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Nesting activity and reproductive output of green turtles in Similajau National Park, Bintulu, Sarawak

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Introduction: Green turtles (*Chelonia mydas*) are ecologically important marine megafauna, yet reproductive information from small and understudied nesting sites in Sarawak remains limited. This study provides descriptive baseline characterization of green turtle nesting activity and reproductive outcomes in Similajau National Park (SNP), Sarawak, from 2015–2017 and 2022–2024 using historical nesting and hatchery records.

Methods: Nest numbers, clutch size, hatching success, apparent incubation duration, and embryo mortality across developmental stages were analyzed using descriptive statistics to evaluate nesting activity and reproductive outcomes.

Results: Nesting activity in SNP was low and inconsistent throughout the study period, with a mean annual nesting number of 3.33 nests, whereas the mean hatching success rate from the study period was 45.47%. In 2024, four nests were successfully relocated, with clutch sizes ranging from 119 to 137 eggs (mean = 129.75 ± 7.72) and apparent incubation durations ranging from 54 to 62 days (mean = 58.5 ± 3.70). Hatching success in 2024 averaged 41.8% (± 26.8), showing substantial variation among nests. Predation, inundation, and delayed nest detection were observed as key challenges affecting nest survival in SNP.

Discussion: This study emphasizes the importance of continued long-term monitoring, habitat protection, and improved nest management strategies. The findings provide baseline reproductive data for this understudied nesting site and may support future conservation planning and targeted management interventions in SNP.

KEYWORDS

green turtle, nesting activity, reproductive output, Sarawak, Similajau National Park

1 Introduction

Sea turtles are keystone species, playing an ecologically vital role in maintaining the health of marine ecosystems. They function as hunters, competitors, pathogen carriers, hosts, prey, and sometimes even the apex predator (Fukumori et al., 2016; Cáceres-Farias et al., 2022; Rubini et al., 2023). In particular, adult green turtles (*Chelonia mydas*) graze on seagrasses, thus maintaining healthy seagrass meadows (Lal et al., 2010). There are seven species of sea turtles, namely green turtles (*Chelonia mydas*), hawksbill turtles (*Eretmochelys imbricata*), loggerhead turtles (*Caretta caretta*), flatback turtles (*Natator depressa*), Olive

ridley turtles (*Lepidochelys olivacea*), Kemp's ridley turtles (*Lepidochelys kempii*) and leatherback turtles (*Dermochelys coriacea*), the largest extant sea turtle species (Chan, 2006; Thomson et al., 2021; Davenport, 2024).

While sea turtles in general are comparatively well-studied globally, conservation management of specific rookeries may be lacking due to insufficient crucial information regarding the reproductive status of individual populations (Hamann et al., 2010). Understanding the reproductive output of a nesting population is key to understanding the suitability of an incubation system and the general population health, useful in informing conservation efforts (Miller, 1999). Although the conservation status of green turtles has shifted to Least Concern globally due to population recovery driven by long-term conservation, uneven rookery status across regions and persistent local threats mean continued research and management remain necessary (Rguez-Baron et al., 2026).

Malaysia is one of the important nesting regions for five out of the seven species: green turtles, locally named “*penyu agar/hijau*”; hawksbill turtles, “*penyu karah/sisik*”; Olive Ridleys or “*penyu lipas*”; leatherbacks or “*penyu belimbing*”; and loggerhead turtles (Leh, 1985; Chan, 2006; PERHILITAN, 2010; Jolis et al., 2015; Fadli et al., 2023). The green turtle is the most widely distributed species in Malaysia, with nesting areas recorded across Sabah, Sarawak, Terengganu, Perak, Pahang and Johor and annual nest counts reaching 15,000 in Sabah Turtle Islands, Malaysia and 700 to 1500 nests in Redang Island (Najwa-Sawawi et al., 2021; Katni et al., 2022; Fadli et al., 2023; Jolis et al., 2023). The loggerhead turtle has been reported to nest in small numbers in Sarawak (Leh, 1985; Ali et al., 2004; World Wide Fund for Nature (WWF), 2024).

In Sarawak, the Sarawak Forestry Corporation (SFC) has incorporated a Species Conservation Action Plan (SCAP) for Marine Turtles to mitigate extinction risks (WWF, 2024). While well-known rookeries, such as Talang-Satang National Park and Tanjung Datu National Park, are relatively well studied (Wan Arman et al., 2019; Hassan and Yahya, 2022; Shakawi et al., 2024), other sites remain under-researched. One of these sites is Similajau National Park (SNP), Bintulu, Sarawak, gazetted in 1976 (Duckworth, 1997), and governed by SFC under the National Parks and Nature Reserves Ordinance (1998) (WWF, 2024).

