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Artificial light at night on nesting beaches of the green turtle, *Chelonia mydas*, in the eastern Mediterranean and its possible effect on populations

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Abstract: Artificial light associated with coastal development is becoming a major threat to coastal biodiversity. Sea turtles are coastal breeders, and it is well-known that hatchlings tend to move toward lighter objects on the beach, which prevents them from reaching the sea. It is, therefore, essential to identify the impact of artificial light at night (ALAN) on the nesting beaches. Here, we investigated ALAN levels using imagery from satellites at important green turtle (*Chelonia mydas*) nesting beaches in the Mediterranean. Mean August radiance levels at nesting beaches ranged from 0.00473 nW/cm^{2}sr (Northern Cyprus-South Karpaz Beach) to 14.44 nW/cm^{2}sr (Türkiye-Davultepe Beach). Of the thirteen nesting beaches examined, five were below the threshold value of high ALAN effect (>2 nW/cm^{2}sr). A statistically significant increasing trend in mean radiance levels over the years was detected in Kazanlı ($r = 0.88$, $p < 0.01$), Samandağ ($r = 0.91$, $p < 0.01$), Alata ($r = 0.89$, $p < 0.01$), and Davultepe ($r = 0.88$, $p < 0.01$). Based on scenarios from previously published scientific results, the present work reveals the negative impact of ALAN, which degrades habitat quality on the core nesting beaches of green turtles in the Mediterranean.

Key words: Artificial light at night, ALAN, light pollution, disorientation, sea turtles, red list assessment

1. Introduction

Coastal areas are fragile ecosystems that serve as habitats or breeding grounds for many vertebrate and invertebrate species. These areas are also aesthetically pleasing to humans, leading to increased pressures from construction and tourism. Nevertheless, coastal areas are of great importance for the survival of many species that rely on them for reproduction. One such species is the sea turtle, which spends most of its life in the sea and uses coastal areas for reproduction. Sea turtles are threatened worldwide by increasing fishing pressure, growing human pressure from tourism in nesting areas, marine pollution, increasing maritime line traffic, climate change, plastic pollution in nesting areas, and light pollution (Gilman et al., 2010; Lazar and Gracan, 2011; Dimitriadilis et al., 2018; Roman et al., 2020; Schofield et al., 2021; Sönmez et al., 2021).

Light pollution has demonstrable effects on communication within and between species, reproductive behaviors, competition, and predation in the ecosystem (Longcore and Rich, 2004). Increasing demand for urban and industrial development on or adjacent to sea turtle nesting beaches results in a subsequent increase in artificial illumination falling on coastlines (Kamrowski et al., 2012, 2014, 2015). Artificial light at night (ALAN) frequently disrupts nesting female turtles and the sea-finding ability of emerging hatchlings (Lorne and Salmon 2007; Bourgeois et al., 2009; Berry et al., 2013). When hatchling sea-finding behavior is disrupted, the prospect of hatchling survival significantly diminishes (Witherington and Martin, 2003). The prolonged crawling duration on the beach weakens the ability to respond to cues used for sea finding while also compromising their swimming orientation away from the shore (Lorne and Salmon, 2007), thus further impairing survival probability.

Dimitriadis et al. (2018) observed a distinct disorientation effect from ALAN on loggerhead (*Caretta caretta*) hatchlings in Zakynthos, Greece, with 7% of the hatchlings heavily disoriented, meaning 7% reduction in population recruitment. A recent study with olive ridley hatchlings (*Lepidochelys olivacea*) indicated that sea turtles swim towards artificial lights even after reaching the sea (Cruz et al., 2018), meaning that ALAN impact is not limited to terrestrial areas. On Heron Island, Australia, Truscott et al. (2017) found that *Chelonia mydas* hatchlings that successfully completed their journey from nest to

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sea were lured back by shore-based light pollution (i.e., ALAN), decreasing their offshore recruitment success. Experimental manipulations have shown that ALAN on nesting beaches may significantly reduce the successful outcome of nesting attempts by individual *Caretta caretta* females by up to 20%–35% (Silva et al., 2017). Recent studies deploying advanced satellite-based remote-sensing methods have found nest density is significantly negatively correlated with ALAN (e.g., Israeli coastline; Mazor et al., 2013), but alarmingly also at nesting beaches even at deficient ALAN levels (e.g., Florida coast; Hu et al., 2018; Heron Island; Vandersteen et al., 2020). Colman et al., (2020) determined that 63.7% of the nesting beaches of four sea turtle species across the Brazilian coast experienced an increase in ALAN levels over 16 years and found a significant adverse effect on nest densities; however, high nest densities were also seen in lit areas.

