Estuaries and Coasts
https://doi.org/10.1007/s12237-024-01341-y

SPECIAL ISSUE: RESILIENCE TO GLOBAL CHANGE IN SGOM

Assessing Southern Gulf of Mexico Resilience: Least Tern Nesting Failure During the COVID-19 Pandemic

Julio César Canales-Delgadillo[1,2] · José Gilberto Cardoso-Mohedano[2] · Nallely Vázquez-Pérez[3] · Rosela Pérez-Ceballos[1,2] · Arturo Zaldívar-Jiménez[4] · Enrique Benítez-Orduña[5] · Mario Alejandro Gómez-Ponce[2] · Omar Celis-Hernández[1,2] · Martín Merino-Ibarra[6] · Carlos Robinson-Mendoza[6]

Received: 23 March 2023 / Revised: 31 December 2023 / Accepted: 26 February 2024

Abstract

The COVID-19 lockdown opened an opportunity to assess the response of animal populations to diminished human activities. As coastal dunes face many disturbances caused by increasing human activities, we assessed the effect of reduced human mobility on coastal bird diversity and abundance and on the Least Tern nest failure rate on an island in the southern Gulf of Mexico before, during, and after the lockdown to test the hypothesis that diminished tourism and recreational activities can contribute to the conservation of coastal ecosystems by increasing species richness and abundance and decreasing the nest failure rate. We used data from 2016 to 2021 to estimate nesting failure probabilities using Bernard's cumulative distribution function, Kaplan−Meier tests, and Cox regression for hazard rates. Bird species richness and abundance were compared using Kruskal−Wallis rank tests. Factors related to breeding site preference were assessed using the BIOENV method. The lockdown did not affect species richness, but bird abundance was inversely related to pedestrian traffic ($rho = -0.908$, $p < 0.0001$, $n = 48$). Nest failure decreased during the lockdown in 2020 ($p < 0.0001$) due to reduced presence of people, which allowed occupancy of sites never used before. During the lockdown, the proportion of nest failure was lower than that in the other sampling years ($p < 0.0001$, φ range $= -0.445$ to -0.278). Accordingly, diminished pedestrian traffic can increase nest survival (log-rank $p < 0.0001$). Policies to reduce beach pedestrian traffic will help strengthen wildlife conservation and building coastal resilience.

Keywords Lockdown · Nesting birds · Disturbance · Coastal habitat · Laguna de Términos · *Sternula antillarum*

Communicated by Abby N. Powell

✉ Julio César Canales-Delgadillo
jccanalesde@conahcyt.mx; cadj0506@gmail.com

1 CONAHCYT, Consejo Nacional de Humanidades Ciencia y Tecnología, Av. Insurgentes Sur 1582, C. P. 03940 CDMX, Mexico

2 Present Address: Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Estación El Carmen, C. P. 24157 Ciudad del Carmen, Campeche, Mexico

3 Centro de Estudios Tecnológicos del Mar No. 29, C.P. 24129 Ciudad del Carmen, Campeche, Mexico

4 ATEC Asesoría Técnica y Estudios Costeros SCP, C. P. 97283 Mérida, Yucatán, Mexico

5 Biólogo Independiente, Calle 48 No.19, Aviación, C. P. 24170 Ciudad del Carmen, Campeche, Mexico

6 Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, C. P. 04510 Coyoacán, Ciudad de Mexico, Mexico

Introduction

Birds are considered good indicators of ecosystem change (Fraixedas et al. 2020), and marine fish-feeding species such as terns can indicate both the availability and energy density of their prey (Diamond and Devlin 2003; Ramos and Furness 2022) and the health of coastal marine habitats (Ogden et al. 2014). The Least Tern (*Sternula antillarum*) is the smallest Tern species in the Americas. Its distribution includes continental and coastal zones in North, Central, and South America and the Antilles (Thompson et al. 2020). Although it is a species of least concern globally, its population trends, habitat availability, and quality are declining (IUCN 2022). In addition, because of the rapid habitat loss and modification and the increasing human activities near or in the coastal breeding areas in Mexico, the Least Tern is a species that deserves special protection according to Mexican law (SEMARNAT 2010).

During 2020, the COVID-19 pandemic imposed a series of restrictions on human populations worldwide to stop the spread of infection. The reduced number of people raised the idea that human confinement and the lockdown to human mobility benefited habitat occupancy for various wildlife species (Chethan 2020; Estela et al. 2021; Gordo et al. 2021).