Research on the status and conservation needs of green turtles in SNP is insufficient, probably due to the low and scattered nesting numbers. In 2015, nesting activity resumed to nest in SNP after their last nesting on 28 July 2010 (Sarawak Government, 2015), and this five-year hiatus further contributed to gaps in the ecological knowledge of this nesting site. Although Tisen and Bali (2001) reported the presence of green turtle nesting in SNP, their work lacked crucial data on landing and nesting, clutch sizes, hatching success, and other relevant analyses. Bali (2005) reported the importance of the reefs surrounding SNP as foraging grounds of hawksbill turtles, but no nesting of this species was recorded in the park. The green turtles remain as the main nesting species in SNP, with only a single case of leatherback turtle nesting reported back in 1998 (Tisen and Bali, 2001).

Therefore, this study examines the nesting patterns and outcomes of green turtles in SNP from 2015–2017 and 2022–2024,

focusing on the annual nest numbers, clutch sizes (of nests in 2024), hatching success rates and the distribution of embryonic mortality rates across developmental stages. Given the paucity of long-term reproductive data from SNP, this study addresses a critical gap in understanding the status of this understudied nesting site. The findings provide a descriptive baseline characterization of the nesting status and reproductive output in SNP and may support the ability of the park to provide targeted species protection.

2 Materials and methods

2.1 Study site description

SNP (3°20'54.3"N, 113°9'29"E) is located approximately 30km northeast of Bintulu town (Figure 1). This totally protected area (TPA) was gazetted in 1976, spanning 89.96 km² (Duckworth, 1997; Forest Department Sarawak (FDS), 2025). It is known for its golden sandy beaches facing the South China Sea, as well as mixed-dipterocarp forests and kerangas woodlands rich in biodiversity (Mohamad et al., 2020; Noor-Faezah et al., 2023). This park supports diverse fauna, including primates such as the Bornean banded langurs and Hose's Suruli endemic to Borneo (Duckworth et al., 2011; Noor-Faezah et al., 2023), birds (Orenstein et al., 2010), bats (Kumaran et al., 2016), beetles (Bogenberger, 1984), fish such as trevallies and groupers (Nyanti et al., 2014), giant squirrels and barking deer (Lading, 2007).

It consists of four main nesting beaches, namely the Chalet Beach, situated near SNP headquarters and chalets; Turtle Beach 1, roughly six kilometers north of the headquarters; Turtle Beach 2, adjoined with Turtle Beach 1; and Golden Beach, 10 km from the headquarters. Chalet Beach, easily accessible to tourists from the SNP headquarters, is exposed to light pollution from the chalets and flaring from a nearby onshore gas plant. These four beaches constitute the primary nesting areas used in the analysis of nesting records in this study.

2.2 Monitoring effort and data availability

Long-term monitoring of green turtle nesting in SNP was performed by SFC rangers as part of routine park management efforts. It should be noted that these efforts were not conducted under a standardized research sampling design. Records for the period 2010–2014 were not available from SFC. Consequently, it was not possible to determine whether the absence of nesting records reflected true zero observations or unavailable data, and these years were excluded from the analysis to avoid potential misinterpretation.

During the COVID-19 pandemic from 2019 to 2021, the park was closed, and no data were recorded. Meanwhile, the reason for the absence of data in 2018 was unclear. There was no confirmed green turtle nesting in 2023 despite routine patrols from the rangers of SNP. Clutch size data from 2015 to 2023 were unavailable as only the total annual egg counts were recorded. Detailed clutch-level information was recorded starting from 2024.

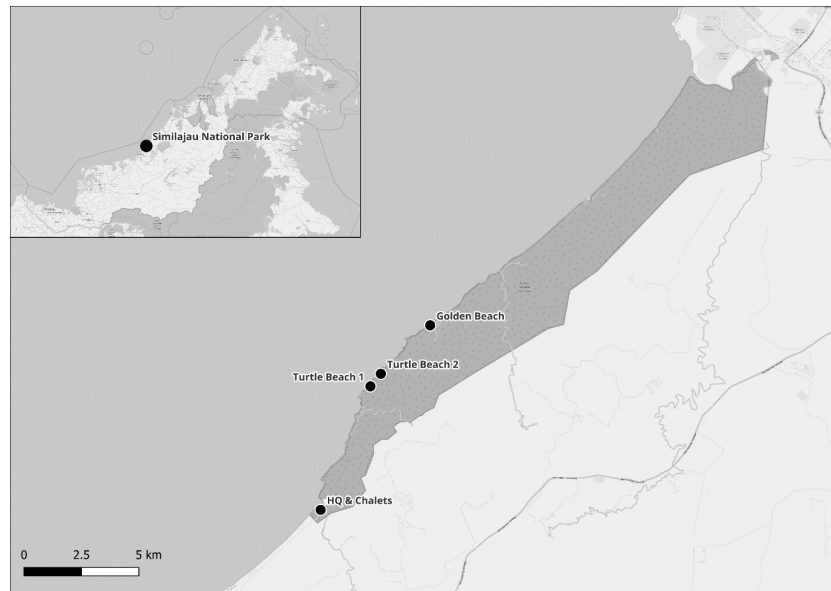


FIGURE 1

Location of Similajau National Park, Sarawak, Malaysia, and the distribution of nesting beaches. The grey shaded area indicates the park boundary derived from OpenStreetMap administrative boundaries. The black points show the location of nesting beaches, namely Chalet Beach, Turtle Beach 1, Turtle Beach 2 and Golden Beach.

