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Photo-id as an alternative to monitor marine turtles in the Gulf of Venezuela

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A R T I C L E   I N F O

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A B S T R A C T

Conservation management programs have used diverse methods to monitor populations of threatened species that vary in effectiveness, duration, and costs; making its implementation a challenge. The present study was carried out to test the use of photo-identification as an economical and efficient alternative for marine turtle monitoring in the Gulf of Venezuela. The implementation of this protocol is possible due to the unique and unrepeatable facial scales pattern of individuals in the marine turtles. We created a database of photo-identifiable profiles available from records of turtles captured, tagged, and released in the Gulf of Venezuela from 2000 to 2017 (n = 118). Likewise, we used two photo-matching software (I^3S Pattern and Nature Pattern Match) to optimize the process of compatibility of individuals and we evaluated their efficiency in comparison with the non-assisted manual method ("by human eye" or "by naked eye"). We found that I^3S Pattern was more effective during the matching process than NPM (90 % and 65 % accuracy respectively), while the manual method was much more accurate than the software. However, the former method is impractical when working with large databases. Our results indicate that I^3S Pattern represents the most efficient software of image matching by reducing the time needed and simplifying the manual "by human eye" analysis. We recommend incorporating more photos in the database in order to verify the effectiveness of both studied software, and regularly to corroborate the results generated by the software assessed on this research using the "human eye" manual method.

1. Introduction

Most marine turtle species are highly moveable and migratory (Hays et al., 2019; Shimada et al., 2020). Due to their current situation and its migratory nature, it is essential to improve conservation efforts and population monitoring (e.g. mark-recapture programs). Therefore, this is considered one of the research priorities by the IUCN Marine Turtle Specialist Group (Hamann et al., 2010; Rees et al., 2016) to estimate demographic values such as survival, stability, and increase or decrease of populations (Plotkin, 2003; Seminoff and Shanker, 2008; Bevan et al., 2016). This information can be really helpful as an early prevention system for possible problems and as a base for marine turtle conservation programs and action measures (Amorocho et al., 2016; Koch et al., 2006; Nichols, 2003), especially in foraging areas such as the Gulf of Venezuela, considering that it is the habitat where most of the marine turtle life cycle occurs, and their globally demonstrated high-fidelity to these areas (Casale et al., 2008; Shimada et al., 2016; Shimada et al., 2020).

The 'capture-mark-recapture' method (CMR) is an effective and popular technique used in many marine turtle monitoring programs (Barrios-Garrido et al., 2020a; Bell et al., 2020; García-Cruz et al., 2015; Whiting et al., 2020). The most common protocol to mark the animals consists in applying monnel, inconel, and/or titanium tags to both front flippers (if possible) that are engraved with sequential numbers. Despite being a method commonly used in programs worldwide, it has some limitations that must be considered; such as tag loss, barnacle, bivalves

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and algae encrustation, advanced corrosion of materials, or incrustation in the turtle's swollen tissue which make it impossible to identify the tag, and consequently, the identification of the individual (Reisser et al., 2008).

As an economic alternative to the traditional tagging method, photo-identification has been used as a reliable method for individual identification in wildlife (de Faria Oshima and de Oliveira Santos, 2016; Reisser et al., 2008; Williams et al., 2017). This method involves taking photos of a predefined standardized region of all animals found during sampling sessions and comparing them with photographs taken on previous occasions to determine their identities (Gatto et al., 2018; Montagna et al., 2023).

In reptiles, genetic and environmental factors during their embryonic development and hatching, generate variations in the morphology of their scales, which results in an exquisite variability in the scale arrangement and coloration patterns of each individual (Brown et al., 2017; Chang et al., 2009). Turtles of the Cheloniidae family present a unique and unrepeatable facial scale pattern unalterable over time, which allows a very clear differentiation between individuals (Carpentier et al., 2016; Reisser et al., 2008). To recognize these patterns, many computer-aided photo-matching algorithms have been developed recently to improve photo-identification studies and match images in databases with thousands of photographs in a more efficient way (Matthé et al., 2017). These methods are not completely automatic and usually, they require user assistance to select the region to be evaluated and to confirm the pairing between a numbers of images selected according to similarity scores.

Within the many software and algorithms used for scale pattern recognition, the Interactive Individual Identification System (I^3S) stands out among all in marine turtle photo-identification studies. Its different packages have been used for identification of marine turtles, including the specialized version 'I^3S Pattern' that offers a specific protocol for marine turtle facial scales recognition (Araujo et al., 2016; Baeza et al., 2015; Calmanovici et al., 2018; Dunbar et al., 2014). Other algorithms such as NaturePatternMatch (NPM), for example, were developed to recognize any pattern-based identity signatures, colour variations, or camouflage in the animal kingdom, transforming those characteristics into invariant points at scales (Long, 2016; Long and Azmi, 2017; Stoddard et al., 2014).

In the Gulf of Venezuela, taking photographic records of the captured turtle's facial scales is part of the data collection RAO protocol (*Red de Aviso Oportuno, its name in Spanish*) for the population monitoring program (Barrios-Garrido and Montiel-Villalobos, 2016). However, the systematization of the database has not been carried out yet. Implementing this technique is crucial in the study area as represents one of the most important areas in the country and southern Caribbean for foraging, residence and development for diverse marine turtle population stocks. Therefore, it is considered essential to increase the conservation efforts and monitoring of their populations.

Our goal is to create a catalog of photographic records of facial profiles and to test the implementation of an identification software (I^3S Pattern and NPM). Thus, standardize the measures and guidelines to use photo-identification as an alternative method to study marine turtles in the Gulf of Venezuela.

2. Materials and methods

Study area: The Maracaibo Lake System is located to the west of Venezuela, is composed of four aquatic ecosystems differentiated by their unique characteristics (Fig. 1). From south to north are: Maracaibo Lake, Maracaibo Strait, El Tablazo Bay, and the Gulf of Venezuela. Its coastal plain extends between 9° and 12° N and between 70° and 72° W approximately.

Data collection: We took into account the capture records of marine turtles throughout the entire area of the Maracaibo Lake System, with special emphasis on the records from the Gulf of Venezuela due to their frequency. All the turtles evaluated are registered in the database of the Working Group on Sea Turtles of the Gulf of Venezuela (GTTM-GV, by its Spanish acronym), an environmental NGO that works for the conservation of the marine turtles and the habitats used by them. These records range from the northern part of La Guajira in the Gulf of Venezuela to the southern part of the Maracaibo Lake.

