



Nesting dynamics of hawksbill and leatherback turtles: a four-year photo-identification study in Martinique

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ABSTRACT

One major limitation in conservation studies is accurately estimating population size to adapt management efforts. Thus, avoiding individual duplicate counts is essential to prevent any overestimation of population size. Photo-identification (photo-ID) offers a low cost and non-invasive alternative for monitoring migratory animals, and yet, it remains generally under-implemented in marine species. In this study, we applied photo-ID with sea-turtle populations in the French Antilles for the first time, thereby contributing to global population survey efforts in the Caribbean while minimising stress or harm to turtles. We focussed on two species of concern, *Dermochelys coriacea* (leatherback) and *Eretmochelys imbricata* (hawksbill), identified through a semi-automated recognition method to analyse their nesting behaviour. Our multi-annual survey involved 5292 h of night monitoring across three Martinique beaches over four years, yielding valuable data on nesting behaviours, population dynamics and conservation needs. We recorded 57 occurrences of leatherback turtles with a recapture rate of 61 %, and 314 hawksbill observations with a recapture rate of 36 %. The microhabitat of each nest was recorded, providing insights on nesting site preferences. Additionally, leatherbacks exhibited a longer time interval between their arrival on the beach and the start of nesting activity compared to hawksbills. These results reveal significant behavioural differences and specific nesting habits underscoring the potential of expanding photo-ID combined with ecological analysis, as a valuable resource for the conservation management of threatened sea-turtle species.

1. Introduction

Accurately estimating population size is a critical challenge in conservation studies, as it directly informs adaptive management strategies and necessitates meticulous methods to avoid duplicate counts and consequent overestimations. In response, emerging technological advances—especially in image analysis and photo-identification (photo-ID)—are revolutionizing the field, enabling researchers to overcome these traditional hurdles and implement large-scale monitoring of animal populations, with notable promise for studying migratory species (Wursig and Wursig, 1977; McDonald and Dutton, 1996; Wilson and McMahon, 2006; Holmberg et al., 2009). As such, individually identifying animals through naturally occurring markers has become a cornerstone of conservation research (Whitehead et al., 2000; Frisch and

Hobbs 2007) and these non-invasive approaches are now becoming central to capture-mark-recapture studies (Rosel et al., 2011; Dunbar et al., 2021). This shift offers a less intrusive, low cost, and sustainable alternative to traditional marking techniques (Araujo et al., 2016). Conventional methods, such as physical tagging—often leading to significant tag loss (Bradshaw et al., 2000; Reisser et al., 2008)—or the use of microchips, which requires expensive, specialized equipment, and impose stress on animals (Buonantony et al., 2008; Gheorghiu et al., 2010), underscore the urgency of adopting improved strategies in population monitoring of endangered species. In contrast, photo-ID offers a simpler, more portable, and accessible approach that can be used by researchers and citizen scientists alike, making it a valuable tool in modern conservation efforts (Schofield et al., 2008).

Located in the Caribbean, more specifically, in the Lesser Antilles,

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Martinique is an Island covering 1 128 km², recognized as a biodiversity hotspot where its endemic species are facing significant threats due to human activities and climate change (Myers et al., 2000; Anadón-Irizarry et al., 2012; Hrdina and Romportl 2017). For marine turtles, Martinique plays a key role in their development (Chevalier, 2006; Cayol et al., 2008). Each year, from April to October, this island hosts numerous nesting sites for hawksbill (*Eretmochelys imbricata* (Linnaeus, 1766) and Leatherback turtles (*Dermochelys coriacea* (Vandelli, 1761)) (Chevalier, 2006; Dow et al., 2007). Moreover, these two species highly represented in Martinique are classified as “critically endangered” and “vulnerable” respectively (IUCN 2020), placing the island at the forefront of species restoration programs.

Amongst marine turtle, the leatherback turtle is the largest species and the sole representative of the Dermochelyidae family. It can reach up to 2 m in length and weigh more than 900 kg (Eckert and Luginbuhl, 1988). In the Atlantic Ocean, females generally return every 2 to 5 years to nest on tropical and subtropical beaches (Bell et al., 2004; James et al., 2007) before heading back to their feeding areas, which are mostly located in temperate waters (Dodge et al., 2014). During a single nesting season, females may nest up to 11 times (Rostal et al., 1996; Bell et al., 2004) with intervals of 8 to 12 days between nestings (Eckert et al., 1989; Buonantony et al., 2008). Unlike any other sea turtles, leatherback turtle has a unique shell composed of a hard dermal tissue rather than scales. Because traditional photo-ID methods of sea turtles has relied on facial scales, applying them to leatherback turtles has proven unworkable due their unique lack of scales. However, McDonald and Dutton (1996) suggested using the pineal spot –also called “pink spot”- a depigmented mark located on the top of the head. Subsequent research (Buonantony et al., 2008) has demonstrated that this mark persists over time, and its efficiency for population study using photo-ID, allowing reliable individual identification of leatherback turtles (Pauwels et al., 2008; De Zeeuw et al., 2010). Moreover, the pineal spot can be used for individuals encountered in the open sea, enabling comparisons with those photographed in nesting areas (Buonantony et al., 2008).

The hawksbill turtle measures about 90 cm in length (Pritchard and Mortimer, 1999) and nests on subtropical and tropical beaches up to nine times during the nesting season, with intervals of 9 to 21 days between nestings (Limpus et al., 1983; Bjørndal et al., 1985). Females would come back every 1 to 6 years, with an average of 2 years (Richardson et al., 1999; Beggs et al., 2007). Like other members of the Chelonian family, the hawksbill can be identified by its unique scutes pattern. Indeed, the colours and shapes its scutes have been recognized as reliable markers for individual differentiation-whether facial features (Reisser et al., 2008, Calmanovici et al., 2018; Dunbar et al., 2021), flippers (Gatto et al., 2018; Pursley 2020), or the shell (Tabuki et al., 2021). Facial scutes are particularly valuable because they remain very stable and unique, allowing for consistent identification over time (Dunbar et al., 2014). Research has shown that the scute pattern remains unchanged in hawksbill turtles for at least 3 years (Carpentier et al., 2016).