Patrols were conducted by walking along the high tide lines and manually checking the sand for flipper tracks. All recorded nests before 2024 were relocated, while only four nests discovered on Chalet Beach in 2024 were successfully relocated due to timely discovery. Nest relocations were carried out on the day of nest detection. To determine the exact location of the eggs within a nest pit, a metal pole was used, which could break some of the eggs at the top of the nest. Nest relocation was performed by layering the bottom of a bucket with sand before filling in the eggs and burying the bucket together with the eggs in the roofed, fenced and elevated hatchery at SNP headquarters. The bucket and metal net cover functioned to prevent predation by small and burrowing animals.

In 2024, nest observations were classified based on evidence of egg deposition. Confirmed nests were defined as nest pits where eggs were observed or where successful relocation confirmed the presence of eggs. Nest pits with predated eggshell remnants were possible nests due to evidence of previous egg deposition but were excluded from confirmed nest counts when the total number of egg-laying events could not be ascertained. Nest pits without evidence of eggs or eggshells were considered unconfirmed nesting activity and were excluded from the nest count.

N1 was discovered during a routine patrol conducted by SNP's rangers, with the previous patrol conducted five days earlier, introducing up to 120 hours of uncertainty. This patrol interval is consistent with the low nesting frequency in SNP, and the multi-purpose nature of the national park management, which does not focus solely on green turtles. Following the discovery of N1, daily morning patrols at 7 am were conducted, and the remaining relocated nests (N2–N4) were therefore likely detected within 12 hours of oviposition. Frequent monitoring was primarily conducted on Chalet Beach, and less frequent patrols were conducted monthly at the other three nesting beaches in SNP. Records of survey effort consistency over the years were unavailable.

2.3 Nesting data acquisition

Nesting data in SNP from 2015–2017 and 2022–2024, including nest numbers, annual number of eggs, clutch size and number of successfully hatched eggs, were obtained from Sarawak Forestry Corporation (SFC). The emergence success of each nest was not recorded by SFC and thus excluded from this study. However, as the recorded nests were all relocated and the hatchlings were released under ranger supervision, the emergence success should be similar to the hatching success.

The nest excavation data (data obtained from examination of post-emergence nests) in 2024 were obtained from the four nests on Chalet Beach that were successfully relocated. Nest excavations were conducted within two weeks post-emergence as part of routine park management. This was the only year with nest excavation data. The remaining recorded nest pits from 2024 lacked sufficient evidence to determine whether they were unsuccessful nesting attempts or successful nests that were later predated.

The nest excavation records provided by SFC included observations of predation, infection, and embryonic developmental stages based on the protocols outlined by [Eckert and Eckert \(1990\)](#). Unhatched eggs without visible embryonic development were categorized as NED or No Embryonic Development; small pink embryos were characterized as EED or Early Embryonic Death; and fully formed embryos with dark pigmentation were classified as FED or Full-term Embryonic Death as per the protocol of SFC, with reference to [Miller \(1985\)](#). Examples of EED and FED are shown in [Figure 2](#).

2.4 Data analysis

Data from 2015–2017 and 2022–2024, including nest numbers, egg counts, hatching success rates, and embryo mortality rates, were