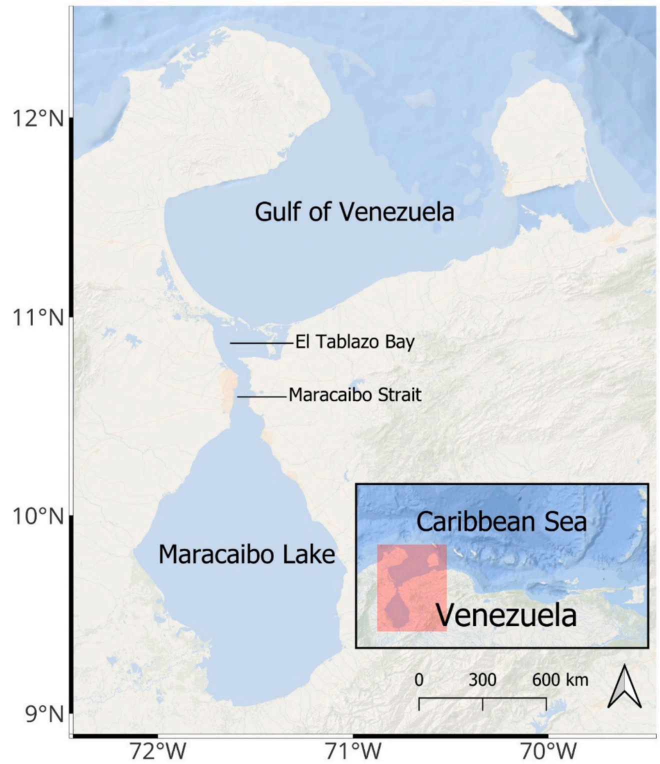

Fig. 1. The Maracaibo Lake System. Detail of the four interconnected aquatic habitat (from south to north): Maracaibo Lake, Maracaibo Strait, El Tablazo Bay, and Gulf of Venezuela. Insert: Geographical location of the Maracaibo Lake System (study area marked in red colour) within Venezuela, showing its relative position within the Caribbean Sea. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We selected photographic data from capture-release events of marine turtles in the Maracaibo Lake System that were part of the GTTM-GV monitoring program between 2000 and 2017. We based our selections of identifiable profiles depending on focus-quality, angle, and visibility of complete facial scale arrangement (postorbital, temporal, subtemporal, tympanic and central scales) (Fig. 2). The selections were organized in individual folders for each turtle (with the possibility of more than one photo of the same profile as long as the selection requirements were met) with their respective assigned name and sorted by year and species. We created a new database for photographic records along with their biometric and physical data obtained during the capture or recapture events: (1) Measures - curved carapace length (CCL) and curved carapace width (CCW) – taken with a flexible tape measure (± 0.2 cm); (2) Weight – measured with a tensile scale of 100 kg capacity; (3) Tag code from the traditional monitoring program protocol; (4) capture, recapture (if applicable), and subsequent release date and location; (5) condition of the animal (alive or dead), plus extra observations on the individual (wounds, illnesses, physical condition); and (6) direct hyperlink to the photographic record selected from the left and/or right profile.

Once the database with the selected photographs was organized, we proceed to analyze the photographs through the computer-aided photo-matching algorithms.

Image processing: Both left and right profiles have a unique and

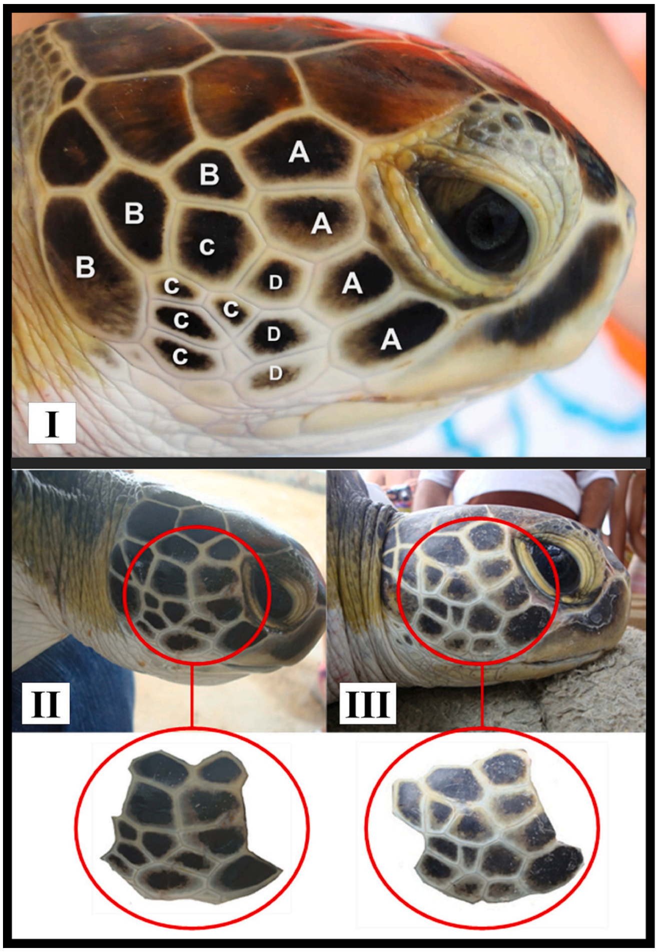

Fig. 2. Photographic records of facial scales patterns. Photo I: A – post-ocular; B – temporal; C – sub-temporal; and D – central of green turtles in the Gulf of Venezuela. Photos II and III as example of mismatching. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different scale pattern (Carpentier et al., 2016), therefore every different photograph of each profile was analyzed separately for each individual. All the selected photographs were processed through two image compatibility software:

(1) Intelligent Individual Identification System (I^{3}S), designed for recognition through patterns and natural marks of various taxa (Van Tienhoven et al., 2007). Specifically, a version created for marine turtle recognition was used, I^{3}S Pattern (den Hartog and Reijns, 2014), previously used in studies of free-ranging animals out and in-water (Araujo et al., 2016; Calmanovici et al., 2018).
(2) NaturePatternMatch (NPM), created for diverse research applications in animal identification, recognition and communication, and can be used to compare natural patterns (Stoddard et al., 2014). Also used for marine turtles recognition through facial scale patterns (Long, 2016; Long and Azmi, 2017).

To evaluate each of the processes of image matching, we *selected* five previously identified individuals (two *Chelonia mydas*, one *Caretta caretta*, one *Lepidochelys olivacea* and one *Eretmochelys imbricata*) whose matching photographs were classified into:

Category 1: images with angle differences;

Category 2: images with obscured features (scale pattern);

Category 3: images under the ideal conditions (den Hartog and Reijns, 2014; Treilibs et al., 2016).

I^{3}S Pattern analysis: In the beginning, I^{3}S requires a database creation and the allocation of the metadata that allows referencing the homologous points in all the photographs. The points assigned were those suggested to reference marine turtle images (den Hartog and Reijns, 2014) (Fig. 3): a) The outer edge of the beak, b) the inner edge of the eye, and c) the edge of the outer scale. Likewise, we assigned the species and orientation of the facial profile (left or right) as metadata to filter the compatibility search results.