The Mediterranean is one of the 11 crucial regional management units (RMU) of green turtles for the conservation of the species (Wallace et al., 2023). In this essential RMU, nesting beaches in Türkiye and Cyprus comprise almost 99% of the overall nesting activity (Casale et al., 2018). These nesting beaches suffer from high levels of anthropogenic coastal development compared to other regions of the world (Biddiscombe et al., 2020). ALAN may be considered a good proxy for anthropogenic coastal development. With this aim, we collected data from the scientific literature to provide a quantitative estimate of the potential effect of ALAN on sea turtle nesting success and hatching survival and the consequences for the Mediterranean *Chelonia mydas* population. We also present data on ALAN levels in important nesting beaches to show the extant proportion of nesting areas exposed to detectable levels of artificial light and are thus prone to adverse effects on reproductive success. Finally, we provide a quantitative estimate of the size of such an effect and suggest how the impact of ALAN should be treated in conservation assessment and management.

2. Materials and methods

We measured ALAN levels at important *Chelonia mydas* nesting beaches in the eastern Mediterranean (Figure 1) by analyzing imagery from satellites (VIIRS-DNB) using the application Radiance Light Trends. The beaches were classified by nesting activity levels as super, major, moderate and dense, moderate not dense, and small not

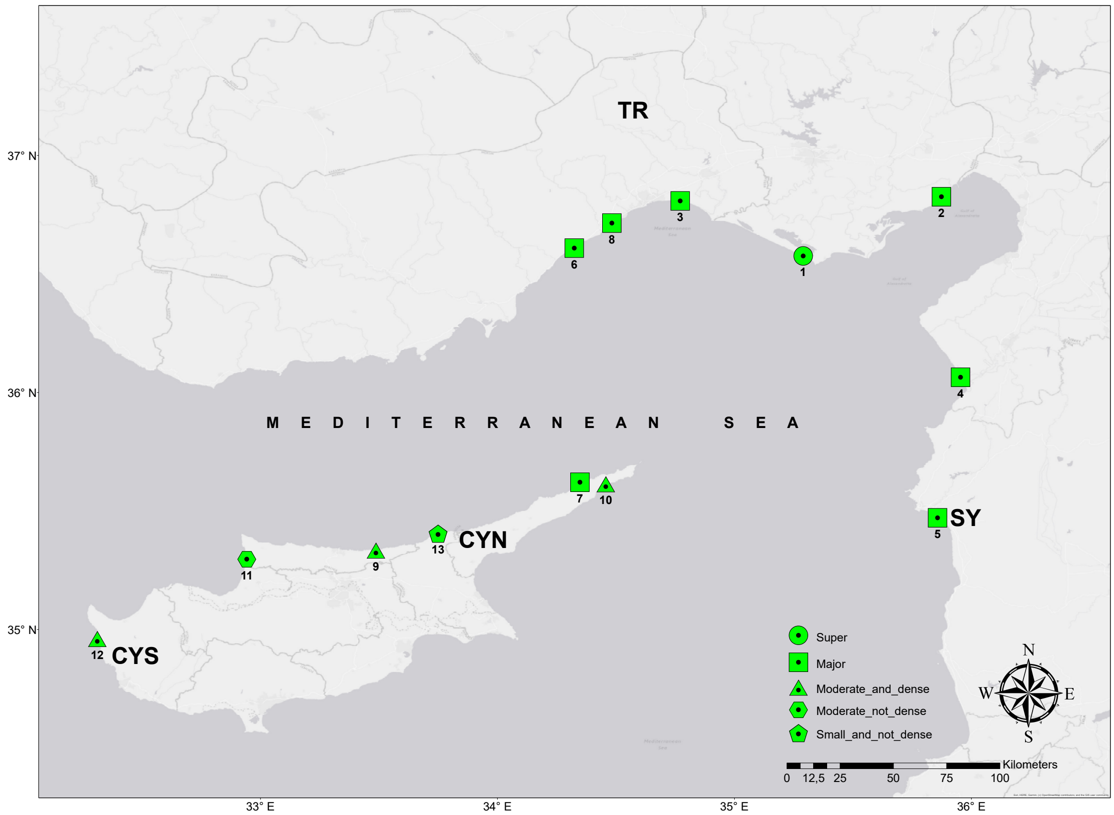

Figure 1. Important green turtle nesting grounds in the Mediterranean (1. Akyatan, 2. Sugözü, 3. Kazanlı, 4. Samandağ, 5. Latakia, 6. Alata, 7. Ronas+Ayphilon, 8. Davultepe, 9. Alagadi, 10. South Karpaz, 11. Akdeniz, 12. West coast, 13. North coast). TR: Türkiye; CYS: Cyprus (S); CYN: Cyprus (N); SY: Syria.

dense, following Casale et al. (2018). Monthly radiance data from 2012 to 2020 was used to quantify the amount of light emitted into space from beach areas. A similar methodology has been applied by Hu et al. (2018) and Kamrowski et al. (2012, 2014). The VIIRS DNB satellite scans the entire Earth each night with a spatial resolution of 750 m (Elvidge et al., 2017; Levin et al., 2020) and typically passes overhead around 1:30 AM. This time is after peak ALAN use but still within the hours of turtle nesting and emergence activity. Radiance is measured in nanoWatt/square centimeter/steridian (nW/cm^2sr). Nightly measurements are averaged in the application into monthly radiance values. From the monthly values from each nesting beach for the period spanning 2012–2020, we analyzed only data from August of each year, as this corresponds to the relevant ALAN conditions at the peak of turtle hatchling emergence and also the representative of the peak nesting season. We measured the area within the contours of each beach, from which the number of representing pixels was then automatically determined. The area covered by each selected pixel is 0.75 km^2. The number of pixels representing each beach is 1–27 (depending on beach length, as detailed in Table 1). We included measurements from 13 nesting sites.

We applied a dose-response relationship approach and set a threshold of 2 nW/cm^2sr to assign beaches as suffering from high levels of ALAN, following Kamrowski et al. (2012), which assigned this value as a maximal risk category. Additionally, we examined values from beaches in Zakynthos and Heron Island and the corresponding biological effect levels described in Dimitriadis et al. (2018) and Truscott et al. (2017), respectively. Although both studies analyzed loggerhead turtles, the effects are assumed to be the same in the loggerhead and green turtles in the predictions. This resulted in three categories of ALAN on beaches based on the magnitude, as follows: no ALAN: < 0.1 nW/cm^2sr, low ALAN: 0.1–2 nW/cm^2sr, and high ALAN: >2 nW/cm^2sr. Furthermore, we determined three scenarios of a reduction effect on *C. mydas* nesting populations based on the literature summary and the categorization of nest beaches based on measurements of ALAN. Our model focuses only on the net impact from ALAN, assuming other prevalent threats do not differ in their effects on different *C. mydas* nesting beaches. We used nonparametric tests for comparing radiance levels and analyzing temporal changes in ALAN using STATISTICA software.

3. Results

Mean August radiance levels at nesting beaches ranged from 0.00473 nW/cm^2sr (Northern Cyprus-South Karpaz Beach) to 14.44 nW/cm^2sr (Türkiye-Davultepe Beach) (Table 1, Figure 2).

Table 1. Radiance values (nW/cm^2sr) for *Chelonia mydas* (CM) nesting beaches and reference beaches. Values are from August of each year, between 2012 and 2020. Primary *Chelonia mydas* nesting beaches in the Mediterranean categorized by size class and ALAN levels. Size classes of the beaches were taken from Casale et al. (2018).