The threatened status of hawksbill and Leatherback turtles is attributed to several factors, including habitat loss (Mazaris et al., 2009; Witherington et al., 2011), climate change (Fuentes et al., 2019; Topping and Valenzuela, 2021), and anthropogenic pressures (Sella and Fuentes, 2019, Stanley et al., 2020; Siqueira-Silva et al., 2020). Estimating individual identification for understanding nesting site preference and site fidelity is vital for assessing nesting success (Richardson et al., 1999; Hays, 2000). Although, counting nesting turtles has long been considered a reliable method (Sims et al., 2008; National Research Council et al., 2010; Santos et al., 2021), this approach can be inaccurate because the same individual may nest several times in one season (Esteban et al., 2017). Based on satellite tracking of green turtles, Esteban et al. (2017) demonstrated that traditional nest counts may substantially overestimate nesting success, by nearly a factor of two, due to repeated nesting by the same individuals. This finding highlights the limitations of relying solely on nest counts without incorporating

individual identification, a bias that likely extends to other species such as hawksbill and leatherback turtles. Although we recognize that photo-identification cannot fully resolve this issue when beaches are not monitored daily, it nonetheless represents a valuable approach for enhancing the accuracy of nesting estimates, particularly in contexts where continuous or extensive monitoring is not feasible. To date, however, similar high-resolution tracking studies aimed at quantifying this overestimation remain scarce or absent across the Caribbean. Although some local monitoring programs have recognized intra-seasonal remigration (Maurer et al., 2022), few provide adjusted nesting estimates that account for this phenomenon. This gap highlights the need to integrate complementary approaches, such as photo-ID, into annual sea turtle monitoring efforts to improve demographic assessments.

Photo-ID offers here an adequate and accurate alternative by preventing duplicate counts, as it distinguishes individuals through their unique patterns, thereby yielding more reliable data to inform conservation strategies (Schofield et al., 2008). Moreover, photo-ID data can be integrated with other information gathered during the nesting seasons (e.g., female body size, number of eggs laid, nest location, and habitat characteristics) to enrich our understanding of local populations (Kamel and Mrosovsky, 2005; Gaos et al., 2021). On a larger scale, photo-ID monitoring can be applied to track individual migrations and estimate migratory routes, making it an effective conservation tool for marine turtles survival.

In this context, our study was oriented towards several objectives: (1) to collect data on female leatherback and hawksbill turtles nesting on three beaches in Martinique, monitored over a four-year period, (2) to determine intra-annual and interannual “recapture” (remigration) rates using photo-ID, and (3) to analyze nesting habits and site fidelity, microhabitat selection, and temporal patterns. This study is based on the assumption that photo-ID is a non-invasive method that reduces bias in population estimates and aids in evaluating interspecific differences in nesting behaviour.

2. Material and methods

2.1. Study sites

This study is based on the population of leatherback and hawksbill turtles nesting on three beaches in Martinique: Madiana, Diamant, and Salines (Fig. 1). Madiana and Diamant beaches are located on the Caribbean coast while Salines is situated along the island’s Atlantic south coast (Table 1).

2.2. Data collection

Sampling was conducted from 2020 to 2024, four nights per week (Monday/Tuesday and Thursday/Friday) between 7:00 p.m. and 1:00 a.m. The duration of the sampling period varied by year, ranging from a minimum of July to September in 2020, to a maximum of April to October in 2023 (Table 2). In 2021 the monitoring stopped in July due to the Covid-19 restrictions in place. This study represents a sampling effort of 5 292 h, or 1 764 h per monitored beach.

A total of 815 hawksbill turtles and 105 leatherback turtles were observed or reported (tracks included) during the 4 years nesting season night patrols.

Teams of at least four students, trained by Aquasearch, conducted their patrols under red light. Each pair within a team began at opposite ends of the beach and moved toward the center, where they paused for a 20-minute break before continuing. This method ensured comprehensive coverage of the beach. Due to its small size (200 m), only Madiana Beach was patrolled by a single pair of students. All collected data and photographs were taken during the laying phase, minimising the impact of data collection on the nesting behaviour of the turtles. Experimental procedures were evaluated and approved by the Ethical-Scientific

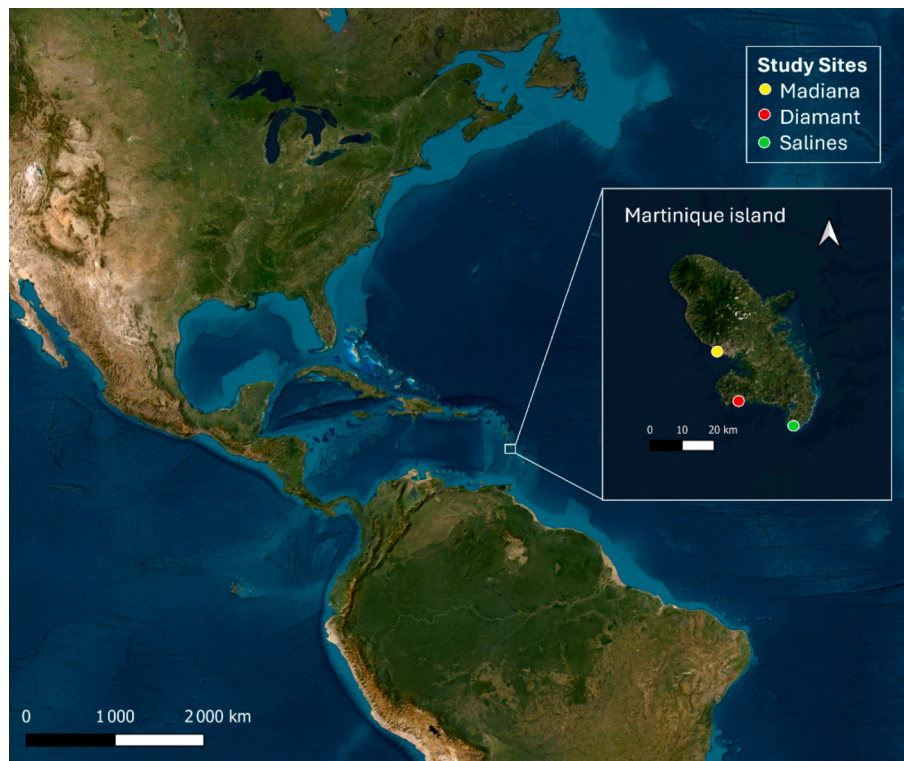


Fig. 1. Location of the three monitored beaches on Martinique Island, Lesser Antilles.