Anthropic pressure may reduce habitat availability and disturb a wide variety of coastal wildlife through habitat invasion, modification, and urbanization (Martínez et al. 2014; Santander-Monsalvo et al. 2018; Sordello et al. 2020). Under such conditions, the lockdown opened a unique opportunity to assess the response of animal populations to diminished human activities (Thurstan et al. 2021), particularly in natural habitats near urban areas. For instance, in urban habitats in Spain, increased bird detectability was observed because of a reduced number of people on the streets (Gordo et al. 2021), and an inverse relationship was found between the number of shorebirds and the number of beach users on the coast of South Africa (Lewis et al. 2022). However, the effects of the lockdown on southern Gulf of Mexico (SGoM) wildlife have not been assessed to date.

The SGoM has approximately 722 km of coastal front that provides several essential ecosystem services (Costanza et al. 1997; Mendoza-González et al. 2012; Benitez et al. 2014; Ruiz-Fernández et al. 2020; Cuevas et al. 2021; Gómez-Ponce et al. 2021; Paz-Ríos et al. 2021; Cardoso-Mohedano et al. 2022), biota refugia, and nursery areas (Canales-Delgadillo et al. 2020; Cuevas-Gómez et al. 2020). Although the SGoM is under great environmental pressure (Mendoza-González et al. 2012; Celis-Hernandez et al. 2020), which significantly impacts coastal ecosystems (Hall 2015; Soto et al. 2021; Steibl et al. 2021; Power et al. 2022), the scarcity of studies makes it difficult to assess the anthropic impacts on SGoM ecosystems (Escudero et al. 2014) and wildlife.

In the SGoM and the Mexican Caribbean, the Least Terns breed from early April to late August on sandy or shell beaches where they build, directly on the ground, a small cup-shaped depression to lay 1–3 eggs (Zuarth et al. 2016; Nefas et al. 2018). Hatching occurs approximately 16–25 days after lying, and chicks can move from the nest two days after being born to hide from predators in low coastal dune vegetation. However, as most of the beaches in Mexico are public and there are no restrictions for jogging, biking, pet walking, or motorized vehicles entering, the Least Terns' nests and chicks are constantly at risk of destruction by the beach's human users, threatening the viability of the breeding populations using areas with limited habitat availability, especially on the islands (Maslo et al. 2018).

In the present work, we aimed to answer the following research questions: Was the Least Tern's failure rate modified by the COVID-19 lockdown in the study area? Were avian diversity and abundance affected by restrictions to human mobility during the lockdown? Why is the study area the only site used constantly to breed in six years, despite the levels of human activity present?

Methods

Study Area

The study area is a public beach, Playa Norte, in Isla del Carmen, Campeche, Mexico (− 91.83854 W, 18.66485 N, Fig. 1). Playa Norte is the most extensive public beach on the island, with significant recreational activities during the mornings and evenings. It is surrounded by urban infrastructure, including an industrial harbor, hotels, and paved roads. Jogging, pet walking, and biking are the most popular activities. However, sand dune areas with native vegetation are still part of the landscape. The vegetation community includes *Coccoloba uvifera*, *Suriana maritima*, *Sesuvium portulacastrum*, *Ipomoea imperati, Sporobolus virginicus*, and *Scaevola plumieri*. Playa Norte is a site used consistently by the Least Tern to nest. However, most breeding sites are unprotected against people and non-native nest predators like domestic and feral dogs.

Nest Monitoring

From 2016 to 2021, we counted and monitored Least Tern nests in Playa Norte. Even though other sites were used for breeding occasionally during the study period, because Playa Norte was the only site with constant breeding activity over the years, our analyses of the lockdown effects on the nest failure rate focused on the data collected there. Once the birds began laying eggs, we used wood sticks (60 cm tall × 0.25 cm wide) with a numeric identifier to mark the nests. Each nest was visited twice weekly between April and August in each breeding season to record the number of active nests and the number of days before they failed (disappeared, were predated) or succeeded (hatched chicks).

