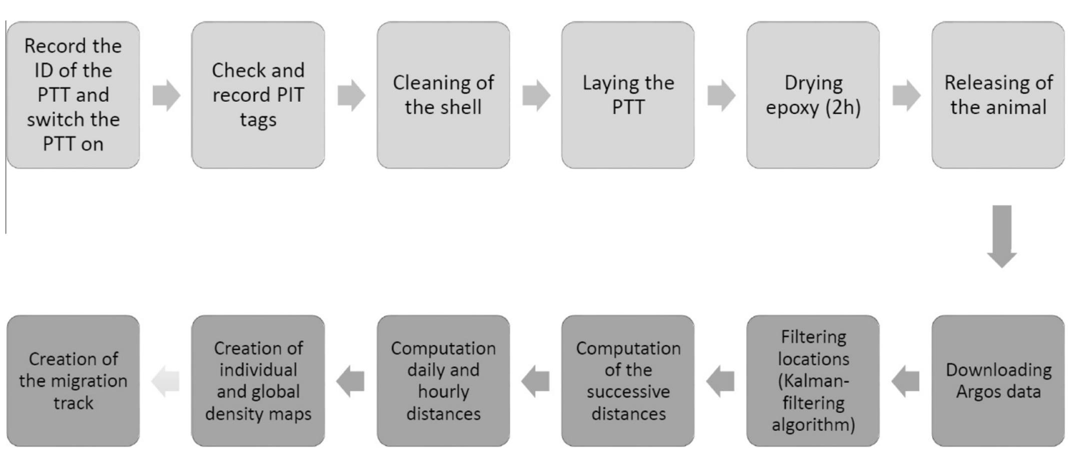

Fig. 1. Methods diagram for steps from the laying of the tag on the 16 green turtles to data analysis.

Table 1
Duration and number of positions of the 16 female green turtles equipped in the Galibi and Amana Natural Reserves in 2012.

Individual (PIT-tag)	Start	End	Duration (d)	Number of positions	Number of positions.d^{-1}
115445	May-8	August-19	103	939	11.0
115446	May-28	August-1	65	793	12.2
115447	May-23	October-24	154	1287	10.6
115448	May-8	September-1	116	1311	12.4
115449	April-26	August-18	114	979	10.5
115450	April-23	October-7	167	2129	13.5
115451	June-8	July-14	36	236	6.7
115452	April-16	August-14	120	1504	13.3
115453	April-25	June-2	38	388	15.5
115454	May-12	September-3	114	1286	12.9
115455	April-18	August-23	127	1620	15.3
115456	June-30	October-18	110	1105	12.0
115457	June-28	October-23	117	1239	12.5
115458	May-28	August-14	78	485	8.0
115459	May-28	October-24	149	1556	12.4
115460	June-13	October-7	116	1026	13.3
Average	–	–	107.8 ± 37.4	1117.7 ± 490	12.0 ± 2.3

>10 km h^{-1}. In order to record the patterns occurring during both inter-nesting and migration phases, the tags were deployed at the beginning of the nesting season and programmed to work for about 8 months.

2.3. Data pre-filtering

Only the data recorded after the last nesting were considered for the study. A Kalman-filtering algorithm was applied by CLS (CLS, Collecte Localization Satellites, Toulouse, FRANCE) to enhance the tags' positions estimates by selecting those with the minimal residual errors (Kalman, 1960; Kalman and Bucy, 1961; Rudnick and Gaspari, 2004; Van Der Merwe et al., 2004). Then a spatial query was performed via ArcGIS version 10.1 in order to identify the date of migration departure based on the distance traveled from the nesting site.

The successive distances between the locations were calculated and the data were processed to obtain the daily distances and speeds with standard deviation for all results. The distance traveled during the day was divided by the result of *final time minus initial time* of the locations.

To highlight areas of significant aggregation of green turtles across the entire migratory path, a density map was created to identify common stopover areas for all turtles, then maps of individual densities to determine stopover areas where individuals remained for longer periods (at least five days in the same area), resulting in a higher number of locations.

3. Results

3.1. General findings

The 16 green turtles were tracked between 1 and 5 months (Table 1). On average, 1118 ± 490 locations were recorded per turtle (Table 1). The migratory paths remained close to the coast (10–15 km off the coast), except when crossing the Amazon river plume, which pushed individuals 30–200 km away from the coast (Fig. 2). The corridor formed by the sum of the individual paths had a width of approximately 22 km on average, with differences at the mouth of the Amazon where some turtles stayed near the coast and others moved up to 200 km offshore (Fig. 2). Positions were recorded for individual no. 115450 over a very long period, with 167 days of tracking. The tracking was however interrupted after a only couple of weeks for two individuals.