Table 1
Characterisation of the three studied beaches.

Beach name	Coordinates		Length (km)	Characteristics	Closest town
Madiana	14°36'43"N	61°05'54"W	0.2	Black sand	Schoelcher
Diamant	14°28'32"N	61°02'10"W	2.3	Mix white/black sand	Diamant
Salines	14°24'14"N	60°52'47"W	1.3	Fine white sand	Sainte-Anne

Table 2
Sampling effort per beaches and years of monitoring.

Year	Sampling period	Total Monitoring (h)	Madiana	Diamant	Salines
2020	July-September	540	180	180	180
2021	April-July	1254	418	418	418
2023	April-October	1782	594	594	594
2024	April-September	1716	572	572	572

Committee for Animal Experimentation of the Université du Québec à Rimouski (Certificate Number CPA-97-23-261). Collected data included the arrival and return times of turtles that came to lay eggs, number of eggs laid, width of the turtles’ tracks, GPS position of the nests, and their habitats. Track width refers to the measurement (in cm) of the marks left in the sand by the turtle’s front flippers. It is taken at the widest point of the flipper imprints using a flexible tape measure. Egg count error indicates the observer’s estimated margin of error when the clutch had already been laid. This study specifically identifies various habitat types and associated microhabitats, as detailed below. Morphometric features of the observed turtles were also recorded by measuring the Curved Carapace Length (CCL) and Curved Carapace Width (CCW) using laser in order to not touch the animal. We used the Long Range Tactical Red SVIP Gift Positioner laser system (red laser pointers, Accessoires Energie, Nice, France), mounted on the end of a calibrated bracket with two laser

beams fixed precisely 30 cm apart. This configuration ensured consistent projection of a 30 cm reference scale. Calibration tests were performed at multiple distances to verify the stability of the spacing. Turtle measurements were obtained by photographing the laser dots projected onto the carapace and estimating carapace dimensions using MESURIM Pro software (Académie de Créteil, France). Photographs were taken with a typical cell phone, as all contributors would have their own. Photographs were taken under red light without flash, at a distance around one metre from the turtle. For the right and left profiles of the head, images were captured horizontally at eye level. The dorsal view of the head was photographed from a height of about one metre directly above the turtle. For leatherbacks, only the top of the head, specifically the area containing the distinctive “pink spot”, was used for identification. In contrast, for hawksbills, both the right and left sides of the head were considered. Pictures were then systematically catalogued each day, with specific information of each individual turtle associated to each picture file. Turtles returning to the water – having only made a nesting attempt or a simple search for future laying grounds – were also photographed. However, to minimise any disturbance, photographs were only taken right before the female entered the water.

2.3. Photo-ID

In order to analyse the pictures, we used the software I3S Pattern v3.0 (Interactive Individual Identification System, © 2020 Reijns/i3s) that allowed a semi-automated recognition of individual turtle. This software is largely used in literature for its effectiveness and reliability

(Speed et al., 2007; Van Tienhoven et al., 2007; Den Hartog and Reijns, 2012; Steinmetz et al., 2018). Based on photo quality (Dunbar et al., 2014; Calmanovici et al., 2018) and user experience (Steinmetz et al., 2018), I3S Pattern is recognized as a reliable semi-automatic tool. Although photo-ID has proven effective for monitoring individual sea turtles (McDonald and Dutton, 1996; Buonantony et al., 2008; Esteban et al., 2017), its reliability is challenged by several factors. Image quality remains a major limitation; suboptimal lighting, motion blur, and inconsistent angles can significantly impair the performance of automated recognition software (Calmanovici et al., 2018). These issues become even more pronounced as database size grows, making manual verification of proposed matches increasingly time-consuming yet still essential (Dunbar et al., 2014). To address these challenges, we standardized our photo collection protocols—ensuring consistent capture angles, among other measures. In this study, three anchor points were used to guide the software and outline the studied area, here, the top head of the leatherback and scales on the right or left profile of the hawksbill. Once the studied area was established, the software, I3S pattern, will automatically designate 35 key reference points (Den Hartog and Reijns, 2014) for size and location comparison in each image of the database. The software will then suggest matches by assigning them a score. Scores between 0 and 20 typically reflect a high likelihood of accurate identity matching, whereas higher values indicate a substantially lower probability of true correspondence. Despite this, users were encouraged to visually assess the top-ranked image suggestions regardless of score. Final verification of each match was conducted manually to ensure data integrity. To reduce observer bias, the same individual reviewed all data twice, followed by an independent check by a second reviewer. These methodological refinements reinforce the validity of photo-ID as a reliable, non-invasive tool for recognizing individual sea turtles in conservation efforts.

2.4. Habitat characterization

We identified four primary habitat types. The first is the **waterline**, extending up to 20 m from the low tide mark. The second is the **sand strip**, whose width varies depending on the beach, for instance, Madiana is characterized by an expansive sandy area with minimal vegetation. The remaining two habitats are the **forest edge** and the **forest interior**. The forest edge is defined as the transitional zone encompassing the final two metres of the sand strip and the initial two metres of the forest, typically influenced by partial shading from the canopy. Beyond this lies the forest interior, which is generally dense and markedly darker due to the overhead vegetation.

In spring 2023, we characterized microhabitats at Madiana and Diamant, followed by Salines in 2024, using the Braun-Blanquet method to ensure a systematic and standardised approach (Meddour, 2011; Lemercier, 2023). This method allowed us to define microhabitats based on distinct plant species compositions and abundance level. Through this process, we identified three vegetation types: ground cover, short shrub and tall shrub. Vegetation cover density for each habitat type was evaluated using the Braun-Blanquet phytosociological method (Westhoff and Van Der Maarel, 1978; Meddour, 2011; Lemercier, 2023). To randomly determine the lower left corner of each sampling quadrat, a stone was thrown within the microhabitat. Vegetation cover was then visually estimated using the semi-quantitative Braun-Blanquet abundance-dominance scale, based on the proportion of ground covered by vegetation—including ground-level, shrubby, and arboreal species—relative to bare surface area. In treeless microhabitats, 1 m × 1 m quadrats were used, whereas 2 m × 2 m quadrats were applied in areas containing trees. To ensure data reliability and capture spatial variability, five replicates were carried out per microhabitat. To minimise observer bias and ensure consistency, all characterisations were performed by a single observer on each beach. Identified microhabitats are available in Appendix 1.