Nesting Site Preferences

In addition to Playa Norte, other locations on the island were occasionally used by the Least Terns to establish breeding colonies: Puerto Real and San Julian (used once each in 2020) are two popular places for tourists and fishers; Km28 (used once in 2016 and once in 2021) is the place with less human activity. We visited all the known sites where the birds nested on the island each year. The visits occurred at least twice monthly during the first half of each breeding season to discard missing habitat use due to late occupancy (Holyoak et al. 2014). To determine why Playa Norte was used to nest over the other sites, we characterized the vegetation structure and the topography of the four breeding

Fig. 1 The known Least Tern's breeding colonies in Isla del Carmen, Campeche. In the general map, the red ellipse shows the location of Isla del Carmen within the Gulf of Mexico. Below the general map is a close-up of the study area (Playa Norte) and three additional sites used occasionally to nest before, after, or during the COVID-19 lockdown. The orange polygons represent the extent of each known colony up to 2021

sites, including those used at least once to nest during the study period.

We characterized the vegetation using three 10 × 10 m sampling plots by breeding site. We measured vegetation height and width (m), cover (%) using two perpendicular diameters to the plant canopy (Gold et al. 2004), and density (individuals ha^{-1}). The topography characterization followed the *stop-and-go method*, which uses a known referenced point with differential GPS and the datum WGS84 to measure the elevation of additional measuring points scattered over each sampling site (Haldar 2013).

Data Analysis

Avian Species Richness and Abundance

To assess the effects of the COVID-19 lockdown on the bird community of Playa Norte, we used Kruskal–Wallis rank tests to compare bird species richness and abundance through the different human mobility restriction phases implemented by the government in our study area, which limited the number of people in public places. The restriction scenarios were classified as high restriction (mid-June to mid-August 2020), in which only people doing essential economic activities were allowed to go on the streets; mid restriction (mid-August to mid-October 2020), in which more commercial establishments were opened and a limited number of people were allowed to enter the locals; and low restriction (mid-October 2020 to May 2021), in which most of the people were allowed to go out using facial masks. Furthermore, we used species richness data from the same beach area collected between 2012 and 2016 to compare the species proportions of these years vs. the species richness estimated during the lockdown months (mid-June 2020 to May 2021) using chi-squared tests. Surveys for bird species richness estimation for all years were conducted using a 2 km line transect with a width of 70 m on each side of the line to include bird sightings on the land, the shore, and offshore within the study area. As surveys in 2012–2016 were year-round, we filtered data to keep only records made during the same seasons as the 2020–2021 survey. In addition, when the 2020–2021 bird survey occurred, a second observer conducted beach user counts using a manual counter to record each person jogging, walking with pets, biking, swimming, or fishing within the bird survey area. The relationship between bird species richness and abundance and the number of beach users was investigated using Spearman's correlation tests.

Nest Failure Rate

We used a nonparametric estimation method to estimate the failure probability of Least Tern's nests over the years. Such a method consists of estimating the cumulative distribution function (CDF) using Bernard's approximation formula (Bernard & Bos-Levenbach, 1953), which gives the median rank values:

$$F(t_i) = \frac{1-0.3}{n+0.4}$$

However, this formula is applicable only when all the samples tend to fail. Thus, by using Johnson's method (Hensel & Barkemeyer, 2021), it is possible to adjust the ranks when failed and successful nests are included:

$$j_i = j_{i-1} + x_i \bullet I_i, \text{with} j_0 = 0$$

where $j_i - 1$ is the adjusted rank of the previous failure, x_i is the number of failed nests at time t_i, and I_i is the increment that corrects the considered rank. Then, the CDF can be estimated with Bernard's approximation using the R function *estimate_cdf* from the *Weibulltools* package (Hensel & Barkemeyer 2021).

As a complement, we also estimated the survival probability of the Least Tern's nests from time to egg laying to typical hatch time. We used a Kaplan−Meier test as implemented in the R package *survival* (Therneau 2022):

$$S(t) = Pr(T > t) = 1 - F(t)$$

where the survival probability $S(t)$ of a nest (in a term between 3, 10, 16, and 25 days) is the number of nests that are active without loss to follow-up at that time divided by the number of active nests just before that term. To determine whether there were differences in the failure rates among years, we used a log-rank test based on the chi-square estimate of equality through the function *survdiff* (Therneau 2022). In addition, we used a Cox proportional hazard (CPH) regression analysis to investigate the relationship between clutch size and hatching time and nest survival time (Deo et al. 2021). We used the maximum clutch size recorded for each nest and coded the hatching time into three categories: early nests (EN) were all nests with hatchings within 16 days. On-time nests (OTNs) were all nests with hatchings within 17–25 days, the expected time of Least Tern hatching. Finally, old nests (ON) were all nests with no hatched eggs in a time interval of > 25 days, which usually do not produce chicks and are abandoned by the adults. In addition, we compared the proportion of nest failures and successes of each year of study vs. the proportion of failures and successes observed during the lockdown in 2020 using a two-proportion z test.