3.2. Distances traveled

3.2.1. Total distance

On average, the 16 turtles traveled 3683 ± 1007 km. Turtle no. 115453 traveled the shortest distance (1360 km), whereas individual no. 115450 traveled 5278 km (Table 2).

3.2.2. Daily distances

The average daily distance of all tracked turtles was 42.7 ± 8.7 km (Table 2). For each turtle, the average daily distance varied from 33.4 km to 61.1 km (Table 2, no. 115450 vs. 115460 respectively) and was significantly different between individuals (ANOVA, $F_{15,75165} = 3.314$, $p < 0.001$).

3.2.3. Hourly speed & distance

On average, the green turtles moved at 1.6 ± 0.2 km h^{-1} (Table 2). Tracked individuals traveled at an average speed of 1.3 ± 1.7 km h^{-1} to 2.1 ± 2.2 km h^{-1} (Table 2, no. 115449 vs. 115451 respectively), and speed was significantly different between turtles (ANOVA, $F_{15,437} = 7.526$, $p < 0.001$). However, much higher speeds were also identified, with bursts of speed attaining 10 km h^{-1}.

3.3. Migratory stopovers

The number of stopovers obtained for each turtle varied from zero to five. Among the 16 turtles, only four did not make any stopover at all during their migration. On average, the other green turtles made 3.5 ± 1.8 stopovers during their journey.

Six main stopover areas were highlighted (Fig. 2): one along the Guianese coast, the second at the estuary of the Oyapock river (border between French Guiana and Brazil), the third before the mouth of the Amazon, a fourth just after the mouth of the Amazon, the fifth on the coast of the state of Maranhão, and the sixth on the coast between the states of Piauí and Ceará (Brazil). The first three were the most frequented, with five to seven turtles stopping there.

3.4. Final area

The end of the long migration of the turtles was marked by their arrival along the coast of the state of Ceará (Brazil). Whatever their individual date of arrival, all the individuals stayed in this area between June and October. On reception of the last Argos signal, most turtles had already been there for over a month.