2.5. Data analysis

All statistical analysis were carried out using R Statistical Software (V.4.2.1; R Core Team 2022) and Microsoft Excel. Photo-ID results were compared with the habitat data as well as the monitoring collected information (turtle's size, nest coordinates, behaviour). Descriptive statistics (mean ± SD) were used to summarize morphological traits and clutch data. Inter-species differences in time intervals on the beach of each female were assessed using Welch's *t*-test. Beach potential preference was tested by one-way ANOVAs tested for variation in the number of hawksbill and leatherback observations and recaptures across different beaches. When assumptions of normality or homoscedasticity were violated, Kruskal-Wallis tests were applied. To account for spatial variability, data were normalized per 100 m of beach length and compared using *t*-tests. Nest site fidelity was investigated by individual identification through photo-ID and GPS coordinates of nests across habitat types and microhabitats were analyzed and interpreted descriptively. To assess the spatial distribution of nesting activity, we employed QGIS spatial tools to calculate the nesting area of individual hawksbill turtles. For each female that nested at least three times during the season and for whom GPS coordinates of nest locations were available ($n = 14$), we generated a polygon encompassing all recorded nest sites. The resulting polygons represent the spatial extent of each turtle's nesting activity (in m²). These values were subsequently used to examine the relationship between turtle size, measured as curved carapace length (CCL), and nesting area.

2.6. Data privacy and ethical considerations

To safeguard sensitive ecological data, such as nesting site locations and individual turtle identifications, all GPS coordinates and photo-ID images are stored on secure, access-restricted servers managed by Aquasearch. Access is granted solely to authorized researchers directly involved in the project. Given the potential risk of nesting site exploitation—particularly concerning endangered species like hawksbill and leatherback turtles—precise location data are not made publicly available. However, these data may be shared with qualified researchers upon request to Aquasearch, pending approval.

3. Results

3.1. Population monitoring

A total of 314 hawksbill turtles were photographed over the four-year study period (Table 3). Image analysis using I3S pattern software identified 113 matches, representing 45 unique individuals, resulting in a recapture percentage of 36 %. Among these recaptures, three hawksbill turtles were defined as remigrants, indicating that these females returned to nest on the same beach across nesting seasons.

In contrast, 57 leatherback turtles were photographed during the study period. Image analysis identified 35 matches, representing a recapture rate of 61 %. A closer examination of these 35 pictures using I3S revealed that they corresponded to 11 individuals with multiple intra-annual recaptures. This result suggests a certain degree of fidelity to their nesting sites. It is important to note that no observations of leatherbacks were recorded in 2020, likely due to the late start of monitoring in 2020 that started after the end of the leatherback nesting season in Martinique (March-June). Additionally, leatherback turtles were recorded on only two out of the three monitored beaches (Diamant and Salines).

CCL and CCW measurements were performed on a sample of 281 nesting hawksbill turtles and 86 leatherbacks (Table 4; Appendix 2). The measurements include all data collected by the monitoring teams, regardless of whether the turtle was seen only once or was recaptured during the season. The average size was 85 ± 6 cm for CCL and 73 ± 7 cm for CCW. Regarding leatherbacks, average CCL size was 157 ± 7 cm,

Table 3

Number of observations (pictures) and recaptures of hawksbill and leatherback turtles on the beaches of Madiana, Diamant, and Salines during the nesting season monitoring of 2020, 2021, 2023, and 2024. Absence of leatherbacks nesting in 2020, could be likely due to the late start of monitoring in 2020 after the end of the leatherback nesting season in Martinique (March-June).

Hawksbill (<i>E. imbricata</i>)						
Year	Madiana Observations	Madiana Recaptures	Diamant Observations	Diamant Recaptures	Salines Observations	Salines Recaptures
2020	4	0	21	3	14	0
2021	6	0	36	10	26	15
2023	12	4	52	21	17	4
2024	11	5	65	22	50	29
Leatherback (<i>D. coriacea</i>)						
Year	Madiana Observations	Madiana Recaptures	Diamant Observations	Diamant Recaptures	Salines Observations	Salines Recaptures
2020	0	0	0	0	0	0
2021	0	0	3	2	5	3
2023	0	0	2	0	21	13
2024	0	0	11	9	15	8

Table 4

Encountered turtle measurements (CCL and CCW) and track width (in cm) with SD; number of eggs and error during the nesting season monitoring of 2020, 2021, 2023, and 2024.

Hawksbill (<i>E. imbricata</i>)					
Year	CCL	CCW	Tracks width	Nb eggs	Error
2020	86 ± 6	74 ± 5	69 ± 12	152	10
2021	86 ± 5	75 ± 4	79 ± 7	127	12
2023	87 ± 5	77 ± 6	72 ± 11	111	10
2024	82 ± 7	65 ± 12	75 ± 8	120	8
Leatherback (<i>D. coriacea</i>)					
Year	CCL	CCW	Tracks width	Nb eggs	Error
2020	–	–	–	–	–
2021	149 ± 6	106 ± 10	159 ± 29	123	11
2023	152 ± 8	115 ± 13	178 ± 37	109	11
2024	154 ± 6	109 ± 8	157 ± 26	108	8

and 110 ± 10 cm in width (CCW). In addition, the average number of eggs laid per nest was 127 ± 10 for hawksbill turtles, compared to 113 ± 10 for leatherbacks.

Analysis of hawksbill turtles presence per beach using year as replicate revealed that Madiana presents a globally lower values for observations (df: 9, F = 7.28, p = 0.02) and recaptures (Kruskal-Wallis: df: 2, p = 0.12), in particular between Diamant and Madiana which has a significant difference (padj = 0.00411) (Fig. 2A). However, when data were normalized based on the beach length using a standardized 100-meter scale, absence of differences were obtained for observations (t-test: df: 5, F = 1.45, p = 0.31) and recaptures (df: 9, F = 0.46, p = 0.64) results. These last results suggest that hawksbill turtles do not show a clear preference for any of the three beaches (Fig. 3). The Leatherback turtles were not observed on Madiana beach and their presence in the two other beaches was similar (df: 4, F = 2.62, p = 0.18 for observations and df: 4, F = 0.81, p = 0.41 for recaptures) and lower than hawksbill turtles (Fig. 2B).