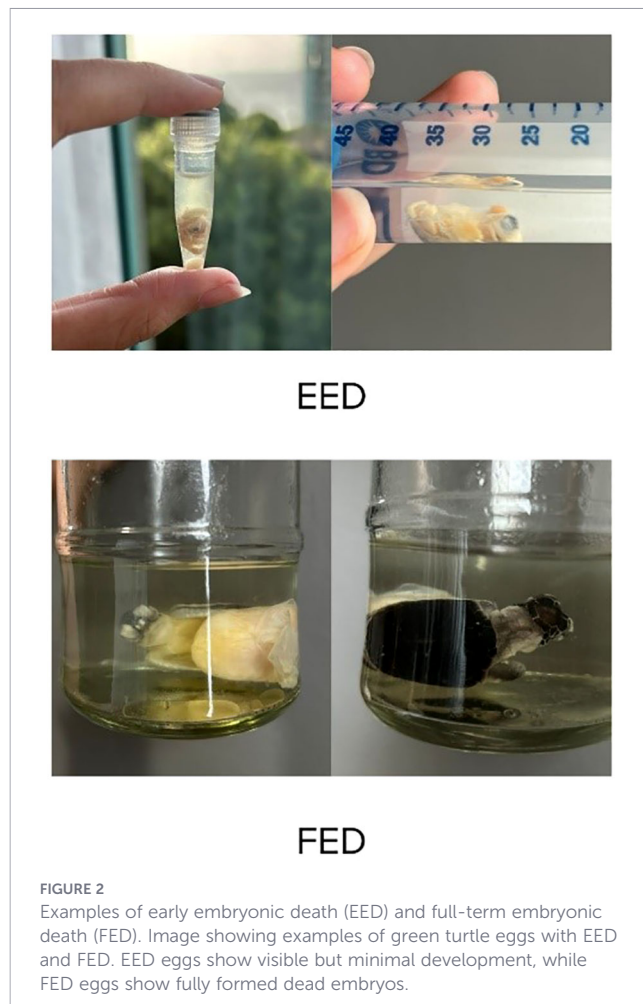


FIGURE 2
Examples of early embryonic death (EED) and full-term embryonic death (FED). Image showing examples of green turtle eggs with EED and FED. EED eggs show visible but minimal development, while FED eggs show fully formed dead embryos.

summarized using descriptive statistics. Years 2018–2021 were excluded from the statistics, while 2023 was included as a zero year. All analyses were performed in Microsoft Excel using the built-in functions.

Clutch size refers to the number of eggs deposited per nest, excluding yolkless eggs; hatching success is defined as the number of hatchlings that hatch out of their eggshells or the number of empty eggshells in the nest; while emergence success refers to the number of hatchlings reaching the beach surface, excluding live or dead hatchlings that remain in the nest (Miller, 1999). By dividing the number of hatched eggs by clutch size, multiplied by 100, the hatching success rate was obtained (Miller, 1999). Broken eggs identifiable as individual eggs were included in clutch size.

Assessments of the incubation period and the distribution of embryonic mortality across developmental stages were conducted for the four relocated nests in 2024, Nests 1–4 (N1–N4). The incubation period is the interval between oviposition and first hatchling emergence (Eckert and Eckert, 1990). In this study, the apparent incubation duration was calculated with the date of relocation and the date of emergence, as the exact dates of oviposition were unclear. The first emergence date was used in the calculation in cases where the hatchlings emerged on two different days. As the exact oviposition date could not be

determined due to detection delay, the incubation period for N1 may be underestimated by approximately five days.

2.5 Study limitations

The small and incomplete dataset is a key limitation of this study, restricting detailed analyses. The results should therefore be interpreted cautiously due to fragmented temporal coverage and limited sample sizes. Although methods such as imputation or modelling missing data could be applied, these approaches are unlikely to yield reliable estimates given the current dataset structure and consistency.

Detection bias may also occur due to variability in patrol coverage and beach accessibility, so the true nesting frequency could be higher than the current records. However, the magnitude of under-detection cannot be reliably estimated from the available records as detection probability and other information are not provided. For example, patrol intervals ranged from daily monitoring after detection of the first nest in 2024 to monthly visits at the other three beaches, indicating substantial variation in detection opportunity. Therefore, longer-term and more standardized data collection is required before robust inferential analyses can be attempted.

Another key limitation of this study is that successful nesting events could not be reliably distinguished from failed nesting attempts or post-oviposition loss. In many cases, the nest pits could not be confidently classified due to disturbances from natural predation, environmental erosion, and other natural processes. Consequently, the total number of nests recorded in 2024 should be regarded as an estimate and interpreted with caution.

3 Results

3.1 Annual nesting data

Nesting activities in 2024 were recorded on Chalet Beach, Turtle Beach 1 and Turtle Beach 2. Although no nesting activity was observed on Golden Beach in 2024, it had been documented in previous years. Based on anecdotal observations by SNP rangers, false crawls had previously been observed on Chalet Beach, but 2024 was the first known year with successful nesting. Overall, the annual number of nests at SNP was low, ranging from 0 to 6 nests (Table 1).

In 2024, 20 nest pits were detected, but only four were confirmed nests and included in the nest counts. Among the remaining 16 nest pits, predated eggshell remnants were found scattered near five, providing evidence of egg deposition, while the others had no confirmed evidence of oviposition. However, because the nest pits were located close together, it was not possible to determine whether the eggshell remnants represented separate nesting events or originated from the same nesting event. Due to this uncertainty, only four confirmed nests were included in the final nest count. Five were classified as possible nests with evidence of egg deposition and the remaining 11 observations were considered unconfirmed nesting activity.

TABLE 1 Nest composition from the study years between 2015 and 2024.

Year	Number of nests with eggs	Nest pits with unconfirmed nesting activity	Total number of nests	% Nests with eggs
2015	5	0	5	100
2016	6	0	6	100
2017	3	0	3	100
2022	2	0	2	100
2023	0	0	0	N/A
2024	4	16	20	20
Mean	3.33	–	6	–

The total number of eggs collected varied across the years (Figure 3), with the highest number recorded in 2015 (545 eggs). Mean hatching success rate during the study years was 45.47%, ranging from 24% in 2016 to 90% in 2022.