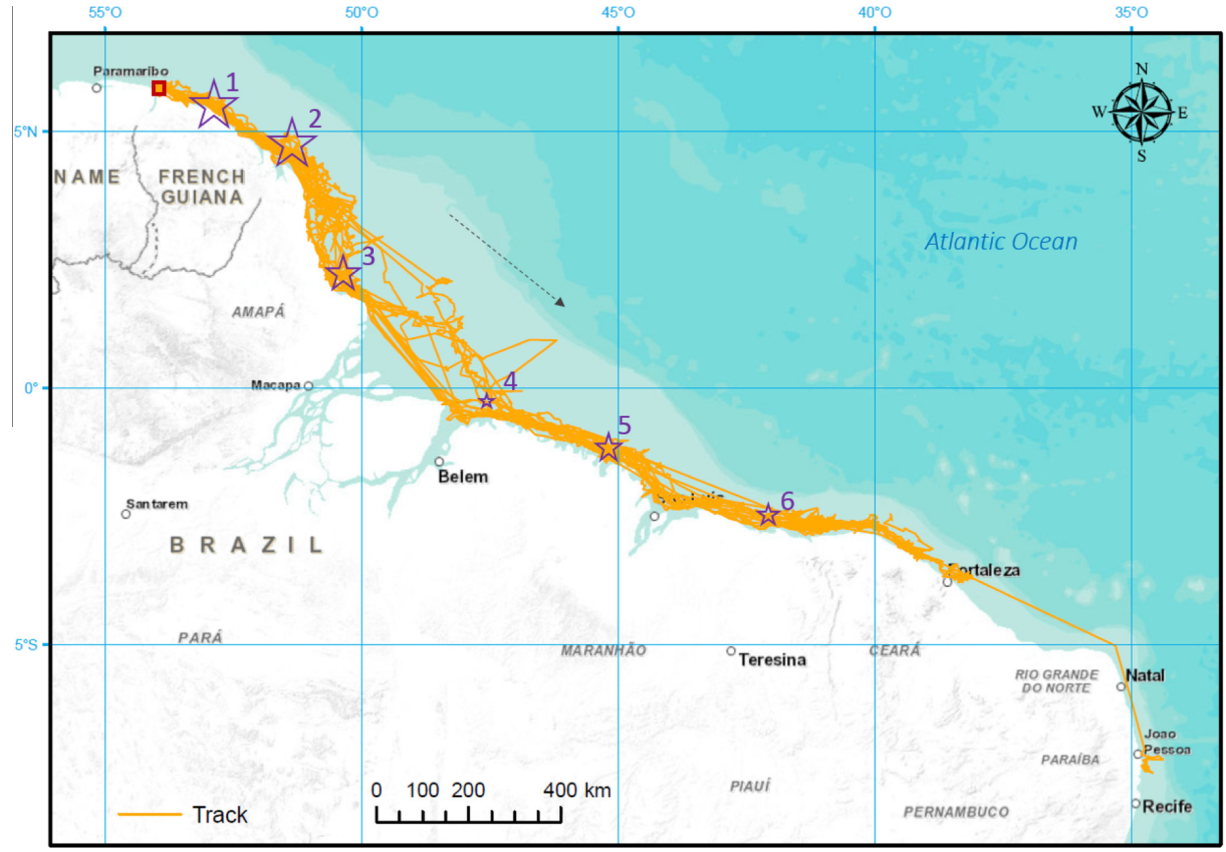

Fig. 2. Tracking of 16 green sea turtles along the north-eastern coast of South America. The red square indicates the starting location and the arrow shows the direction of their migration from the nesting sites in French Guiana and Suriname. The areas of particular interest (stopovers) are indicated by stars that are proportional to the number of turtles remaining in these areas, at least 5 days during their travel (in order: 7, 7, 5, 2, 4, and 3). (For interpretation of the references to color in this Fig. 2 legend, the reader is referred to the web version of this article.).

Table 2
Total distance, daily distance and speed of the 16 female green turtles equipped in the Galibi and Amana Natural Reserves in 2012. The total distances are in km, daily distances in km d^{-1} and speeds in km h^{-1}.

Ptt	Total distance	Daily distance	Speed	Maximum speed
115445	3578	42.1	1.6 ± 2.0	9.8
115446	3090	47.5	1.8 ± 2.0	10.0
115447	4268	35.3	1.3 ± 1.8	9.9
115448	4175	39.4	1.6 ± 2.0	9.9
115449	3306	35.6	1.3 ± 1.7	9.8
115450	5278	33.4	1.4 ± 1.9	10.0
115451	2071	59.2	2.1 ± 2.2	9.5
115452	4488	39.7	1.7 ± 2.0	9.8
115453	1360	54.4	1.8 ± 2.1	9.6
115454	3826	38.3	1.5 ± 2.0	9.8
115455	4019	37.9	1.5 ± 1.9	9.8
115456	3287	35.7	1.3 ± 1.9	10.0
115457	3849	38.9	1.5 ± 2.0	9.7
115458	2939	48.2	1.6 ± 1.9	9.9
115459	4692	37.5	1.6 ± 2.1	10.0
115460	4706	61.1	1.6 ± 2.0	9.8
Average	3683 ± 1007	42.7 ± 8.7	1.6 ± 0.2	9.8 ± 0.1

4. Discussion

This is the first detailed study of the post-nesting migration of green turtles on the Guiana Shield, and it includes paths, travel distances, speed and stopovers. These data may therefore contribute to improve our general understanding of sea turtles migratory patterns and to better define the regional conservation strategy of this endangered species.

The migration path closely follows the northeastern coast of South America (generally less than 15 km from the shore, except in the vicinity of the Amazon). This supports the idea that the populations of green turtles nesting on the continent remain on the continental shelf during their post-nesting migration (Godley et al., 2007). While all sixteen turtles followed the same path, high inter-individual variations were observed in the total distances traveled, and also a great heterogeneity in the daily distances of a single animal journey. This suggests different movement behaviors during migration that could be related to the different environmental conditions (currents, food resources, predation, *etc.*) met by each turtle at some time during their journey. The hourly distances traveled by green turtles are in accordance with the existing literature (Table 3; Cheng, 2000; Cheng et al., 2009; Craig et al., 2004; Godley et al., 2002; Hays et al., 1999; Luschi et al., 1998; Luschi et al., 1996; Seminoff et al., 2008; Troëng et al., 2005). We observed that during crossing the plume of the Amazon, some turtles followed trajectories away from coast. At this location, eddies are created from the North Brazil Current, moving at a velocity that can exceed 1 m s^{-1} (Ffield, 2005). Furthermore, the plume of the Amazon has a surface current which can also exceed 1 m s^{-1}, depending on the winds (Nikiema et al., 2007). Although these global currents generally have a northwestern direction and therefore flow directing towards the migrating green turtles, their direction can change locally depending on the tides and the strength of tradewinds (Nikiema et al., 2007). Seminoff et al. (2008) and Cheng et al. (2009) showed the influence of surface currents on the movements of green turtles and revealed that they could swim either in concordance with or against some currents or eddies.

Table 3
Track duration (d), total distances (km) and speeds (km h^{-1}) of post-nesting migrations for green turtles throughout the world.