3.1.1. Nesting patterns and beach arrival timing

In order to gain insight into the behavioural habits of individual turtles, we focussed on turtles observed more than twice, as identified through photo-ID using I3S Pattern software. The behavioral analysis focuses on 12 hawksbills and 6 leatherbacks, each observed more than twice—primarily within the same season. However, the small sample size, particularly for leatherbacks, limits the scope for robust statistical

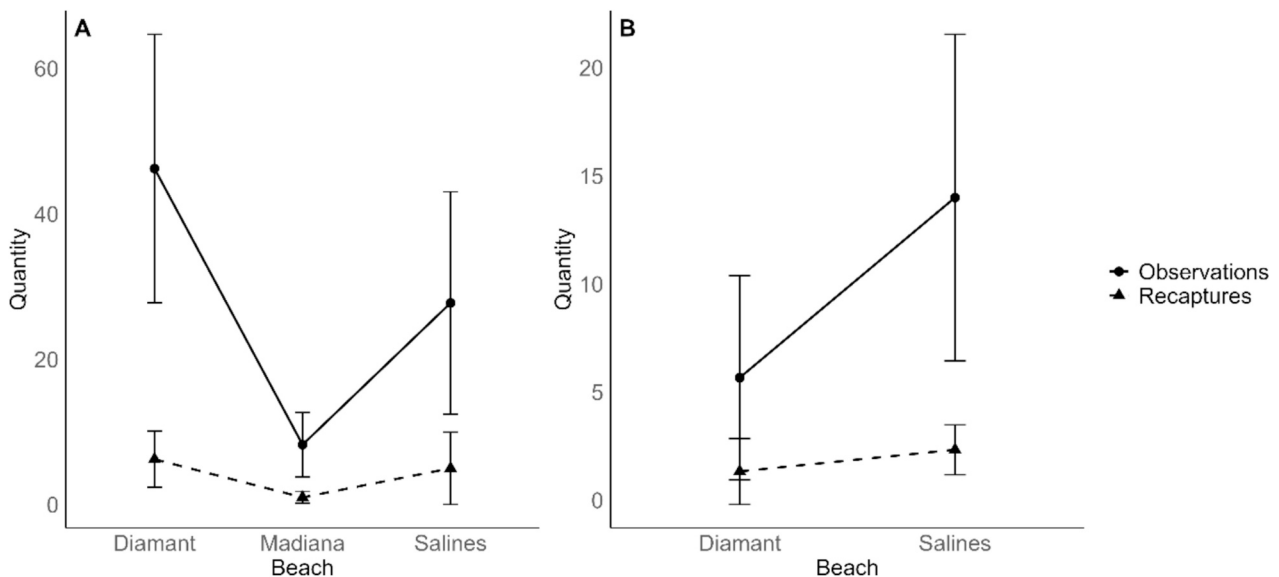


Fig. 2. Number of *E. imbricata* (A) and *D. coriacea* (B) observations and recaptures per beach (Madiana, Diamant and Salines). Solid lines represent initial individual observations, while dashed lines indicate photo-ID-based recaptures.

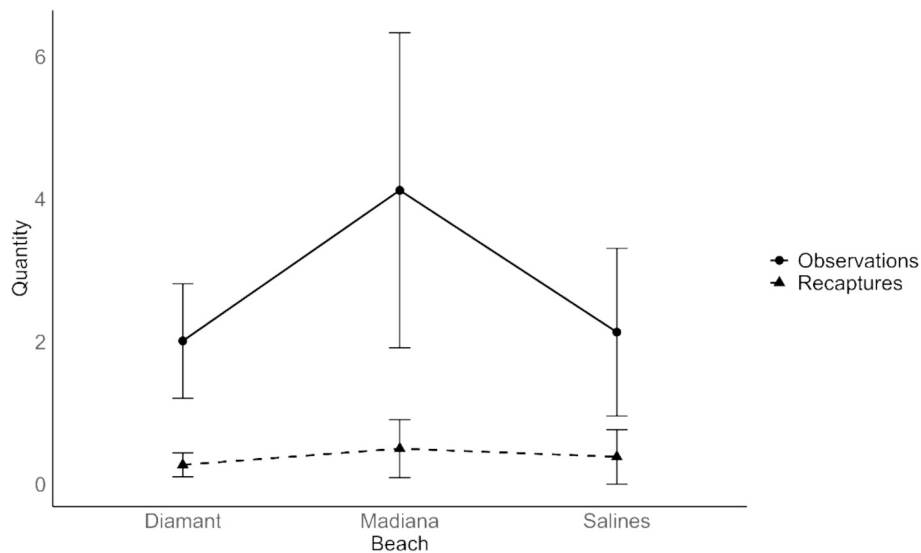


Fig. 3. Number of observations and recaptures of *E. imbricata* turtles per beach and per monitored year normalised on a 100 m beach length. Solid lines represent initial individual observations, while dashed lines indicate photo-ID-based recaptures.

analysis. Subsequent analyses were conducted exclusively on these repeatedly observed individuals to elucidate patterns in nesting behaviour and site fidelity.

Using QGIS spatial tools, we calculated the area (in m²) encompassing the nest locations of individual turtles. This analysis was conducted for hawksbill turtles that nested at least three times during the season and for which nest coordinates were available (n = 14). The resulting polygons represent the spatial extent of each female’s nesting activity. On average, hawksbill turtles laid eggs in areas measuring 2 931 m² ± 2 695 m². We aimed to observe how the size of hawksbill turtles (CCL) influences their use of habitat. However, no statistically significant correlation was found (R² = 0.231; p = 0.135). A comparable analysis could not be performed for leatherback turtles due to insufficient data, thereby limiting the scope of our conclusions.