Country	Beach	Beach length (km)	Mean no. of nests	Size class	Number of pixels	N	Mean radiance ± SD	Range	ALAN category
Türkiye	Akyatan	22	322	Super	27	9	0.05±0.012	0.04–0.07	No
Türkiye	Sugözü	3.4	213	Major	1	9	5.35±1.742	2.49–7.78	High
Türkiye	Kazanlı	4.5	365	Major	2	9	2.56±0.607	1.67–3.69	High
Türkiye	Samandağ	14	306	Major	11	9	3.03±1.196	1.46–4.57	High
Türkiye	Davultepe	2.8	113	Major	2	9	14.44±4.651	7.04–24.06	High
Türkiye	Alata	3	125	Major	2	9	10.00±3.386	5.27–14.79	High
Syria	Latakia	12	140	Major	8	9	0.75±0.207	0.48–1.10	Low
Cyprus (N)	Ronnas+Ayphilon	3.2	220	Major	3	9	0.02±0.019	0–0.057	No
Cyprus (N)	Alagadi	1.7	154	Moderate and dense	5	9	0.34±0.137	0.25–0.70	Low
Cyprus (N)	South Karpaz	7.6	59	Moderate and dense	12	9	0.01±0.019	0–0.03	No
Cyprus (N)	Akdeniz Beach	8.6	70	Moderate and not dense	11	9	0.03±0.010	0.004–0.04	No
Cyprus (N)	North Coast	2.7	11	Small and not dense	4	9	0.14±0.045	0.09–0.21	Low
Cyprus (S)	West Coast	5	108	Moderate and dense	2	9	0.03±0.031	0–0.08	No

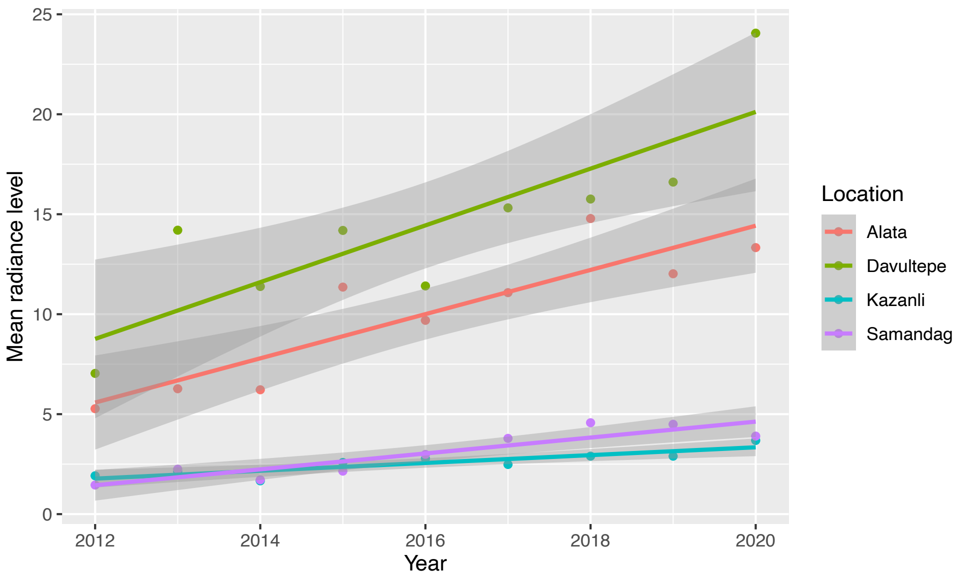

Figure 2. Annual mean radiance values (in nW/cm²sr) showing an increasing trend for four major *C. mydas* nesting sites categorized as high ALAN. The dotted blue line indicates the threshold (2) for determining high ALAN levels.

Of the 13 core nesting beaches examined, 8 were below the threshold value of high ALAN effect. Five of the six nesting beaches in Türkiye were classified as High ALAN, while one (Akyatan) was classified as no ALAN (Table 1, Figure 1). Four of the six beaches in Cyprus were classified as no ALAN, while the remaining two had low ALAN levels. In Syria, low ALAN levels were recorded.

The most important nesting site for *C. mydas* (determined as super) at Akyatan, Türkiye, was classified as no ALAN (Table 1). However, of the seven beaches defined as major nesting sites, five were classified as High ALAN, one as low ALAN, and only one major site—Ayphilon and Ronnas Beach, Cyprus—was ranked as no ALAN. All other moderate or small nesting beaches were classified as having low or no ALAN. The mean radiance level was the highest in Davultepe (14.44) followed by Alata (10), Sugözü (5.35), and Kazanlı (2.56). The mean radiance values of Sugözü, Alata, Davultepe, and Kazanlı were significantly different from those of other beaches ($p < 0.001$) with the exception that Kazanlı and Samandağ were not different ($p > 0.05$).

Our results show that overall, about 50% of the cumulative nesting beach length of *C. mydas* is experiencing ALAN, and 30% suffers from high ALAN levels. Likewise, 65% of *C. mydas* nests are laid on beaches experiencing ALAN, and 51% are laid on beaches suffering from high ALAN levels (Table 2).