Season	Ocean (Country)	Number of turtles	Duration	Total distance	Speed	Citations
1993 to 1995	West Pacific (American Samoa)	7	40	1599	1.80	Craig et al. (2004)
1998–1999	Mediterranean (Cyprus)	6	8–44	1364	1.98	Godley et al. (2002)
1994	West Pacific (Malaysia)	4	25.5	1135	–	Luschi et al. (1996)
1997	Central Atlantic (Ascension)	6	35	1968	2.59	Luschi et al. (1998) and Hays et al. (1999)
2003 and 2005	East Pacific (Ecuador - Galàpagos)	12	65.6	1657	–	Seminoff et al. (2008)
1994 to 1997	West Pacific (Taïwan)	8	188.8	193–1909	1.2–2.8	Cheng (2000)
1996 to 2004	West Pacific (China)	6	20	1204	0.80	Cheng et al. (2009)
2000 to 2002	West Atlantic (Costa Rica)	10	265.3	753.6	2.2	Troëng et al. (2005)

We identified six areas of migratory stopovers for the sixteen turtles. The green turtle is a capital breeder: it builds up energy reserves before migration in specific feeding areas, and does not feed during the nesting period (Hays et al., 1999). These stopovers areas (and particularly the first three, which are widely used) are probably used by turtles for occasional resting and feeding in order to build the body fuels requested to undertake their migration and lead them to a preferential feeding area. This kind of strategy has been observed for this species during coastal migration in the Mediterranean Sea (Godley et al., 2002) and in the Pacific Ocean in Asia (Cheng, 2000): in both cases, turtles fed several times during their migration. The adult green turtle is strictly herbivorous, and spends most of its life in coastal feeding areas (Senko et al., 2010) consisting of sea grass beds in shallow waters (Hirth, 1997; Bjorndal, 1985). A detailed study of turtle behavior at stopover sites would be useful to clarify the importance of these hotspots in the conservation of green turtles. It would also be of interest to determine if the green turtles make the same stopovers each year; i.e. at the same localizations we pinpointed in this study.

The fact that post-nesting green turtles from French Guiana and Suriname may spend more than one month at their final destination is also of great importance for their conservation. This suggests either the possibility of a long stop after this journey to restore body fuels and reach the body condition requested to keep traveling further south, or until the arrival at their migratory destination. That one individual (no. 115460) continued its migration to a site on the coastal regions of Natal and Recife (Brazil), which is also an area used for feeding by the green turtle population nesting on Ascension Island (Hays et al., 2002; Luschi et al., 1998), making it a key area in the spatial ecology of green turtles from the southern Atlantic. Hays et al. (2002) showed that the green turtles from Ascension Island move spontaneously towards the Brazilian coast before continuing their migration along these Brazilian coasts, ignoring the areas with abundant food resources that are available in the early stages of their journey. Food availability might therefore not be the only selection criterion and in addition to the quality and quantity of food available. In this case, other abiotic factors could influence the decision of sea turtles to stop and stay in these areas, or move further away.

The migration patterns observed in the present study should also be analyzed in relation to the location and intensity of fisheries and therefore the risk of bycatch for the migrating turtles. For two of our sixteen turtles, the tracking was interrupted before the depletion of the GPS satellite tag batteries. Yet, the tag has operated during a few weeks for one of them, indicating that it was brought ashore in a Brazilian fishers village and therefore that it had been accidentally caught by fisheries. Interestingly, this interruption occurred around the mouth of the Amazon, where bycatch is known to occur with longlines and gillnets (Wallace et al., 2013). However, Wallace et al. (2013) do not include the effect of coastal gillnet fishing, which is widespread on the Brazilian coast and difficult to assess (see Bioinsight and DIREN Guyane, 2003; Chevalier et al., 1998).

This corridor from eastern Suriname border to northeastern coast of Brazil is crucial because it could connect the Atlantic South Caribbean, Atlantic Southwest and Atlantic South Central RMUs (Wallace et al., 2010). Thus, one can see here that, rather than dealing with each RMU individually, it would be wiser to evaluate the potential connections between these units, and build a consistent and applicable global management strategy for all three RMUs.

5. Conclusion

This study provides detailed information about the post-nesting migratory paths of green turtles nesting at the border between French Guiana and Suriname, describes the areas used by turtles (resting areas) along the Brazilian coast and identifies the hot spot that appears to be their goal at the end of their travel. A high rate of bycatch occurs along this migratory path (Davies et al., 2009; Wallace et al., 2013) and could have a substantial impact on the green turtle population. The next step should be to investigate how far legal and illegal fishing overlap with the paths and final destination of migrating turtles. Finally, as at least two turtle populations use the same feeding area, the efficient protection of foraging areas of turtles along the extensive Brazilian coast may then consolidate populations thousands of kilometers away (Naro-Maciel et al., 2007). International conventions, regional protection plans and transnational actions such as those already implemented in Argentina (González-Carman et al., 2012) or in the state of Sergipe in Brazil (Coelho Dias da Silva et al., 2010) should be also applied in these foraging areas of green turtles if we want to ensure the conservation of this species.

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