When observed, the exact time each female turtle emerged from the water to come ashore was recorded, regardless of whether she ultimately laid eggs. This allowed us to compare time intervals for each species during the nesting season (n = 6 for leatherbacks and n = 12 for hawksbill). Important individual variability was observed, but on average hawksbill turtles exhibited a shorter water emergence time interval of 1h12min ± 12 min comparatively to 2 h48 min ± 24 min for leatherback turtles (Fig. 4; t-test = -3.0297, df: 8.23, p = 0.02).

3.2. Dynamics of habitat utilization

We identified nine distinct types of microhabitats (Fig. 5) across the three beaches studied, distinct from the four main types of habitats defined previously which are more general (waterline, sand strip, forest edge and forest). Madiana Beach, as a small beach (200 m long), was characterised by low density vegetation predominantly composed of sandy soil (59 %) and high sun exposure. This beach featured sparse populations of coconut trees (*Cocos nucifera*) and seaside grape trees (*Coccoloba uvifera*), classified as Microhabitat M1. In contrast, Diamant Beach exhibited a narrower sand strip (M4 habitat at 62 %) with more diverse vegetation (M5 habitat at 20 %) indicating the dominance of this vegetation structure within this beach. Salines Beach presented a more uniform composition in microhabitats, being primarily dominated by M4 (70 %) characterised by dense arborescent vegetation, and M6 (24 %), which consists of predominantly bushy vegetation.

GPS coordinates of the nests of 100 hawksbill and 29 leatherback turtles identified using photo-ID indicated that the turtle laid eggs were characterised according to two criteria: the type of habitat (forest, forest

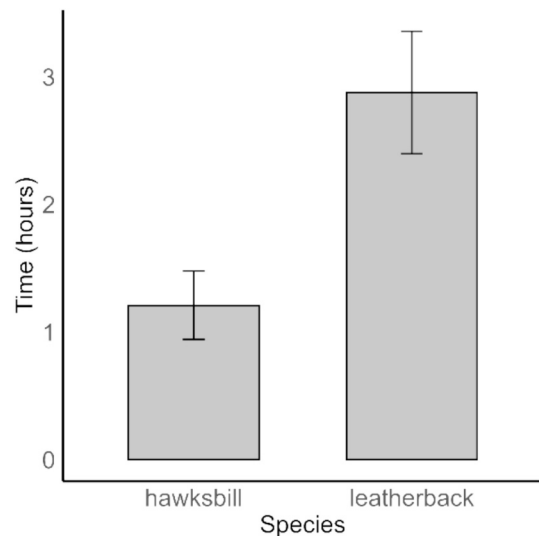


Fig. 4. Average time (in hours) between different arrival (water emergence) of hawksbill and leatherback turtles individuals, observed at least 3 times.

edge, sand and waterline) and the microhabitat. Concerning the type of habitat used by the turtles as nesting grounds (Fig. 6), hawksbills seems to prioritise the forest unlike the leatherbacks that almost always choose the sand strip and sometimes even the waterline.

Of the nine microhabitats defined, six of them contained at least one hawksbill nest (Fig. 7). However, the totality of leatherback turtle nests were situated directly on the beach sand strip (55 %) or on the waterline (45 %) thus preventing us from classifying these nests into microhabitats. Specifically, on Salines beach, leatherback turtles preferred to lay eggs near the edge of the forest, while avoiding close proximity to it. These nests were located on bare sand areas, sometimes slightly shaded by coconut trees bordering the forest, which prevented the identification of specific microhabitats for leatherbacks. Consequently, the microhabitat analysis focusses on hawksbill turtles.

Our observations indicate that 50 % of the nests were laid in microhabitat M4, which is characterized by arborescent vegetation, primarily located in the back forest. M4 is particularly extensive at Diamant and Salines beaches, covering more than 60 % of the surface

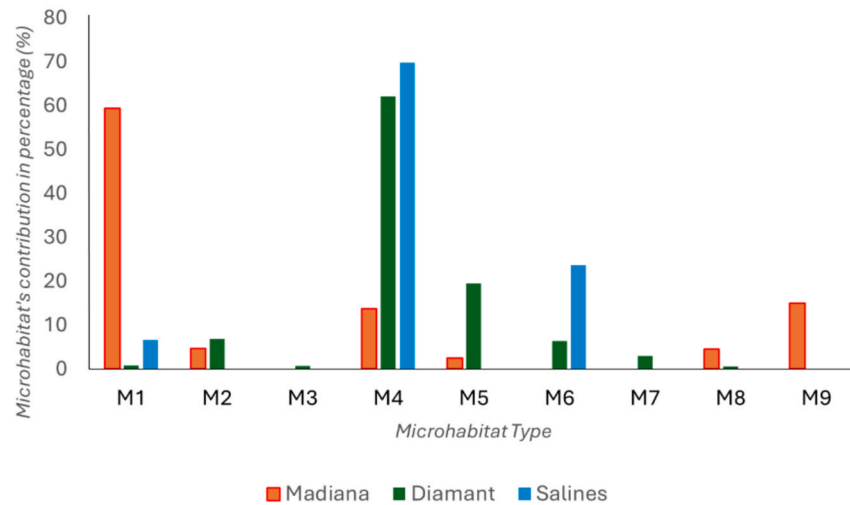


Fig. 5. Distribution (in %) of microhabitats (M) by ranges. The floral characteristics of the microhabitats determine their classification. Description in Appendix 1.

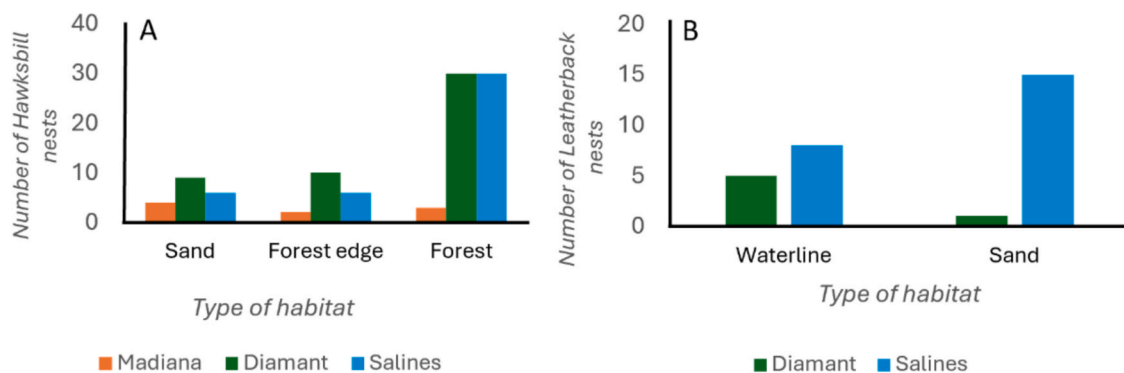


Fig. 6. Distribution of clutches across different habitat types (waterline, sand, forest edge, and forest) at Madiana, Diamant, and Salines for: (A) Hawksbills (*Eretmochelys imbricata*) and (B) Leatherbacks (*Dermodochelys coriacea*).