The algorithm identifies a number of distinctive features (key points) between the pattern and the coloration of the scales, allowing it to be correctly matched. Then, the software selects the possible compatible images determining the similarity - using the metric distance - of the key points of the evaluated images. Matching photos are ranked according to their similarity score. A lower score indicates greater compatibility between photos, due to the short distance between the points each photograph (Dunbar et al., 2014).

NPM analysis: The analysis protocol for NPM comprises two general procedures executed in different commands: image processing (npm_process) and image matching (npm_match). The former performs all image preparation steps such as image enhancement (in terms of rotation and coloration), manual selection of the region of interest (ROI) of each photograph, and the selection of the distinctive features extraction algorithm (Fig. 4). In this case, we selected the SIFT algorithm to extract key points for each image. Then, we proceed with the image matching protocol, using the extracted features to compare and match an image or a set of images with an existing database.

Manual analysis versus computer-aided analysis: To evaluate the efficiency of the photo-matching methods, we time-controlled the minutes required for both software and manual methods ('by eye') with novice and expert observers and the effectiveness of successfully matching photos. We selected random photographs of ten individuals to be classified as a 'new individual' or as a 'match' when compared to the image catalog provided. Each classification made by observers or by the photo-matching software was categorized as Match-Match (MM) when the evaluated photograph was paired with the correct image, False-Match (FM) when the photograph was mistakenly paired with another individual in the database, New-New (NN) when a photograph incompatible with the database was classified as 'new individual', and False-New (FN) when a photograph was indicated as a new individual

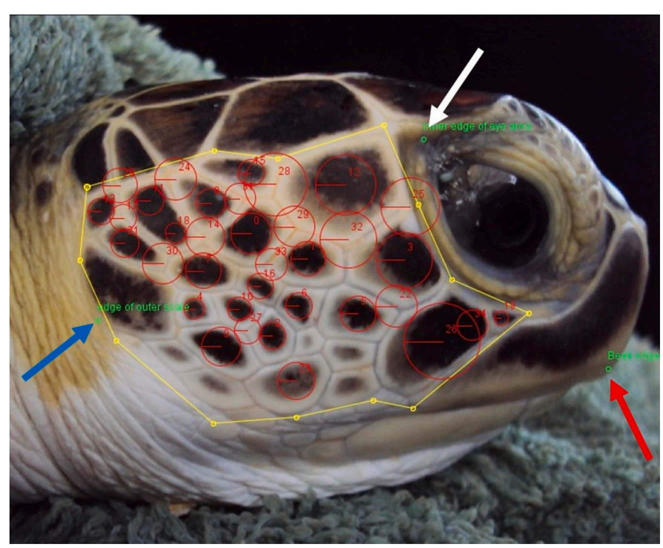

Fig. 3. Analysis protocol and points extraction of the right profile of an individual *C. mydas.* Selection of reference points (red arrow: outer edge of the beak; white arrow: inner edge of the eye; blue arrow: edge of outer scale. The 'region of interest' (yellow lines) and key points were extracted by the software (red circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

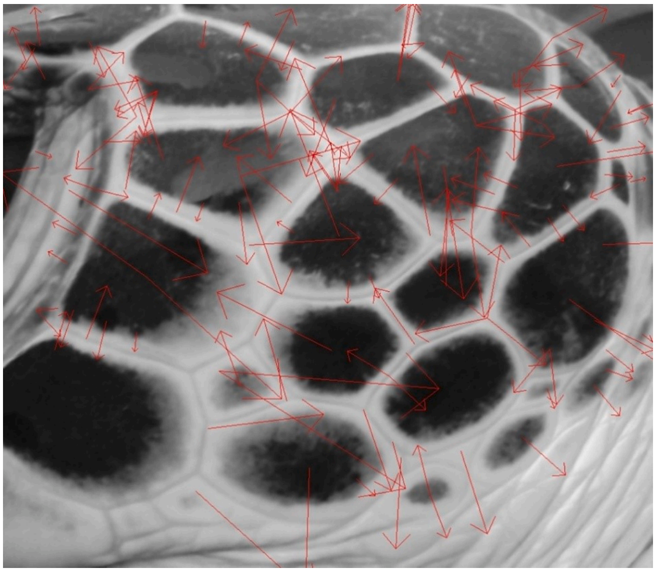

Fig. 4. Illustrative image resulting from the image processing protocol of NPM. ROI of an individual *C. mydas.* The red arrows indicate the key points extracted by the algorithm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

having a matching image in the database (modified from Schofield et al., 2008). We evaluated the efficiency of the methods with the sum of the correct results (MM + NN) and the average time required (modified from Calmanovici et al., 2018).

3. Results

Photo-ID database: We selected 258 digital and printed photographs of identifiable profiles (facial scales). These corresponded to 118 individuals captured from 2000 to 2017 in the Maracaibo Lake System through the marine turtle conservation program of the GTTM-GV. Most of the identifiable records occurred in the period of 2008–2011 (78.81 %, *n* = 93), followed by the period 2012–2017 (16.11 %, *n* = 19), and finally the few photographic records made during the period 2000–2007 (5.08 %, *n* = 6) (Fig. 5).

The majority of the records with images of identifiable profiles were *C. mydas* individuals, constituting 77.96 % (*n* = 92) of the records. Additionally, they constituted 77.5 % of the photographs in the database (*n* = 200). 25.58 % of the photographic records (*n* = 29) belonged to *C. caretta* individuals, 16.10 % (n = 19) to *E. imbricata*, and only 2.54 % to L. *olivacea* (*n* = 3).

Most of the individuals had photographs of both profiles (88.14 %; *n* = 104), while 6.78 % (*n* = 8) had only records of the right profile and 5.08 % (*n* = 6) of the left profile. Only 12.7 % (*n* = 15) individuals had more than one photo of the same profile that met the selection requirements.

The photographic database registered 49.7 % of the individuals captured in the study area (*n* = 118; Ncap+Nnt). Prior to the creation of this catalog, 13.5 % (*n* = 32) of the registered individuals were 'non-identifiable' due to their release without tags and 42.5 % (*n* = 86) were registered with both tag numbers and photographic record. However, 28.6 % of the tagged individuals did not have photos of identifiable profiles (*n* = 73) (Table 1).

Twelve individuals cataloged had recapture (of the living animal) records, these were analyzed through both identification methods (photograph and tag number). 33.33 % (n = 4) of the individuals were correctly identified using both methods, while 50 % (n = 6) could only be identified by the traditional method through tag numbers due to lack of photographic data of the recapture event. However, 16.67 % (*n* = 2) of the individuals were identified for the first time only through photo-identification after being recaptured with a tag loss injury or previously released without them.