3.2 Nest excavation data (2024)

The 2024 nest excavation data are presented in Table 2. Four nests were excavated in 2024, with clutch sizes ranging from 119 to 137 eggs (mean $\pm$ standard deviation, SD = 129.75 ± 7.72) and apparent incubation durations ranging from 54 to 62 days (mean $\pm$ SD = 58.5 ± 3.70). Hatching success rates varied considerably, from 7.69% in N1 to 73.11% in N4 (mean $\pm$ SD = $41.88\% \pm 26.8$). The *in-situ* site of N1 was reportedly inundated before relocation. Notably, hatchling emergence in N4 occurred over two separate days. Broken eggs had been recorded in N1 (6) and N3(9) during relocation.

A breakdown of unhatched eggs showed that approximately 95% experienced mortality at the NED stage (Figure 4). N1 recorded the highest proportion of NED mortality, whereas N4 showed the lowest overall embryonic mortality. Minor discrepancies in the total number of unhatched eggs observed during excavation were attributed to broken or missing eggs.

4 Discussion

4.1 Annual nesting data

This study provides the first overview of green turtle reproductive activity in SNP from 2015–2017 and 2022–2024. Nesting activity was low, with a mean of 3.33 nests per year. In comparison, Talang-Satang National Park, Sarawak (194.14 km²) records an annual average of over 2,000 nests (223,558 eggs), Redang Island, Terengganu (~40 km²) records up to 2,500 nests per year, and the Sabah Turtle Islands, Sabah (17.4 km²) record up to 15,000 nests per year (Fisher et al., 2008; Saleh et al., 2013; Hassan and Yahya, 2022; Joseph et al., 2022; Fadli et al., 2023; MyBIS, 2025). This indicates that the recorded nesting activity at SNP is relatively low. Nevertheless, it represents one of the documented green turtle nesting site in Sarawak and warrants continued conservation attention.

The low nesting numbers in SNP may be linked to mass mortality events in the 1990s, when approximately 100 sea turtle carcasses were recorded annually along Sarawak coasts (Bali et al., 2014). These events were largely attributed to illegal trawling in key foraging areas, migratory routes and inter-nesting habitats (Bali

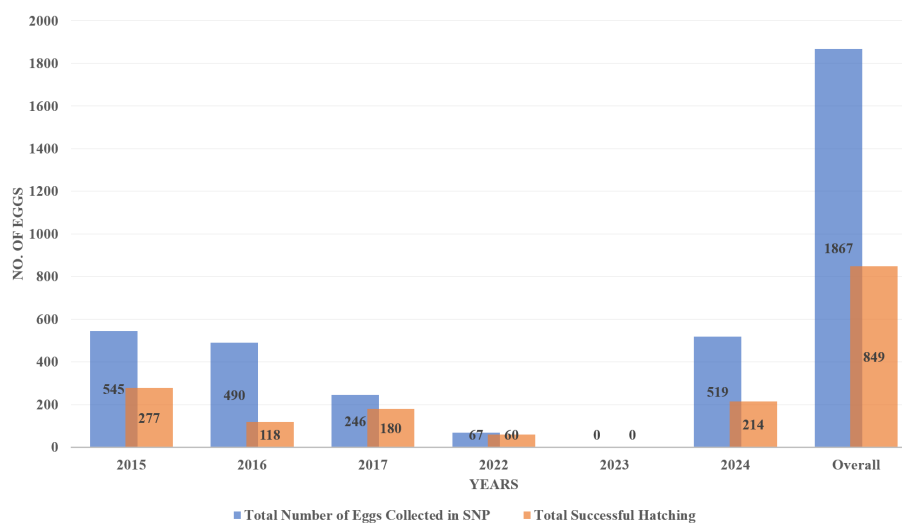


FIGURE 3

Egg counts from the study years between 2015 and 2024. Graph showing annual green turtle egg counts recorded during the study years between 2015 and 2024, with inter-annual fluctuation.

TABLE 2 Post-emergence nest excavation data of 2024.

Nests	Date of detection	Date of emergence	Date of excavation	Apparent Incubation duration (days)	Clutch size	No. of broken eggs	Number of hatched eggs	Hatching success rate (%)
N1	31.07.2024	26.09.2024	01.10.2024	57	130	6	10	7.69
N2	05.08.2024	05.10.2024	16.10.2024	62	133	0	60	45.11
N3	14.08.2024	13.10.2024	28.10.2024	61	137	9	57	41.61
N4	23.08.2024	16.10.2024	28.10.2024	54	119	0	87	73.11
		21.10.2024		59				
Mean	–	–	–	58.50	129.75	–	53.50	41.88
SD	–	–	–	3.70	7.72	–	31.98	26.80