Nesting Site Preferences

We applied the BIOENV method (Oksanen et al. 2022) to investigate the environmental variables that could influence nesting site preferences in Isla del Carmen. With this approach, we tested the correlation (Spearman's rank correlation) of the nest abundance in our study area (Playa Norte) and the other only known nesting colonies (Km28, San Julian, and Puerto Real) within the study period with the vegetation structure (species diversity and richness, density, height, and cover) and physical site characteristics such as beach width and minimal, average, and maximal topographical elevation.

Effect sizes were computed either as the eta squared based on H-statistic: $\eta^2 [H] = (H - k + 1)/(n - \text{k})$; where H is the value obtained from Kruskal–Wallis tests, k is the number of groups, and n is the number of observations or as the Phi (φ) coefficient for the two-proportion z test. All tests were performed in R 4.3.1 (R Development Core Team 2023).

Results

During the lockdown in 2020, we recorded 44 bird species in Playa Norte, including the Least Tern. Most of the birds were resident species (86%, $n = 38$) and were mainly shorebirds (Scolopacidae, Charadriidae, and Ardeidae) and marine bird species (Laridae, Pelecanidae, and Fregatidae), but species of raptors, doves, parakeets, and several Passeriformes were also recorded. We did not find differences in species richness between the lockdown sample (2020–2021) and the samples from the non-lockdown study period (2012–2016) ($\chi^2 = 7.592$, df = 6, $p = 0.269$, $n = 66$, $\eta^2[H] = 0.013$, Table 1).

We counted significantly fewer users on the beach during the high-restriction than in the mid and lower-restriction phases (Kruskal−Wallis: $\chi^2 = 23.365$, df = 2, $p < 0.0001$, $n = 48$, $\eta^2[H] = 0.474$). Although bird species richness

Table 1 Comparison of the species richness observed during the COVID-19 lockdown and the species richness recorded in previous years in Playa Norte

Year	Lockdown	Sample size	Observed species richness	Mean species richness
2012	No	6	28	26.30
2013	No	12	47	28.70
2014	No	12	49	25.20
2015	No	12	40	25.20
2016	No	12	55	22.80
Lockdown 2020–2021	Yes	12	44	25.70

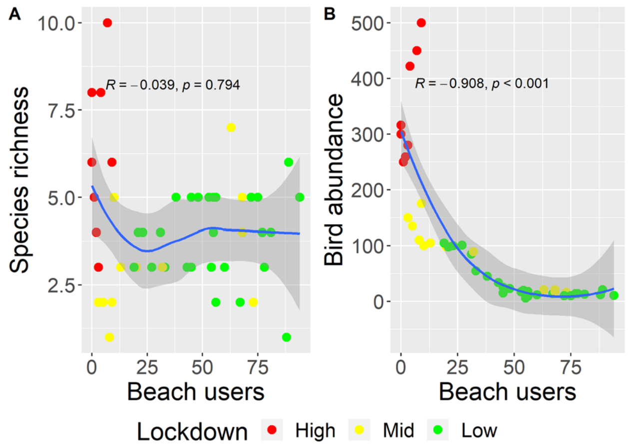

Fig. 2 Relationship of bird species richness **(A)** and abundance **(B)** with the number of users on the beach during the COVID-19 pandemic lockdown 2020–2021 in Playa Norte. In both charts, *R* is the Spearman's correlation coefficient, and *p* is the significance level. Colored dots are the months with high (red), mid (yellow), and low (green) restrictions to human mobility in public areas; the greens are the months without restrictions. The shaded area is the 95% confidence interval

was not affected by reduced human mobility (Fig. 2A), when the number of beach users increased in the mid- and lower-restriction phases, the bird abundance significantly decreased (Spearman's rank correlation: $rho = -0.908$, $p < 0.0001$, $n = 48$, Fig. 2B).