I[3]S analysis: The automated processing and feature extraction protocol took approximately 1:03 min/image (SD = 0.01). The software extracted 35 elements (by default) as key points of each image. Those

Table 1
Number of individuals captured and released in the study area (Ncap), individuals with tag and photos (Ntp), individuals with only tag (Nnp), individuals with only photographic record (Nnt).

YEAR	N_{cap}	N_{tp}	N_{np}	N_{nt}
2000	7	1	4	1
2001		1		0
2002–2006	18	1	17	0
2007	2	0	0	2
2008	15	9	4	2
2009	36	5	0	12
2010	77	40	26	6
2011	38	14	15	5
2012	17	5	10	0
2013	14	4	6	3
2014	2	0	0	1
2015	3	0	3	0
2016	8	3	4	0
2017	8	3	5	0
Total	237	86	73	32

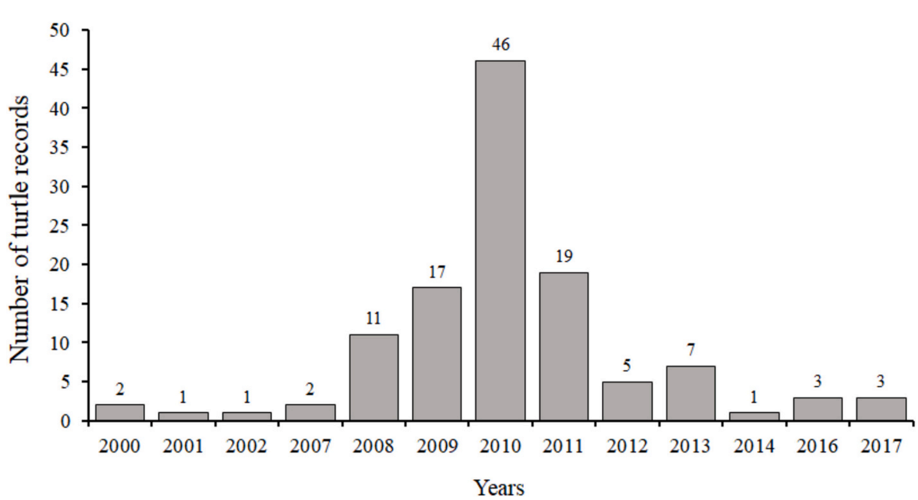

Fig. 5. Number of individuals with photographic records.

points that were outside the ROI were manually eliminated from the selection considering only the points that represent changes in the coloration and the patterns of the post-ocular, tympanic, temporal, subtemporal and central scales.

All photographs used for validation were matched correctly, ranking the appropriate individual in the first place in the classification of possible matching images. However, the compatibility was considered "completely satisfactory" if the similarity score was <10 points. 60 % (n = 3) of the photographs were matched completely satisfactory, while 40 % (*n* = 2) were matched correctly in the first place but with a score > 10 (photographs corresponding to category 1).

All photographic records of recaptures matched the first option suggested by the software as a potential match (top 1) after the database assessment. This indicates that the software accurately identified the correct individual from the database in almost every case. However, only one match (16.66 %) achieved a score greater than 10, which reflects the software's confidence level in the match. Despite this, the pairing for the remaining recaptures was entirely satisfactory, demonstrating the reliability of the software in correctly identifying individuals, even with lower confidence scores. This highlights the effectiveness of the software in facilitating photo-identification for monitoring purposes.

NPM analysis: The NPM processing protocol was performed in batches by sub-directories (species) and took an average time of 0:50 s/photo (*n* = 118, SD = 1.60). The matching process resulted in a ranking list with all the images according to their compatibility score, higher score means higher compatibility. The key points extraction obtained an average of 267.4 characteristics extracted (SD = 498.7) for *C. mydas* individuals and an average of 176.2 characteristics (SD = 242.0) for *E. imbricata*. Likewise, *C. caretta* obtained an average of 61.9 characteristics (SD = 99.1) and L. *olivacea* an average of 96.6 characteristics (SD = 77.2).

The 9.13 % (*n* = 11) of the compatible images positioned in the first place were correctly paired including individuals with more than one photo of the same capture event. Regarding recaptures, only 40 % (*n* = 2) of the images were placed at the top of the list, and 60 % (*n* = 4) of them was incorrectly matched with scores>1.

Manual analysis versus computer-aided analysis: Novice observers obtained 80 % accuracy when selecting compatible (or not compatible) photographs on the first try. The average time taken was 11:23 min/photo (1:47 m-20:00 m) comparing with a catalog of 93 possible compatible individuals. For each round, the novice observer reduced the matching time and improved the ability to match the selected photographs correctly. Expert observers obtained 100 % accuracy every time with an average time of 4:16 min/photo (7:10 m-0:59 m).

On the other hand, I^3S obtained an effectiveness of 95 %, and an average time of 0:03 s/photo (0: 06 s - 0: 02 s) when compared to a database of 119 individuals and 256 images. However, 5 % of individuals (n = 1) were incorrectly classified as incompatible.

The effectiveness of NPM was 60 %. However, 50 % (*n* = 5) of the correct results were incompatible with the database (similarity scores <1) and only 10 % (n = 1) correctly matched. Therefore, 30 % (n = 4) of the samples to be evaluated were incorrectly classified as false incompatible and 10 % (n = 1) as a false match (similarity score of an incorrect photograph in position # 1 of the possible compatible).

4. Discussion

Photo-identification has been used as monitoring method for various taxa in last decades (Beck et al., 2014, Koivuniemi et al., 2016, Schofield et al., 2008, Montagna et al., 2023) and it has gained popularity in marine turtle monitoring programs also including citizen science sfforts (Hall and Mcneill, 2013; Dunbar et al., 2014; Chew et al., 2015; Su et al., 2015; Araujo et al., 2016; Long and Azmi, 2017; Calmanovici et al., 2018). However, the implementation of photo-identification has not been carried out in conservation programs of marine turtles in Venezuela under standardised protocols; therefore, this photographic catalog is a useful tool that, attached with their biometric and physical information, it may be used as an alternative method at national level to identify individuals and in future research of population models, residence parameters, growth rate, population size, among others (Hall and Mcneill, 2013, Araujo et al., 2016; Long and Azmi, 2017; Mancini et al., 2015).

The increase in conservation efforts and the inclusion of the photographic record in the data capture protocol in the marine turtle capture events in the Maracaibo Lake System as of 2008 (Barrios-Garrido and Montiel-Villalobos, 2016) resulted in a considerable increase in records during the period 2008–2011. The standardized application of photo-identification through citizen science could expand the data and become a useful and economical tool to extend the knowledge of marine turtle species (Araujo et al., 2016; Montagna et al., 2023), with special emphasis in the area of study due to the presence of biological sciences students (biology, veterinary science, zootechnics, and related), as well as local tourists and people from the community.