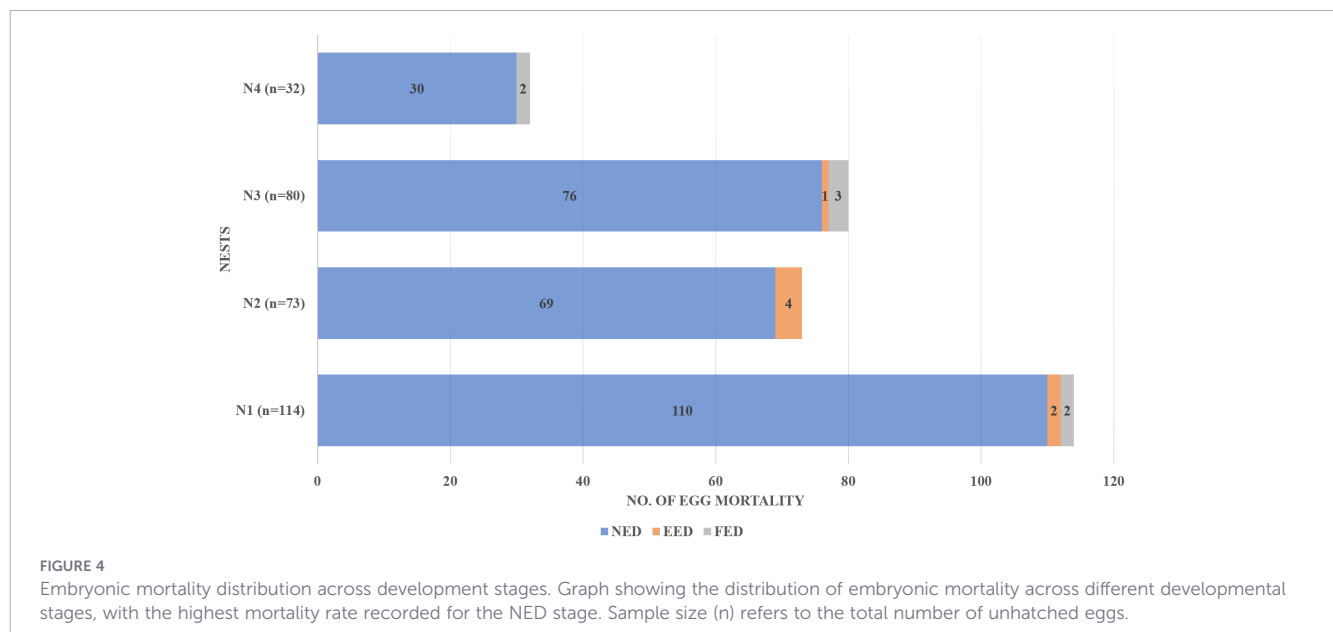
et al., 2014). Although most carcasses were reported near Sematan, Talang-Satang National Park and Telaga Air, the green turtles nesting at SNP may have been indirectly affected, given the highly migratory nature of green turtles across Sarawak waters (Nishizawa et al., 2018; Pilcher et al., 2020; SFC, 2022).

In addition, current low nesting activity in SNP may also reflect ongoing anthropogenic pressures that are prevalent within Malaysia. These threats include habitat degradation, climate change, egg and meat poaching, fisheries bycatch and ghost nets, unsustainable tourism, marine debris entanglement and vessel strikes (Chan, 2006; Fadli et al., 2023; Roslan and Harun, 2023; Chelliah et al., 2024; Mohd Salleh and Mohd Sah, 2024; Cham et al., 2025). Given their long lifespan and late sexual maturity, any changes in nesting activity at SNP is expected to be slow and requires sustained conservation intervention (Bjorndal et al., 2013). These factors collectively highlight the importance of continued monitoring and public education on green turtle conservation in the region.

No nesting in 2023 could suggest absence in nesting activity or detection failure due to monitoring limitations, while nest numbers across the recorded years showed minor variation, indicating natural fluctuations in nesting activity. A similar irregular annual

pattern has been reported in Talang-Satang National Park (Hassan and Yahya, 2022). Sea turtles generally exhibit inter-annual nesting behavior, returning to nest every two to four years, with peaks in nesting density occurring at intervals of one to four years (Broderick et al., 2003; Sims et al., 2008; Chan, 2010). Weishampel (2003) further noted that green turtles often display a biennial pattern of alternating high and low nesting years. However, such a pattern could not be identified in SNP due to fragmented data collection and the absence of individual female identification records.

The mean hatching success rate across study years between 2015 and 2024 was 45.47%, which falls within the range reported for Talang-Satang National Park (33.4%–77.7%) (Hassan and Yahya, 2022). A possible factor contributing to reduced hatching success is the relocation of nests outside the optimal timing window following nesting events. Nest relocation is ideally carried out before attachment of the yolk sac membrane to the shell, with the best results achieved within one to two hours after oviposition, although it can still be performed within 12 hours with significant declines in hatching success (Limpus et al., 1979; Steenacker et al., 2023). The remoteness of nesting beaches in SNP likely contributes to irregular patrol coverage, which may delay nest detection and subsequent relocation.