3.1. Temporal changes

ALAN has significantly increased between 2012 and 2020 in four of five nesting beaches marked as major nesting sites and categorized as High ALAN beaches (Figure 2). Radiance levels in 2020 were 1.9–2.6 times higher than in 2012. Statistically significant increasing trends were detected over the years on mean radiance levels on Kazanlı ($r = 0.88$, $p < 0.01$), Samandağ ($r = 0.91$, $p < 0.01$), Alata ($r = 0.89$, $p < 0.01$), and Davultepe ($r = 0.88$, $p < 0.01$), while statistically insignificant decreasing trends were observed on Sugözü ($r = -0.37$), Latakia (−0.37), Ronnas+Ayphilon (−0.28), and North Coast ($r = -0.91$).

3.2. Scenarios and quantitative effect of ALAN on the Mediterranean *C. mydas* nesting population

Scenario I: ALAN will affect hatchling disorientation on the beach. Based on the findings by Dimitriadis et al. (2018), we estimate a 20% reduction in the number of hatchlings successfully reaching the water at high ALAN beaches and only a 5% reduction in the number of hatchlings successfully reaching the water at low ALAN beaches. Hatchlings at no ALAN beaches are not negatively affected.

Scenario II: After completing their journey from nest to sea, sea turtle hatchlings may be lured back to the beach by shore-based light pollution. Based on the findings of Truscott et al. (2017), we estimate that this will affect 25% of hatchlings that have already reached the water at high ALAN beaches and 10% at low ALAN beaches. Hatchlings at no ALAN beaches are not negatively affected.

Scenario III: ALAN at nesting beaches may significantly reduce the successful outcome of nesting attempts by individual *C. mydas* females. Based on the findings by Silva et al. (2017), we estimate this will have a reduction effect of

Table 2. Total beach length (km) and number of nests categorized by ALAN levels.

ALAN	Beach length (km)	Mean no. of nests	% Length	% no. of nests
No	46.4	779	51	35
Low	16.4	305	18	14
High	27.7	1122	31	51
Total	90.5	2206	100.0	100.0

25% of nests laid at high ALAN beaches. Low ALAN and no ALAN beaches are not negatively affected.

Assuming a constant clutch size of 115 eggs per nest (Glen et al., 2005; Özdemir and Türkozan, 2006; Ilgaz, 2001), 80% hatching success (Zárate et al., 2013), and an insignificant emergence loss, the annual recruitment is estimated at 202,952 turtles, assuming no effect of ALAN (Table 3). Scenario I, in which hatchling seaward orientation is disrupted, leads to a reduction of 11% in recruitment. Adding Scenario II, in which shore-based ALAN may lure those hatchlings that do reach the water back to the beach, leads to a total reduction (Scenarios 1+2) of 22%. If we assume that high ALAN levels interrupt successful nesting attempts by females by 25% (Scenario III), we may see a reduction in nests in High ALAN beach segments and, consequently, a reduction in recruits. Taken together with the effect on hatchlings (Scenarios 1+2+3), overall yearly recruitment may thus be reduced by up to 30%, meaning a potential loss of more than 60,000 turtles.

4. Discussion

Our results clearly show that most of the major nesting beaches for *C. mydas* females in Türkiye currently suffer from high ALAN levels that are rapidly increasing. Some protected beaches remain dark, mainly in Cyprus; however, ALAN from nearby developments is encroaching. Considering the known adverse impacts of ALAN on hatchling disorientation (Witherington and Martin, 2003), decreased nesting attempts, increased predation risk (Silva et al., 2017), and alteration of turtle nesting distribution (Windle et al., 2018), we anticipate a significant negative impact on the major nesting sites of *C. mydas* in the Mediterranean. This could potentially result in approximately 30% decrease in yearly hatchling recruitment from ALAN alone. This decrease, coupled with other sources of known or predicted threats (e.g., plastics, oil and gas rigs, blast injuries, fishing), could severely impact the species' future in the Mediterranean, despite ongoing conservation efforts. The relationship between

Table 3. Number of successful yearly recruits (number of hatchlings successfully dispersing into the water) under three cumulative scenarios for the effect of ALAN on sea turtle nesting.
[a] Mean clutch size from Mediterranean populations (Glen et al., 2005; Özdemir and Türkozan, 2006; Ilgaz, 2001); [b] Mean hatching success from Mediterranean populations (Zárate et al., 2013); [c] Numbers in parentheses for high ALAN row indicates calculations for scenario III, 25% reduction in female nesting success.