In the Maracaibo Lake System and especially in the Gulf of Venezuela, the abundance of *C. mydas* much higher than the other species (Barrios-Garrido et al., 2020b; Rojas-Cañizales et al., 2020), for this very reason, the large number of photographic records of the species. Likewise, the records of the rest of the species concur with the abundance described by Rojas-Cañizales et al. 2020 with a low percentage of *C. caretta* (5.4 %) and a much smaller percentage of *E. imbricata* (1.8 %), and the one described previously for the species L. *olivacea* with barely a record of 0.5 %. This abundance pattern coincides with the one obtained by Barrios-Garrido et al. (2020b) and Rojas-Cañizales et al. (2020). Although *D. coriacea* is present in the Gulf of Venezuela, its records have been only by stranding and/or skeletal remains (Barrios-Garrido and Montiel-Villalobos, 2016, Rojas-Cañizales et al., 2021), therefore, it was not added in this study. Besides, this species lacks facial scales and its photo-identification has been made only through the pink spot in the dorsal area of its head (De Zeeuw et al., 2010).

Due to the low similarity between the arrangement of the scale patterns on both facial sides (Su et al., 2015). Several authors have highlighted the importance of obtaining photographs of both profiles to increase the possibility of correct identification in cases where only one side of the new turtle can be photographed. This avoids overestimating (or underestimating) the number of individuals in abundance studies, population models and monitoring (Chew et al., 2015; Long and Azmi, 2017; Su et al., 2015).

Tag loss has been previously estimated for individuals with double or single tag (Casale et al., 2017; Hyun et al., 2012; Limpus, 1992; Rivalan et al., 2005); however, these studies do not take into account cases in which double tagging cannot be performed (due to injuries or limb loss) or capture events where it is impossible to apply tag to the animal due to difficulty in logistics or lack of material, as it occurred during a period of time in the Gulf of Venezuela. The photo-identification represents in these cases the only simple and low-cost method for future identification (Carter et al., 2014; Reisser et al., 2008).

The results of recapture individual identification through photographs are similar to those obtained by Reisser et al. (2008) where the use of facial profiles was effective when individuals included both methods (photograph and plate number) or only had a photographic record. Also, as in this study, the only turtles not identified by photo-identification corresponded to individuals that did not have a photographic record of the capture or recapture event.

Photo-matching methods: We obtained a remarkable performance with the I^3S software. I^3S packages ('Classic' and 'Pattern') have been previously validated for marine turtle photo-identification (Araujo et al., 2016; Baeza et al., 2015; Calmanovici et al., 2018; Dunbar et al., 2014). We agree with other authors on the importance of quality and angle of the image to improve matching results. The standardization of photos in the database can mean an increase in the matching success (den Hartog and Reijns, 2014, Long and Azmi, 2017).

Although the software recommends a standardization in the taking of images (den Hartog and Reijns, 2014), we were dealing with historical records and images from different sources so this possibility was lost. However, the results with I^3S Pattern were favorable regardless of the different conditions in the images (category 1, 2, 3 and 4). These categories were also evaluated with this software by Treilibs et al. (2016) with a species of Australian reptile (lance), *Liopholis slateri*, and obtained less satisfactory results (67 % of correct pairings) possibly because the software was not suitable for their evaluated species.

The results were more favorable than those obtained by Calmanovici et al., 2018, when evaluating the matching accuracy of I^3S Pattern with photographs of *C. mydas* and *E. imbricata* obtained through citizen science programs (92 % accuracy) and much more effective than other I^3S packages such as the Classic (82 % accuracy) (Dunbar et al., 2014). Those errors obtained by Calmanovici et al., 2018 were mostly due to factors of photo quality and distortions from photos taken underwater. I^3S Pattern was 97 % accurate with the use of photographs out of the water and 100 % accurate with the photographic recapture photographs analyzed in the present investigation.

I^3S tends to match false positives in databases with a small number of individuals (Calmanovici et al., 2018). The performance of automated identification systems can be improved by including a greater number of photographs in the database and multiple images of the same individual (Carter et al., 2014). Therefore, the results obtained in the evaluation of *C. caretta* and L. *olivacea* images could be affected by the low reference set (photographic database) with which it was evaluated.

Previous studies using NPM to identify marine turtles have evaluated only photographic records of facial scales patterns of *C. mydas* and *E. imbricata* or the unique pink spot of *D. coriacea* (Long, 2016; Long and Azmi, 2017; De Zeeuw et al., 2010). These mentioned species have a high contrast in the pigmentation of the facial scales, which allows the extraction of a greater number of characteristics as key points of each image. This is because NPM uses the SIFT algorithm (Stoddard et al., 2014) which detects those regions in which significant gradient differences (minimum and maximum points) occur on both sides of a given point (Lowe, 1999). The low contrast in the pigmentation the *C. caretta* and *L. olivacea* scales resulted in lower number of extractable characteristics compared to those obtained with *C. mydas* and *E. imbricata* individuals, and therefore a low possibility of obtaining the same key points in different photographs of those species using this software, which leads to the reduction of the match success.

The observed underperformance of NPM compared to I^3S in this study may be attributed to several factors. First, NPM's reliance on point-matching algorithms may be less effective in distinguishing the intricate and often variable patterns of turtle facial scales, particularly under inconsistent lighting conditions or varying photographic angles. Second, the software's sensitivity to image quality and calibration may limit its utility when working with diverse photographic datasets. In contrast, I^3S's algorithm, which emphasizes pattern recognition and edge detection, appears to be more robust under these conditions. Future studies should explore these differences further by testing the software with larger, more diverse datasets to identify specific limitations and areas for improvement.

The results of manual matching methods ("naked eye" or using scale classification keys) have been significantly more effective than computer-aided methods (Calmanovici et al., 2018; Schofield et al., 2008). Expertise improves the accuracy in the image matching (Schofield et al., 2008), therefore trained observers can improve the efficiency of the method, as it was demonstrated in this study with the high effectiveness of the expert observers (100 %) and the reduction of the time and increase in the accuracy of novice observers for each round made. The manual comparison of images does not require standardization of the photograph (angles or resolution) and can be used in a wide range of photographs as long as all the facial scales are visible (Jean et al., 2010).

However, manual matching is feasible in a database with a low number of individuals (less than 20) otherwise recognition becomes much more laborious and less efficient. This could lead observers to be prone to subjective errors when working with a large catalog of images, and thus, loss of precision.

The high effectiveness obtained in the results of the images matching with I^3S Pattern (95 % accuracy) in a significantly shorter time than the "manual" matching method coincides with Calmanovici et al., 2018 results, whose identification through the software was four times faster than the manual method. On the contrary, as it was discussed previously, NPM was less suitable for the records of the database used in the present investigation. Long and Azmi, 2017, describe that the low number of individuals and the few extractable characteristics of certain species decrease the matching success of the software.