area (Fig. 5), but is considerably smaller at Madiana beach, where it comprises only about 10 % (Fig. 5). Microhabitat M6, the second most extensive habitat at Salines (over 20 %), also served as a significant nesting area for hawksbill turtles, accounting for 16 % of the nests recorded at this site. This habitat consists mainly of bushy vegetation interspersed with coconut trees (see Appendix 1). Additionally, a notable proportion (20 %) of hawksbill nests were located in the sand strip area.

4. Discussion

This study is the first to report long-term monitoring of hawksbill and leatherback turtle nesting in the French Lesser Antilles, demonstrating the potential of photo-ID in tracking these populations. The postorbital scales of sea turtles are renowned for their stability over time (Carpentier et al., 2016), making them an ideal feature for photo-ID. Hawksbill females recaptured three years after their previous nesting season showed no apparent changes in their head scale patterns. Nevertheless, Carpentier (2016) emphasized the importance of further research and continued photo-identification efforts to monitor potential long-term changes in these patterns. Photo-ID technique not only facilitates a more detailed analysis of turtle behaviour during egg-laying but also highlights individual differences, that remain largely unexplored such as specific habitat use or nesting habits. Moreover, tools such as I3S

enhance our understanding of sea turtle population dynamics by providing critical data to inform future conservation efforts. Our findings confirm the hypothesis that photo-ID is an efficient method for assessing population estimates by avoiding duplicate counts and preventing overestimations. With recapture rates of 61 % for leatherback turtles and 36 % for hawksbills, our results underscore the significant risk of overestimating the reproductive effective population if duplicates are not properly identified. For instance, two hawksbill turtles observed in 2020 returned in 2023, and a third individual seen in 2021 reappeared in 2024 (see Appendix 2). This demonstrates site fidelity over multiple years and qualifies them as inter-annual matches. These observations align with the conclusions of Carpentier et al., (2016) and Buteler et al., (2022), demonstrating that photo-ID is a reliable tool for inter-annual monitoring. While hawksbill nesting habits are well-supported, leatherback interannual patterns and limited data are less thoroughly tied to literature. The absence of returns is attributed to longer remigration intervals (Bell et al., 2004), but additional studies on detection challenges or migration could deepen the interpretation. Moreover, the presence of Leatherbacks only reported in Salines and Diamant shows a difference in spatial distribution that may reflect a nesting sites selection due to specific preferences, but this would need further investigations to clarify the ecological factors influencing beach selection by this species.

We also demonstrated that photo-ID is an efficient tool to infer differences in nesting behaviour between marine turtles species. Our

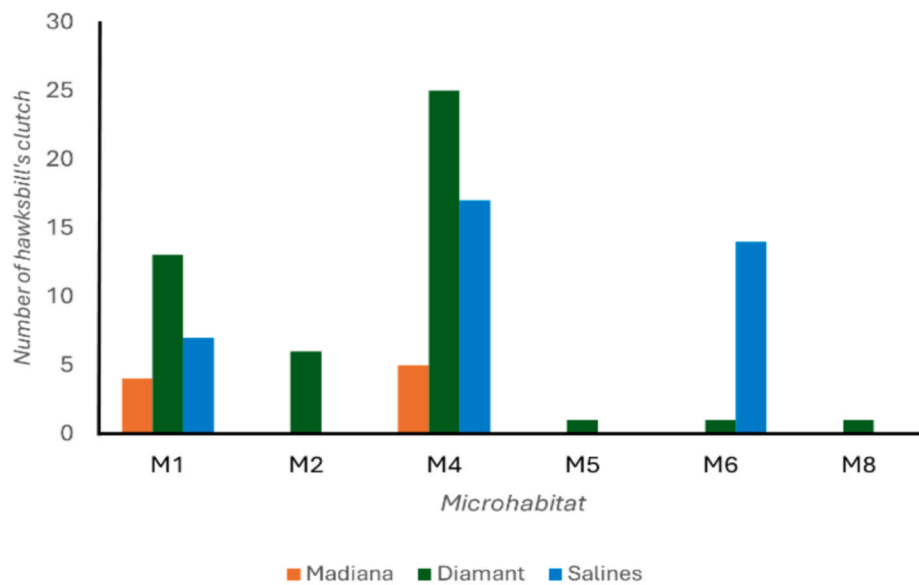


Fig. 7. Number of hawksbill's clutches per beaches depending on the microhabitat. The floral characteristics of the microhabitats determine their classification. Description in Appendix 1.

observations reveal a distinct nesting site preference between the two species studied. Leatherback turtles systematically favours sandy areas close to the water, a behaviour reported by other studies (Whitmore and Dutton, 1985; Kamel and Mrosovsky, 2005). This makes them particularly vulnerable to extreme climatic phenomena. A significant case occurred during our 2024 sampling campaign: Hurricane Beryl struck Martinique on July 1st, at the end of the leatherback turtle nesting period, resulting in the destruction of numerous nests that had not yet emerged. Even in the absence of extreme weather event, nests in these open sandy areas remain at risk of submersion, which can suffocate the embryos (Whitmore and Dutton, 1985). Whitmore and Dutton (1985) suggested that this nesting behaviour is partly due to the physical constraints imposed by the large size of leatherback turtles, which preventing them from accessing more forested areas. Conversely, hawksbill turtles appear to prefer nesting in or near forested areas. Our microhabitats analysis revealed that female hawksbill turtles often select wooded forests with sparse creeping plants and bushes (M4, see Appendix 1). Such vegetation, characterized by a dense canopy, provides essential shading that mitigates the effect of solar radiation on nests temperature (Janzen, 1994; Hernández-Cortés et al., 2018). In fact, we observed that 63 % of hawksbill nests were located in the forest, including 50 % in M4, a finding consistent with previous studies on Caribbean hawksbill (Horrocks and Scott, 1991; Kamel and Mrosovsky, 2005; Serafini et al., 2009). Likewise, Hernández-Cortés et al., (2018) demonstrated that a vegetation cover of 29 %, composed exclusively of trees and similar to M4, resulted in significantly higher hatching (97.1 %) and emergence (96 %) rates, with an average nest temperature of 30.46 °C (± 2.32 °C) at Chenkan Beach, Mexico.