From 2016 to 2021, we marked 1030 nests in Playa Norte. It is worth noting that in 2020, the breeding effort was similar to that in the other years (250 nests counted). However, 127 nests were destroyed by a swell-caused flood due to the storm "Cristobal" (1st to 6th June 2020, wind speed up to 110 km/h, CONAGUA 2020). As the flood lasted approximately five days and the birds moved to a nearby place to establish a new breeding colony, nest destruction was not considered an anthropic disturbance. Because no hatches were recorded before the storm, estimation of the nest's failure/survival was not possible. Thus, we used left-truncated data (see Landes et al. 2020), and analyses of the failure or success rates used the 123 new nests of the season. In addition, note that there are no data for 2018 because this year, no breeding activity occurred in any of the known nesting sites on the island, and the birds were present in the study area for no longer than two weeks. In addition to Playa Norte, during the high-restriction phase of the COVID-19 lockdown, Least Tern occupied two areas (Puerto Real and San Julian, Fig. 1), usually visited by many people and not selected as nesting sites before 2020. All the nests recorded at these two sites failed, and they were not used again after the lockdown when people returned for fishing or recreational activities, which highlights the importance of human-caused disturbance on nesting site preferences.

The BIOENV model showed that vegetation height (up to 0.22 m) and cover (approximately 22%) were the environmental variables best correlated with nest abundance across the four nesting sites ($rho = 0.880$). In addition, the beach width of the preferred nesting sites was at least 30 m. Birds also preferred flat areas (slope approximately 7 cm/m) over steep slopes ($rho = 0.790$). Thus, preferred nesting areas should have shorter plants, lower cover, and gentle slopes. Playa Norte is the broader and flatter place among nesting sites, showing lower plant height.

The proportion of nest failures was higher before and after the 2020 lockdown. Accordingly, our results showed that higher nest success was related to diminished human mobility on the beach (Table 2). The estimated CDF showed that a lower nest failure rate occurred in 2020 and that before and after the lockdown, the failures were greater (Fig. 3A, Fig. S1). The Kaplan−Meier test also showed that in 2020, the risk of nest failure was lower as the nest survival rate was above the rates recorded for the other sampled years, more noticeable between 16 and 25 days after egg laying, the expected time for least Tern chicks hatching (Fig. 3B). The CPH regression analysis showed that in 2017 and 2020, the risk of nest failure was lower than that in the other sampling years (Table 3). In addition, nests with clutch size = 2 showed higher chances of success than those with clutch sizes = 1, 3, or 4 (Table 3). Additionally, the risk of nest failure because of predation significantly decreased when nests

Table 2 Comparison of nest failures and successes between pairs of years; *n* is the sample size of each compared pair of years; Prp_1 is the proportion of failures or successes for the years 2016, 2017, 2019, and 2021; Prp_2 is the proportion of failures or successes observed in 2020. The last four columns show the estimator, degrees of freedom, *p* value obtained from the *z* test, and the *phi* (φ) coefficient as a measure of effect size

Year	n	Failure		Success					
		Prp_1	Prp_2	Prp_1	Prp_2	χ^2	df	*p* value	φ
2016 vs. 2020	165 vs. 123	0.587	0.235	0.412	0.764	34.085	1	< 0.0001	−0.351
2017 vs. 2020	183 vs. 123	0.513	0.235	0.486	0.764	22.488	1	< 0.0001	−0.278
2019 vs. 2020	245 vs. 123	0.706	0.235	0.293	0.764	71.278	1	< 0.0001	−0.446
2021 vs. 2020	314 vs. 123	0.732	0.235	0.267	0.764	88.279	1	< 0.0001	−0.455