I^3S Pattern offers a user-friendly platform and a high performance to the different evaluations in its application with marine turtles. Similarly, all computerized-aided programs follow the "garbage in, garbage out" principle which implies that every analysis requires great human work for its effectiveness. Therefore, the opportunity offered by I^3S reducing the working time with long databases in conjunction with the requirement of "manual" confirmation in the last step of the matching process, makes this a fully functional tool to identify marine turtles at individual level.

Management and conservation implications: Photo-identification offers an opportunity for the inclusion of citizen science, and it is an open door to initiate programs to train volunteer staff in the communities to collect data and photographs (Montagna et al., 2023). This can be really helpful to reduce logistical field problems and lack of material or low budgets. It also can be easily adapted to the conservation strategies currently used in Venezuela, such as RAO initiative (Vernet and Gómez, 2007).

Limitations and future directions: This study represents a preliminary assessment of the use of photo-identification methods for monitoring marine turtles in the Gulf of Venezuela. While our findings demonstrate the effectiveness of both manual and computer-aided techniques, the relatively small size of our database limits the generalizability of the results. Based on statistical sampling principles and previous studies in similar contexts, we recommend a database size of at least 1000 individuals to ensure a more rigorous evaluation of software performance.

The application and standardization of these photographic catalogs in the conservation programs of marine turtles in Venezuela accompanied by their biometric and physical data can result in a national database that could be used to expand the knowledge on the behavior and status of marine turtles in the Venezuelan coast. This protocol is appropriate for use in regions where marine turtle conservation and monitoring programs are in their early stages of development.

5. Conclusions

The use of photographic records of facial scales patterns (post-ocular, temporal, sub-temporal and central) is effective to identify marine turtle individuals and it represents a simple and inexpensive alternative tool to reduce the problems related to the traditional tag method (flipper tag loss, logistical problems, lack of material, among others) in the follow-up studies of marine turtles. The creation of a catalog with facial profiles images facilitates the process of recognizing individuals and their implementation can be easily replicated.

The matching effectiveness through the manual method is much greater than computer-aided photo-matching software. However, its efficiency is inversely proportional to the number of individuals in the database, so the use of software or algorithms allows the reduction of the time required for image matching processes and can be complemented with the manual method to increase the accuracy in the results.

It is recommended to carry out more studies to validate the use of photo-matching algorithms in species such as *C. caretta* and *L. olivacea* due to the low dissimilarity between the pigmentation of the facial scales patterns. The optimization and standardization of the images added to the database and the increase in the number of images per individual will increase the compatibility success of the recognition software.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to rephrase some sentences for conciseness and readability. After using this tool the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

María Gabriela Sandoval: Visualization, Methodology, Investigation, Formal analysis, Data curation. **Héctor Barrios-Garrido:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, 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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Data availability

Data will be made available on request.

References

Amorocho, D., Leslie, A., Fish, M., Sanjurjo, E., Amoros, S., Avila, I.C., Toral, V., Gerhartz, J.L., Bilo, K., Guerrero, P., Zapata, L.A., Douthwaite, K., 2016. Marine Turtle Action Plan. WWF Latin America and the Caribbean: 2015–2020. WWF-Colombia, Cali, Colombia, 122 pp.

Araujo, G., Montgomery, J., Pahang, K., Labaja, J., Murray, R., Ponzo, A., 2016. Using minimally invasive techniques to determine green sea turtle *Chelonia mydas* life-history parameters. J. Exp. Mar. Biol. Ecol. 483, 25–30.

Baeza, L., Wright, M.K., Dunbar, S.G., Hayes, C., Wright, M.K., Salinas, L., Dunbar, S.G., 2015. Photo Recognition for In-water Identification of Hawksbills in a Marine Protected Area of Honduras. Science and Mathematics Faculty Presentations, 246.

Barrios-Garrido, H.A., Montiel-Villalobos, M.G., 2016. Strandings of Leatherback turtles (*Dermochelys coriacea*) along the western and southern coast of the Gulf of Venezuela. Herpetol. Conserv. Biol. 11 (1), 244–252.

Barrios-Garrido, H.A., Becker, P., Bjorndal, K.A., Bolten, A.B., Diez, C., Espinoza-Rodríguez, N., Fastigi, M., Gray, J., Harrison, E., Hart, K.A., Meylan, A., Meylan, P., Montiel-Villalobos, M.G., Morales, F., Nava, M., Palmar, J., Petit-Rodriguez, M.J., Richardson, P., Rodríguez-Clark, K.M., Rojas-Cañizales, D., Sandoval, M.G., Valverde, R.A., Van Dam, R., Walker, J.T., Wildermann, N., Hamann, M., 2020a. Sources and movements of marine turtles in the Gulf of Venezuela: regional and local assessments. Reg. Stud. Mar. Sci. 36, 101318.

Barrios-Garrido, H.A., Montiel-Villalobos, M.G., Palmar, J., Rodríguez-Clark, K.M., 2020b. Wayuú capture of green turtles, *Chelonia mydas*, in the Gulf of Venezuela: a major Caribbean artisanal turtle fishery. Ocean Coast. Manag. 188, 105123.

Beck, S., Foote, A.D., Koetter, S., Harries, O., Mandleberg, L., Stevick, P.T., et al., 2014. Using opportunistic photo-identifications to detect a population decline of killer whales (Orcinus orca) in British and Irish waters. J. Mar. Biol. Assoc. U. K. 94 (6), 1327–1333. https://doi.org/10.1017/S0025315413001124.

Bell, I.P., Meager, J.J., Eguchi, T., Dobbs, K.A., Miller, J.D., Madden Hof, C.A., 2020. Twenty-eight years of decline: nesting population demographics and trajectory of the north-East Queensland endangered hawksbill turtle (*Eretmochelys imbricata*). Biol. Conserv. 241, 108376.

Bevan, E., Wibbels, T., Najera, B., Sarti, L., Martinez, F., Cuevas, J., Gallaway, B., Pena, L., Burchfield, P., 2016. Estimating the historic size and current status of the Kemp's ridley sea turtle (*Lepidochelys kempii*) population. Ecosphere 7, 1–15.

Brown, G., Madsen, T., Dubey, S., Shine, R., 2017. The causes and ecological correlates of head scale asymmetry and fragmentation in a tropical snake. Sci. Rep. 7 (1).

Calmanovici, B., Waayers, D., Reisser, J., Clifton, J., Proietti, M., 2018. I^{3}S pattern as a mark-recapture tool to identify captured and free-swimming sea turtles: an assessment. Mar. Ecol. Prog. Ser. 589, 263–268.

Carpentier, A.S., Jean, C., Barret, M., Chassagneux, A., Ciccione, S., 2016. Stability of facial scale patterns on green sea turtles *Chelonia mydas* over time: a validation for the use of a photo-identification method. J. Exp. Mar. Biol. Ecol. 476, 15–21.