We demonstrated that hawksbill turtles exhibit individual-specific nesting areas, averaging 2 931 m², with a standard deviation of ± 2 695 m². Although there is a significant variability in these size sites, this variability modest compared to overall beach areas—such as Madiana (~8 350 m²), Diamant (~124 580 m²) and Salines (~62 535 m²). Our data further suggest that smaller—and presumably younger—hawksbill turtles tend to utilize more limited nesting areas. This may be attributed to the physiological stress experienced during their initial nesting seasons, potentially constraining their ability to explore broader areas in search of optimal nesting sites (Valverde et al., 1999). The generated polygons represent the spatial extent of each female's nesting activity, with an average nesting area of 2,931 \pm 2,695 m². We investigated

whether turtle size, measured as curved carapace length (CCL), influenced habitat use. However, no statistically significant correlation was detected.

In addition to spatial variability, we observed individual differences in the timing of arrival at the beach (the exact time the turtle lands on shore) for hawksbill turtles. On average, we observed that, a turtle returns to nest 1 h 13 \pm 40 min after its previous recorded water emergence, underscoring both behavioural adaptation and temporal variability that warrant further investigation. For leatherback turtles, our results do not reveal clear individual-specific behaviours in nesting site selection or timing. This may be due to limited observational data concerning the areas used and the timing of arrival. Nevertheless, leatherback turtles are known for their mobile nesting behaviour; previous studies have documented that this species can nest on different beaches, or even on separate islands within the same or across nesting seasons (Dutton et al., 2013; Molfetti et al., 2013; Horrocks et al., 2016). Regarding hawksbill turtles, natal philopatry with nest site fidelity are commonly observed (Bass et al., 1996), exceptions indicate some flexibility in nesting beach selection (Diamond, 1976; Esteban et al., 2015; Iverson et al., 2016). This behavioural plasticity could affect both the apparent remigration interval and regional population counts.

Anthropogenic pressures can also influence nesting behaviours on the studied beaches. We have expanded on this statement (L472–479) to provide greater clarity: A related study conducted on the beaches of Madiana, Diamant, and Salines demonstrated that artificial lighting, human activity, and habitat alterations have a detrimental impact on sea turtle nesting behavior. The findings suggested that in areas with elevated levels of light and noise pollution, as well as frequent human presence, females, particularly leatherbacks, were more likely to abandon nesting attempts or refrain from emerging from the sea. These disturbances were also associated with a significant decline in nesting success and disruption of key nesting phases (Vanleynseele, 2024). Similar findings in other studies (Cayol et al., 2008; Calcagno, 2017; IUCN, 2020) underscore the need for targeted conservation measures, such as reducing light pollution during nesting periods, and implementing revegetation plans based on turtle habitat preferences. In certain instances, local authorities have begun implementing measures in response. For example, in Schoelcher, the municipality now turns off the volleyball court lights—which illuminate the entire beach—around 10:00 p.m. each night, and they remain off unless players are present.

While addressing light pollution is a positive step, broader climate resilience efforts remain crucial. The increasing frequency and severity of extreme weather events, such as hurricanes, pose significant threats to both sea turtle nests and beach stability. To safeguard the long-term viability of nesting habitats, site-specific strategies should be adopted, including nest relocation protocols, post-storm nest evaluations, and erosion control through the use of natural vegetation buffers. Such data-driven strategies are critical for the long-term survival of these vulnerable species.

Finally, our study supports the continued use of photo-ID as a valuable, non-invasive tool for monitoring sea turtle populations. Although software like I3S is highly effective, its performance can sometimes be limited by variations in photo quality angle, and distance (Dunbar et al. 2014; Calmanovici et al., 2018; Steinmetz et al., 2018). Nevertheless, photo-ID remains significantly less intrusive than traditional methods such as handling and capture, which can cause stress, nest abandonment, or delayed nesting (Murphy, 1985; Jacobson and Lopez 1994) and is cost effective compared to tagging methods (Buonantony, 2008).

5. Conclusion

To refine the characterization of Caribbean and Martinique sea turtle populations, expanding the existing photo-ID databases would be highly beneficial. These enhancements should include not only males inhabiting coastal waters but also turtles from neighbouring islands and leatherback turtles that migrate further north in the Atlantic after nesting. Furthermore, it is crucial that these databases be updated annually to maintain accurate records. In conservation efforts, population counts are often based on nighttime monitoring of nesting females (Santos et al., 2021). However, misidentifying remigrant turtles as first-time nesters can lead to significant overestimations of population levels. For instance, our observations indicate that 61 % of the leatherback turtles encountered on the three studied beaches in Martinique were individuals previously photographed during the same season. Additionally, the study also revealed that hawksbill turtles exhibit specific microhabitat preferences, providing valuable insights for habitat restoration and revegetation plans. In Madiana, for example, while the wooded area hosts the highest concentration of nests, its limited size has led to instances where females dig up nests of others. This observation underscores the critical role that habitat quality plays in the preservation of these emblematic species. Ultimately, while our study offers site-specific insights, it contributes to a growing body of evidence supporting the need for coordinated, regional conservation policies that address both nesting beach protection and marine habitat use throughout the turtles' migratory range.

CRedit authorship contribution statement

Jessie-Lee Langel: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Vitoria Calabretta:** Validation, Methodology, Investigation, Conceptualization. **Céline Valin:** Validation, Methodology, Investigation, Formal analysis. **Erwann Fraboulet:** Validation, Funding acquisition, Formal analysis. **Réjean Tremblay:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **El Mahdi Bendif:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis. **Benjamin de Montgolfier:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jnc.2025.127124>.

Data availability

Data will be made available on request.

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