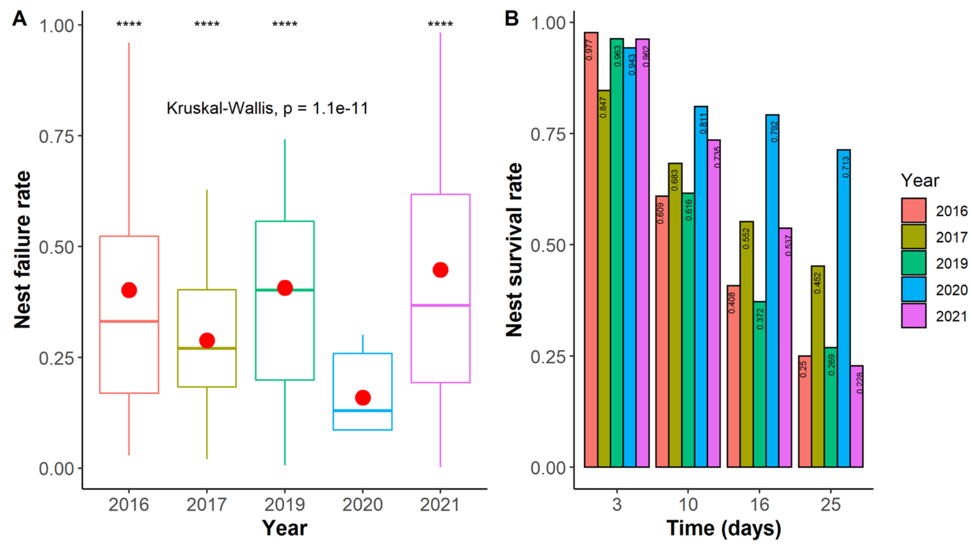

Fig. 3 Nest failure rates **(A)** over the sampling years in Playa Norte. The red dots are mean values, while the stars indicate significant differences regarding the estimated rate during the 2020 lockdown. The estimated nest survival rate **(B)** from egg laying to hatching. The numbers within the bars are the survival probabilities at different times during the Least Tern's nesting period

reached the expected hatching time (16–25 days). Nests aged > 25 days, although not predated or destroyed by human pedestrians, failed because of parental abandonment (Table S1). The distribution of nest clutch size along the egg laying-to-hatch time is shown in Table 4.

Discussion

Although there is high variability in the measured effects of the COVID-19 lockdown on wildlife, our results provide insights into the effect of increasing human mobility on wildlife populations and habitats of coastal areas and could be used to develop policies to reduce the negative anthropic impact of human activities on breeding populations to preserve coastal wildlife biodiversity.

Nesting Site Preference and Disturbances

Although only one breeding colony (Playa Norte) thrived during the lockdown, the reduced number of people on the beach areas allowed the selection of new nesting sites (Puerto Real and San Julian). However, as sites such as Km28, Puerto Real, and San Julian have narrow beach areas with higher vegetation and an average slope of 50 cm/m, only a few terns select them occasionally during the study period to breed. Least Terns usually search for open, broad, lightly vegetated, and flat areas (Gochfeld 1983; Lewinson & Deutchman 2014; Burger & Gochfeld 1990), such as Playa Norte.

Before and after the 2020 lockdown, the presence of people in the Puerto Real and San Julian beach areas generated noise pollution and limited habitat availability because of pedestrian movement, which could have influenced the avoidance of these beaches as breeding sites (Francis et al. 2009; Barber et al. 2011; Derryberry et al. 2020). Although it is assumed that noise pollution is less disturbing for birds in open areas (such as dunes) than in forested areas, it has been demonstrated that when breeding pairs are exposed to noise, the productivity of birds decreases (Bernat-Ponce et al. 2021). Furthermore, as Puerto Real and San Julian are narrow beach areas (beach strip wide range = 25–35 m) subject to car, ATV and pedestrian traffic, high-volume music from portable speakers, the presence of feral and domestic dogs, and fishing activities, the Least Terns were likely not to consider these areas as suitable breeding sites in the prior or post-pandemic time. In addition, some ground-nesting marine birds are sensitive to aircraft or motorized vehicles

Table 3 Cox hazard ratio estimation for Least Tern nests. Negative coefficients indicate a lower risk of failure. The exp(coef) column indicates the effect size of the included variables and gives the value of failure risk

Factor	coef	exp(coef)	se(coef)	Wald *z* value	Pr(> |*z*|)
Year 2017	− 0.406	0.667	0.128	− 3.157	0.001
Year 2020	− 1.170	0.310	0.200	− 5.848	< 0.0001
Clutch size = 2	− 0.409	0.664	0.083	− 4.893	< 0.0001
16–25 days	− 3.972	0.019	0.182	− 21.848	< 0.0001
> 25 days	− 7.004	0.001	0.508	− 13.801	< 0.0001

Table 4 Least Tern's clutch size distribution for early (EN), on-time (OTN), and old nests (ON) in Playa Norte during the study period

Clutch size	EN	OTN	ON
1	234	93	13
2	381	233	31
3	20	21	1
4	1	2	0

within a range from 100 to 400 m apart from nesting sites (Mallory 2016). Thus, disturbances at shorter distances likely influenced the nesting site preference (Maslo et al. 2018; Darrah 2020) in Puerto Real and San Julian.