Nest relocation is typically carried out when nests are exposed to high risks of mortality due to anthropogenic disturbance, wildlife predation, or inundation (Phillott et al., 2021; Steenacker et al., 2023). For instance, *in-situ* nests laid below the high-tide line, where tidal flooding may cause embryo loss, are usually relocated to safer sites (Clabough et al., 2022). In SNP, relocation outside the optimal timing window is often necessary because leaving nests *in situ* carries a high likelihood of complete loss due to predation and inundation. Documented natural threats in Malaysia include ghost crabs, macaques and other primates, feral pigs, monitor lizards, ants and fungal infections (Duckworth et al., 2011; Rusli et al., 2020; Khairuddin et al., 2021; Mohd Salleh et al., 2022; SFC, 2022; Chai et al., 2023; Long et al., 2023; Noor-Faezah et al., 2023; See and Latip, 2023; Syafruddin et al., 2024), all of which are present in SNP. Beyond relocation-related mortality and predation, unhatched eggs may also result from other contributing factors, which are further discussed in the subsection “Nest Excavation Data (2024)”.

Unconfirmed nest pits were discovered in 2024. These nest pits may represent failed nesting attempts (nest abandonment or unsuccessful oviposition) or complete predation events post-oviposition. Nest abandonment during nesting attempts may occur due to a range of environmental and anthropogenic influences such as changes in weather conditions (e.g., wind, waves, and rainfall), physical obstruction from large debris washed ashore, such as logs or tires, human or predator disturbance, and unsuitable substrate conditions, such as root entanglement within the nest site (Zavaleta-Lizárraga and Morales-Mávil, 2013; Sarmiento-Ramírez et al., 2014; Bagheri et al., 2021). This happens as nest microhabitat directly affects embryonic development and survival in the absence of parental care (Charles et al., 2023; Stokes et al., 2024a).

The presence of eggshell fragments observed by park rangers near five adjacent nest pits on Turtle Beach 2 suggests that some of these nests were likely predated. Notably, most nests were observed above the high-tide line, although no quantitative measurements were obtained and the influence of tidal processes cannot be assessed. Eggs or eggshell fragments could have been transported by wildlife or removed by rain and tidal waters as the nests could have been up to a month old at the time of detection. As a result, estimating the true number of successful nests based solely on the presence of eggshell fragments may be unreliable, given that nesting beaches are inhabited by diverse fauna and are continually reshaped by tidal, wave, and sediment dynamics that influence beach morphodynamics (Defeo and McLachlan, 2013; Checon et al., 2018).

4.2 Nest excavation data (2024)

The hatching success rate of N1 in 2024 fell below the approximate range of 33% to 80% hatching success rate recorded in various nesting sites across Malaysia, such as Talang-Satang National Park, Redang Island, Tun Mustapha Park, and Melaka (Chan, 2013; Hassan and Yahya, 2022; Jolis et al., 2023; See and Latip, 2023). Among the four monitored nests, the eggs of N4 emerged on two different days. It is normal for hatchlings to emerge on different days, as hatchlings may emerge en masse or trickle out over several days (Clabough et al., 2022). The broken eggs during

nest relocation further contributed to the low hatching success rates in N1 and N3.

One possible explanation for the low hatching success, particularly in N1, is elevated moisture levels associated with nest inundation, as reported by SFC. Nest inundation is a well-documented threat to sea turtle nests globally, with early and late incubation stages being the most vulnerable periods (Patrício et al., 2021). This may account for the high proportion of undeveloped unhatched eggs in N1-4. Since embryonic development requires a narrow range of temperature, moisture, and oxygen conditions, inundation can severely compromise embryo survival (Fuentes et al., 2010; Abd Mutalib et al., 2014; Patrício et al., 2021). Seawater intrusion further disrupts development by creating osmotic stress and reducing oxygen availability in the sand, ultimately leading to embryo mortality (Pike et al., 2015).

Apart from this, fungal infections in sea turtle eggs are known to increase following nest inundation (Gleason et al., 2020). SFC also identified fungal infection as a cause of egg mortality, typically observed as yellow, blue, or grey discoloration on otherwise white eggshells (Sarmiento-Ramírez et al., 2014; Sarmiento-Ramírez et al., 2016). In Malaysia, the main fungal agents associated with sea turtle egg mortality include *Pseudallescheria ellipsoidea*, *Scedosporium aurantiacum*, *Fusarium solani*, and members of the *Fusarium solani* species complex (Chai et al., 2023; See and Latip, 2023). However, no further examination of fungal infection in unhatched eggs was conducted in this study.

There may be additional unobserved causes of egg failure beyond the factors discussed above, including unfertilized eggs and extreme temperatures. It is often difficult to distinguish unfertilized eggs in undeveloped unhatched eggs during post-emergence nest excavation, as the stages of decomposition would have hindered the examination of fertilization status (Wyneken et al., 1988; See et al., 2024). Thermal conditions may also play a critical role, as optimal embryonic development occurs within an incubation range of 28–32 °C (Yao et al., 2022). Prolonged exposure to temperatures above the 34–35 °C threshold can substantially increase embryonic mortality, whereas temperatures at or below 26 °C reduce embryonic development rates (Lyons et al., 2022; Gatto et al., 2021).