ALAN	No. of nests	No. of eggs[a] (mean clutch=115)	Hatching success[b] (mean= 80%)	Scenario 1: Beach disorientation reduction (No ALAN=0%, Low=5%, High=20%)	Scenario 2: Back from sea reduction (No ALAN=0%, Low=10%, High=25%)	Scenario 3: Female nesting success reduction (No ALAN=0%, Low=0%, High=25%) effects nest numbers
No	779	89,585	71,668	71,668	71,668	71,668
Low	305	35,075	28,060	26,657	23,991	23,991
High[c]	1122 (842)	129,030 (96,830)	103,224 (77,464)	82,579 (61,971)	61,934 (46,478)	46,478
Total	2206	253,690	202,952	180,904	157,594	142,137
Cumulative reduction (% of emergence success)			0	–11%	–22%	–30%

nesting density and light pollution would likely indirectly influence nest site selection, subsequently affecting nest temperatures and potentially skewing hatchling sex ratios. Furthermore, looking for a favorable nesting site would increase the crawling period of a female, and that female may be exhausted and more prone to predation risk.

Among the other anthropogenic threats, light is one of the most manageable (Witherington and Martin, 2003) for conserving and managing sea turtles. We, therefore, wish to emphasize two points that we believe necessitate a precautionary approach for both assessment and future conservation management. ALAN is rapidly increasing temporally and geographically with anthropogenic coastal development (Kyba et al., 2017 and this study). Moreover, lighting technology is rapidly changing to more efficient LED lighting. However, due to its high content of short-wave blue-rich light, LED lighting has more pronounced negative ecological, behavioral, and physiological effects on living organisms than previous technologies. Blue-rich LED light is especially problematic for both adult and hatchling *C. mydas* turtles because their vision is sensitive to these wavelengths, and this causes the masking of important natural nighttime cues crucial for navigation (Longcore et al., 2018). Minimizing the effect of ALAN on important nesting sites will thus require addressing the spectral content of light and not simply the amount of light. For example, in Florida, sea turtle protection regulations have led to the development of "turtle safe lighting".

Nesting numbers at important *C. mydas* nesting sites in the Mediterranean have increased over the past 20 years despite increasing light levels. While this appears inconsistent with our prediction on the effect on nesting females, the effect size may be masked by other factors. For example, successful turtle conservation management contributes to reducing impacts and compensating for mortality at sea and/or land, as Colman et al. (2020) suggested. Alternatively, however, one could argue that natal philopatry and late age of reproductive maturity are driving a major lag in response by nesting females (i.e., the youngest nesting females are prone to nesting on the beach where they hatched more than 20 years ago when ALAN levels were probably lower). Nesting *C. mydas* females exhibit precise natal philopatry at ecological timescales (Encalada et al., 1996). Considering that natal philopatry is related to their response to changes in the availability of nesting sites over time, we cannot overlook the possibility of declines, noticeable only in the future, due to response lag. The pronounced impact of ALAN on hatchling recruitment, despite an observed current increase in nesting numbers, may therefore exhibit the same response lag to fully manifest in noticeable negative nesting trends. This realization as to possible future outcomes and consequences warrants urgent action today to limit light pollution on *C. mydas* nesting sites in the Mediterranean.

5. Conclusion

The eastern Mediterranean coasts are important nesting areas for green sea turtles. The high level of the ALAN effect calls for urgent attention at key nesting beaches and requires immediate action by local authorities to mitigate the potential adverse effect. This significant negative impact was recently considered in the most recent Red List assessment of the Mediterranean *C. mydas* turtle population as an indication of current and future decline in the quality of habitat (Broderick et al., 2023)

Authors' contributions

NL and YL conceived the study, with NL conducting the analysis and leading the writing. YL and OT contributed to the writing. All authors approved the final version of the manuscript.

Conflict of interest

The authors declare that they have no conflicts of interest.

Ethical approval

This article does not contain any studies with human participants. We did not conduct experiments with animals. All applicable international, national, and institutional guidelines for caring for animals found stranded alive were followed.

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