Ireland (Basu et al. 2021), Kanpur, India (Mishra et al. 2021), and metropolitan Boston, USA (Terry et al. 2021), reported significant noise pollution reduction during the COVID-19 lockdown due to the reduced human mobility. Thus, it can be inferred that during the lockdown, the reduced noise and pedestrian traffic on the beaches of Isla del Carmen allowed birds to use available space to nest. A similar response of breeding habitat occupancy during the lockdown was observed in a shorebird species (*Charadrius alexandrinus*) on the coasts of northern Italy (Manenti et al. 2020). Furthermore, reduced habitat disturbance allows increased habitat occupancy, while the absence of stressors, such as kitesurfing, boating, and fishing, likely leads to greater foraging efficiency and improved body condition (LeTourneux et al. 2021), which could encourage birds to occupy new breeding sites. Other animals, such as foxes and raccoons, also showed increased habitat use in urban areas of Germany because of the limited presence of people on the streets (Louvrier et al. 2022). Thus, our findings reinforce the premise that lower disturbance, available space, and easy foraging during the COVID-19 restrictions benefited habitat occupancy, as occurred for the Least Terns. Consequently, management actions at breeding sites must be a priority to reduce human-related disturbances in bird behavior and reproduction (Sordello et al. 2020).

Effects of the COVID-19 Lockdown on the Avian Community

Although increased species richness in less disturbed habitats due to the lockdown was reported globally (Chethan 2020; Manenti et al. 2020; Bates et al. 2021; Estela et al. 2021), we did not find such an effect in Playa Norte. Nevertheless, we found a negative correlation between bird abundance and the number of pedestrians on the beach. A similar relationship has been observed in avian communities of urban and suburban areas of India, where vehicle and pedestrian traffic are critical factors affecting diversity and bird abundance (Verma & Murmu 2015; Chethan 2020). Moreover, globally, the abundance of different wildlife groups, especially birds and mammals, increased immediately after reducing human activities because of the COVID-19 lockdown (Bates et al. 2021). Similarly, Schrimpf et al. (2021) found that the COVID-19 lockdown positively influenced the counts of birds in several urban areas of North America due to the reduction in pedestrian presence, highlighting the impact of human-caused habitat disturbance on wildlife communities (Crooks et al. 2017; Williams et al. 2022). Thus, our findings demonstrate that implementing beach pedestrian regulation strategies might increase coastal ecosystem conservation, favoring avian communities and other wildlife.

Reduced Pedestrian Traffic and the Nesting Failure of the Least Tern

The impact of anthropic pressure was noticeable in Playa Norte. The CDF and Kaplan−Meier tests demonstrated that during the no lockdown sampling years, the average rate of nest failure ranged from 0.28 to 0.44, while it was only 0.16 during the 2020 lockdown (Fig. 3A). On the other hand, the nest survival rate was higher at the end of the hatching period during the lockdown than in the other sampled years because fewer disturbances occurred. A similar effect occurred in 2017 (Fig. 3B). In both cases, there was a reduction in the number of beach users. First, because of the oil production crisis between 2016 and 2017, when an essential part of the economic activities and job sources were lost in our study area, the tourism and recreation activities on the beach were reduced by approximately 40% to 50% (Casado Izquierdo 2021; Sovilla et al. 2021), which allowed birds to reach a nest survival rate = 0.45 (Fig. 3B). In addition, some research has found that some ground-nesting marine species are more successful when human or wild mammal-caused disturbances occur at distances larger than 100–200 m apart from nests (Mallory 2016). In Playa Norte, the COVID-19 lockdown reduced the presence of beach users and domestic dogs near the nesting areas. It may also have reduced the number of feral dogs at the beach using human garbage and food offered by people as feeding resources (although this was not measured in this study). Thus, lower disturbance and less bird flushing from nests contributed to lower nest failures during the lockdown in 2020. The CPH regression showed that even though during the first days, the nests of all years had a similar failure risk, during the COVID-19 lockdown, this risk decreased after ten days compared with the failure risk estimated in the rest of the sampling years at 10, 16, and 25 days (Fig. 3B). Increased reproductive and nesting activity due to diminished tourism and recreational activities on the shores has also been reported for other marine and land bird species (Bates et al. 2021), crabs (Soto et al. 2021), and sea turtles (Schofield et al. 2021). Moreover, open-habitat birds might tolerate some disturbance when habituated to human presence (Samia et al. 2015). Coastal birds such as Least Tern showed this behavior in breeding colonies of USA (Hillman 2012). If the Least Terns of Playa Norte behave similarly, they may have benefited from the reduced pedestrian presence during the lockdown, diminishing the rate of nest failure. Thus, because of the limited pedestrian traffic in our study area, the reproductive season in 2020 was the best for the Least Tern since 2016. Our results demonstrate that coastal area management plans and beach use regulations are needed to maintain minimum habitat quality conditions for the breeding sites used by shore and marine bird species. Additionally, our findings support the hypothesis that diminished tourism and recreational activities can contribute to biodiversity by increasing the abundance of different bird species or by increasing reproductive success (Manenti et al. 2020).