Carter, S.J., Bell, I.P., Miller, J.J., Gash, P.P., 2014. Automated marine turtle photograph identification using artificial neural networks, with application to green turtles. J. Exp. Mar. Biol. Ecol. 452, 105–110. https://doi.org/10.1016/j.jembe.2013.12.010.

Casale, P., Abbate, G., Freggi, D., Conte, N., Oliverio, M., Argano, R., 2008. Foraging ecology of loggerhead sea turtles *Caretta caretta* in the Central Mediterranean Sea: evidence for a relaxed life history model. Mar. Ecol. Prog. Ser. 372, 265–276.

Casale, P., Freggi, D., Salvemini, P., 2017. Tag loss is a minor limiting factor in sea turtle tagging programs relying on distant tag returns: the case of Mediterranean loggerhead sea turtles. Eur. J. Wildl. Res. 63 (1), 12. https://doi.org/10.1007/s10344-016-1059-0.

Chang, C., Wu, P., Baker, R., Maini, P., Alibardi, L., Chuong, C., 2009. Reptile scale paradigm: Evo-Devo, pattern formation and regeneration. Int. J. Dev. Biol. 53 (5), 813–826.

Chew, V.Y.C., Liew, H.C., Joseph, J., 2015. Photographic identification of green turtles (Chelonia mydas) at Redang Island, Malaysia. Mar. Turtle Newsl. 146, 1–6.

de Faria Oshima, J.E., de Oliveira Santos, M.C., 2016. Guiana dolphin home range analysis based on 11 years of photo-identification research in a tropical estuary. J. Mammal. 97, 599–610.

De Zeeuw, P.M., Pauwels, E.J., Ranguelova, E.B., Buonantony, D.M., Eckert, S.A., 2010. In: Computer assisted photo identification of Dermochelys coriacea. Springer, Berlin, pp. 165–172.

den Hartog, J., Reijns, R., 2014. I3 S Pattern manual — Inter - active Individual Identification System. www.reijns.com/i3s/download/I3S%20Pattern.pdf.

Dunbar, S., Ito, H., Bahjri, K., Dehom, S., Salinas, L., 2014. Recognition of juvenile hawksbills *Eretmochelys imbricata* through face scale digitization and automated searching. Endanger. Species Res. 26, 137–146.

García-Cruz, M.A., Lampo, M., Peñaloza, C.L., Kendall, W.L., Solé, G., Rodríguez-Clark, K.M., 2015. Population trends and survival of nesting green sea turtles *Chelonia mydas* on Aves Island, Venezuela. Endanger. Species Res. 29, 103–116.

Gatto, C.R., Rotger, A., Robinson, N.J., Tomillo, P.S., 2018. A novel method for photo-identification of sea turtles using scale patterns on the front flippers. J. Exp. Mar. Biol. Ecol. 506, 18–24.

Hall, A.G., Mcneill, J.B., 2013. Inferring sea turtle recapture rates using photographic identification. Herpetol. Rev. 44, 561–569.

Hamann, M., Godfrey, M., Seminoff, J., Arthur, K., Barata, P., Bjorndal, K., Bolten, A., Broderick, A., Campbell, L., Carreras, C., Casale, P., Chaloupka, M., Chan, S.K.F., Coyne, M.S., Crowder, L.B., Diez, C.E., Dutton, P., Epperly, S.P., FitzSimmons, N.N., Formia, A., Girondot, M., Hays, G.C., Cheng, I.J., Kaska, Y., Lewison, R., Mortimer, J. A., Nichols, W.J., Reina, R.D., Shanker, K., Spotila, J.R., Tomás, J., Wallace, B.P., Work, T.M., Zbinden, J., Godley, B.J., 2010. Global research priorities for sea turtles: informing management and conservation in the 21st century. Endanger. Species Res. 11, 245–269.

Hays, G.C., Bailey, H., Bograd, S.J., Bowen, W.D., Campagna, C., Carmichael, R.H., Casale, P., Chiaradia, A., Costa, D.P., Cuevas, E., Nico de Bruyn, P.J., Dias, M.P., Duarte, C.M., Dunn, D.C., Dutton, P.H., Esteban, N., Friedlaender, A., Goetz, K.T., Godley, B.J., Halpin, P.N., Hamann, M., Hammerschlag, N., Harcourt, R., Harrison, A.-L., Hazen, E.L., Heupel, M.R., Hoyt, E., Humphries, N.E., Kot, C.Y., Lea, J.S.E., Marsh, H., Maxwell, S.M., McMahon, C.R., Notarbartolo di Sciara, G., Palacios, D.M., Phillips, R.A., Righton, D., Schofield, G., Seminoff, J.A., Simpfendorfer, C.A., Sims, D.W., Takahashi, A., Tetley, M.J., Thums, M., Trathan, P. N., Villegas-Amtmann, S., Wells, R.S., Whiting, S.D., Wildermann, N.E., Sequeira, A. M.M., 2019. Translating marine animal tracking data into conservation policy and management. Trends Ecol. Evol. 1–16.

Hyun, S.Y., Reynolds, J.H., Galbreath, P.F., 2012. Accounting for tag loss and its uncertainty in a mark–recapture study with a mixture of single and double tags. Trans. Am. Fish. Soc. 141 (1), 11–25. https://doi.org/10.1080/00028487.2011.639263.