During this study, incubation temperatures of nests in SNP were not recorded. However, the apparent incubation duration of monitored nests (58.5 ± 3.7 days, $n = 4$) is comparable to the ~60-day incubation period typically reported for sea turtles (Segura and Cajade, 2010; Nasiri et al., 2023). Since incubation duration is temperature-dependent, with higher temperatures shortening development time and lower temperatures prolonging it (Wyneken et al., 1988; Gatto et al., 2021), the observed durations may indicate that nest temperatures were within a generally suitable range. However, the apparent incubation duration of N1 may be slightly underestimated by approximately five days (according to ranger observation) because it was not detected immediately after oviposition due to patrol gap. Further research on the drivers of egg mortality in SNP is needed to improve hatchery management strategies.

In 2024, the mean clutch size of 129.75 ± 7.72 eggs ($n = 4$) falls within the reported range for green turtles in Malaysia and other regions. For instance, nesting green turtles in Negeri Sembilan have been recorded laying 42 to 150 eggs per clutch (Mohd Salleh and

Mohd Sah, 2024), while those in Diego Garcia, Chagos Archipelago, produce 74 to 179 eggs per clutch (Stokes et al., 2024b). As clutch size is generally correlated with female body size, and older remigrant females tend to be larger than first-time nesters (Hays et al., 2022; Mortimer et al., 2022; Stokes et al., 2024b), this may suggest that nesting females in SNP are relatively larger individuals. However, no direct morphometric or tagging data were available to confirm this.

4.3 Future recommendations

Future studies should prioritize multi-year monitoring with larger sample sizes to evaluate long-term nesting trends and population dynamics. Additional work should also examine environmental drivers of reproductive output (e.g., temperature and humidity), egg viability factors such as microbial and fungal infection, and the effectiveness of nest protection and management interventions.

From a sea turtle conservation management perspective, the results highlight the need for more detailed surveys of nesting beaches to assess natural disturbances and anthropogenic habitat degradation, alongside strengthened habitat protection through restriction of nighttime beach access during nesting seasons. Monitoring protocols should also be improved to ensure consistency and completeness of data collection. Expanding surveys to nearby nesting beaches may also be beneficial, particularly during periods of low or no nesting activity in SNP, as sea turtles may shift nesting sites in response to environmental changes (Hays et al., 2001; Butt et al., 2016).

Given that relocation outside the optimal time window may increase embryo mortality, minimizing the interval between oviposition and relocation should be prioritized in nest management. Patrol efforts could be intensified during peak nesting periods to enhance early nest detection, while remote monitoring approaches such as early-morning shoreline surveys, boat-based and binocular-assisted observation, or drone surveillance may be considered where feasible. However, such intensive monitoring is likely constrained by limited funding, personnel, and site accessibility, particularly given the low nesting frequency at SNP. Alternatively, community-based participation, including involvement of local stakeholders, conservation groups, or university volunteers, may help supplement monitoring efforts during peak seasons. Where immediate relocation is not possible, selected nests in low-risk locations may instead be managed *in situ* using protective measures such as predator exclusion or shading to reduce environmental stress.

5 Conclusion

This study provides descriptive baseline characterization of green turtle nesting activity in SNP based on available records from 2015–2017 and 2022–2024. The findings show a low mean annual nesting number of 3.33 and a low mean hatching success rate of 45.47%. In 2024, the hatching success rate of 41.8% with a high standard deviation ($\pm 26.8\%$) reflects substantial variation among nests. Nest predation and inundation remained major threats to nest survival, particularly at remote beaches with limited monitoring coverage. These results provide insight into ongoing

challenges to reproductive success and support the need to strengthen conservation measures, including improved monitoring of nesting sites. However, due to limited sample sizes, the findings are unable to support inferences regarding the stability of the observed nesting population. Overall, the findings emphasize the importance of sustained long-term monitoring, habitat protection, and timely nest relocation, building on existing conservation efforts. While the reappearance of nesting activity in SNP since 2015 is encouraging, the low and inconsistent nesting numbers highlight the need for continued research and targeted management to support long-term persistence and recovery of nesting activity.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#). Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required in accordance with the local legislation and institutional requirements because this study involved non-invasive field monitoring of nesting activity and did not involve experimental manipulation or handling of live animals requiring ethical approval.

Author contributions

AT: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. RH: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that generative AI was used in the creation of this manuscript. The authors used OpenAI ChatGPT (GPT-4 or GPT-4.1, OpenAI, <https://chat.openai.com>) for language editing and to improve clarity and readability of the manuscript. All scientific content, analyses, and interpretations were developed and verified by the authors.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/famrs.2026.1890215/full#supplementary-material>

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