Jean, C.S., Ciccione, S., Talma, E., Ballorain, K., Bourjea, J., 2010. Photo-identification method for green and hawksbill turtles and first results from Reunion. Indian Ocean Turtle Newsletter 11, 8–13.
Koch, V., Nichols, W.J., Peckham, H., de la Toba, V., 2006. Estimates of sea turtle mortality from poaching and bycatch in Bahia Magdalena, Baja California Sur, Mexico. Biol. Conserv. 128, 327–334.
Koivuniemi, M., Auttila, M., Niemi, M., Levänen, R., Kunnasranta, M., 2016. Photo-ID as a tool for studying and monitoring the endangered Saimaa ringed seal. Endanger. Species Res. 30, 29–36. https://doi.org/10.3354/esr00723.
Limpus, C.J., 1992. Estimation of tag loss in marine turtle research. Wildl. Res. 19 (4), 457–469. https://doi.org/10.1071/WR9920457.
Long, S., 2016. Identification of a dead green turtle (*Chelonia mydas*) using photographic identification. Mar. Biodivers. Rec. 150 (2016), 4.
Long, S., Azmi, N.A., 2017. Using photographic identification to monitor sea turtle populations at Perhentian Islands Marine Park I n. Herpetol. Conserv. Biol. 12 (March), 350–366.
Lowe, D.G., 1999. Object recognition from local scale-invariant features. Proc. Seventh IEEE Int. Conf. Comput. Vis. 2, 1150–1157. https://doi.org/10.1109/ICCV.1999.790410.
Mancini, A., Elsadek, I., Madon, B., 2015. When simple is better: comparing two sampling methods to estimate green turtles abundance at coastal feeding grounds. J. Exp. Mar. Bio. Ecol. 465, 113–120. https://doi.org/10.1016/j.jembe.2015.01.004.
Matthé, M., Sannolo, M., Winiarski, K., Spitzen-van der Sluijs, A., Goedbloed, D., Steinfartz, S., Stachow, U., 2017. Comparison of photo-matching algorithms commonly used for photographic capture–recapture studies. Ecol. Evol. 7, 5861–5872.
Montagna, M., Alatawi, A., Algohane, A., Alturki, S., Barrios-Garrido, H., Mancini, A., Al Mansi, A., Ramalho, R., Rabia Taher, A., Al Zahrani, A., Zamencka, M., Pilcher, N., 2023. Combined photo identification and flipper tagging of green turtles identify connections between Egyptian Red Sea feeding areas and a key nesting area in Saudi Arabia. Indian Ocean Turtle Newslett. 38, 2–7.
Nichols, W.J., 2003. Biology and Conservation of Sea Turtles in Baja California, Mexico. Faculty of the School of Renewable Natural Resources. Vol. Doctor of Philosophy. Univeristy of Arizona, p. 474.
Plotkin, P., 2003. Adult migrations and habitat use. In: The Biology of Sea Turtles, 2, pp. 225–241.
Rees, A., Alfaro-Shigueto, J., Barata, P., Bjorndal, K., Bolten, A., Bourjea, J., Broderick, A., Campbell, L., Cardona, L., Carreras, C., Casale, P., Ceriani, S., Dutton, P., Eguchi, T., Formia, A., Fuentes, M.M., Fuller, W., Girondot, M., Godfrey, M.H., Hamann, M., Hart, K., Hays, G.C., Hochscheid, S., Kaska, Y., Jensen, M., Mangel, J.C., Mortimer, J.A., Naro-Maciel, E., Ng, C., Nichols, W.J., Phillott, A., Reina, R.D., Revuelta, O., Schofield, G., Seminoff, J.A., Shanker, K., Tomas, J., van de Merwe, J., Van Houtan, K.S., Vander Zanden, H., Wallace, B.P., Wedemeyer-Strombel, K.R., Work, T.M., Godley, B.J., 2016. Are we working towards global research priorities for management and conservation of sea turtles? Endanger. Species Res. 31, 337–382.
Reisser, J., Proietti, M., Kinas, P., Sazima, I., 2008. Photographic identification of sea turtles: method description and validation, with an estimation of tag loss. Endanger. Species Res. 5, 73–82.
Rivalan, P., Godfrey, M.H., Prévot-Julliard, A.C., Girondot, M., 2005. Maximum likelihood estimates of tag loss in leatherback sea turtles. J. Wildl. Manage. 69 (2), 540–548. https://doi.org/10.2193/0022-541X(2005)069[0540:MLEOTL]2.0.CO;2.
Rojas-Cañizales, D., Espinoza-Rodríguez, N., Petit-Rodríguez, M.J., Palmar, J., Mejías-Balsalobre, C., Wildermann, N., et al., 2020. Marine turtle mortality in a southern Caribbean artisanal fishery: a threat for immature green turtles. Reg. Stud. Mar. Sci. 38, 101380.doi. https://doi.org/10.1016/j.rsma.2020.101380.
Rojas-Cañizales, D., Espinoza-Rodríguez, N., Rodríguez, M.A., Palmar, J., Montiel-Villalobos, M.G., Wildermann, N.E., Barrios-Garrido, H., 2021. Leatherback turtles (*Dermochelys coriacea*) in the Gulf of Venezuela: an updated stranding assessment 2001-2014. Mar. Fish. Sci. (MAFIS) 34 (1), 113–119.
Schofield, G., Katselidis, K.A., Dimopoulos, P., Pantis, J.D., 2008. Investigating the viability of photo-identification as an objective tool to study endangered sea turtle populations. J. Exp. Mar. Bio. Ecol. 360 (2), 103–108. https://doi.org/10.1016/j.jembe.2008.04.005.
Seminoff, J.A., Shanker, K., 2008. Marine turtles and IUCN red listing: a review of the process, the pitfalls, and novel assessment approaches. J. Exp. Mar. Biol. Ecol. 356, 52–68.
Shimada, T., Limpus, C., Jones, R., Hazel, J., Groom, R., Hamann, M., 2016. Sea turtles return home after intentional displacement from coastal foraging areas. Mar. Biol. 163, 1–14.
Shimada, T., Limpus, C.J., Hamann, M., Bell, I., Esteban, N., Groom, R., Hays, G.C., 2020. Fidelity to foraging sites after long migrations. J. Anim. Ecol. 89, 1008–1016.
Stoddard, M.C., Kilner, R.M., Town, C., 2014. Pattern recognition algorithm reveals how birds evolve individual egg pattern signatures. Nat. Commun. 5 (1), 4117. https://doi.org/10.1038/ncomms5117.
Su, C.M., Huang, C.T., Cheng, I.J., 2015. Applying a fast, effective and reliable photographic identification system for green turtles in the waters near Luichiu Island, Taiwan. J. Exp. Mar. Bio. Ecol. 467, 115–120. https://doi.org/10.1016/j.jembe.2015.03.003.
Treilibs, C.E., Pavey, C.R., Hutchinson, M.N., Bull, C.M., 2016. Photographic identification of individuals of a free-ranging, small terrestrial vertebrate. Ecol. Evol. 6 (3), 800–809. https://doi.org/10.1002/ece3.1883.
Van Tienhoven, A.M., Den Hartog, J.E., Reijns, R.A., Peddemors, V.M., 2007. A computer-aided program for pattern-matching of natural marks on the spotted raggedtooth shark Carcharias taurus.J. Appl. Ecol. 44 (2), 273–280. https://doi.org/10.1111/j.1365-2664.2006.01273.x.
Vernet, P.D., Gómez, Á.J., 2007. Red de aviso oportuno: estrategia para la conservación de las tortugas marinas en la Isla de Margarita, Venezuela. Memoria de la Fundación La Salle de Ciencias Naturales 167, 101–110.
Whiting, A.U., Chaloupka, M., Limpus, C.J., 2020. Sampling nesting sea turtles: impact of survey error on trend detection. Mar. Ecol. Prog. Ser. 634, 213–223.
Williams, J.L., Pierce, S.J., Rohner, C.A., Fuentes, M.M.P.B., Hamann, M., 2017. Spatial distribution and residency of green and Loggerhead Sea turtles using coastal reef habitats in southern Mozambique. Front. Mar. Sci. 3, 288.