Conclusion

This work is the first mid-term study on Least Tern nest failure causes on an island of the SGoM and its relationship with anthropic-caused pressure. The restrictions to human mobility during the 2020 lockdown did not affect the species richness in the study area. However, fewer disturbances increased bird abundance and reduced the rate of nest failure by approximately 12% to 28%. Even though characteristics such as beach width, vegetation height, and cover appear to determine nesting site preferences, human-caused disturbances limit habitat availability and likely discourage birds from occupying some sites, such as Puerto Real and San Julian; accordingly, management policies must be prioritized to reduce anthropic disturbances to enhance reproductive habitat quality and wildlife conservation in coastal habitats.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-024-01341-y.

Acknowledgements The authors acknowledge Barbara Zaldívar and Josefina Santos Ramírez from ATEC and Hernán Álvarez Guillén and Andrés Reda Deara from ICML Estación El Carmen for their technical field support. To Comisión Nacional de Áreas Naturales Protegidas (CONANP) for all the facilities to field surveys. This work was partially supported by the project ICML UNAM-Influence of the COVID-19 pandemic on the Laguna de Términos.

Funding Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, No Award Number, Julio Cesar Canales-Delgadillo.

Data Availability Data on the Least Tern nest survival in 2016-2021 are available on request to the corresponding author.

References

Barber, J.R., C.L. Burdett, S.E. Reed, K.A. Warner, C. Formichella, K.R. Crooks, D.M. Theobald, and K.M. Fristrup. 2011. Anthropogenic noise exposure in protected natural areas: Estimating the scale of ecological consequences. *Landscape Ecology*. https://doi.org/10.1007/s10980-011-9646-7.

Basu, B., E. Murphy, A. Molter, A. Sarkar Basu, S. Sannigrahi, M. Belmonte, and F. Pilla. 2021. *Investigating changes in noise pollution due to the COVID-19 lockdown: The case of Dublin*. Ireland: Sustainable Cities and Society. https://doi.org/10.1016/j.scs.2020.102597.

Bates, A.E., R.B. Primack, B.S. Biggar, T.J. Bird, M.E. Clinton, R.J. Command, C. Richards, et al. 2021. Global COVID-19 lockdown highlights humans as both threats and custodians of the environment. *Biological Conservation*. https://doi.org/10.1016/J.BIOCON.2021.109175.

Benitez, J. A., R. M. Cerón-Bretón, J. G. Cerón-Bretón, and J. Rendón-Von-Osten. 2014. The environmental impact of human activities on the Mexican coast of the Gulf of Mexico: review of status and trends. In *WIT Transactions on Ecology and the Environment*, ed. G. Passerini, 37–50. https://doi.org/10.2495/EID140041.

Benard, A., and E.C. Bos-Levenbach. 1953. The plotting of observations on probability paper. *Statistica Neerlandica* 7 (3): 163–173.

Bernat-Ponce, E., J.A. Gil-Delgado, and G.M. López-Iborra. 2021. Recreational noise pollution of traditional festivals reduces the juvenile productivity of an avian urban bioindicator. *Environmental Pollution*. https://doi.org/10.1016/J.envpol.2021.117247.

Burger, J., and M. Gochfeld. 1990. Nest site selection in Least Terns (*Sterna antillarum*) in New Jersey and New York. *Colonial Waterbirds* 13: 31–40.

Canales-Delgadillo, J.C., E. Benítez-Orduña, R.Y. Pérez-Ceballos, A. Jiménez-Zaldívar, M. Gómez-Ponce, J.G. Cardoso-Mohedano, and M. Merino-Ibarra. 2020. Inter-annual diversity of birds in the shoreline of an island in the southern Gulf of Mexico. *Huitzil Revista Mexicana De Ornitología*. https://doi.org/10.28947/hrmo.2020.21.1.433.

Cardoso-Mohedano, J.G., J.C. Canales-Delgadillo, M.-L. Machain-Castillo, W.N. Sanchez-Muñoz, J.A. Sanchez-Cabeza, K. Esqueda-Lara, M.A. Gómez-Ponce, et al. 2022. Contrasting nutrient distributions during dry and rainy seasons in coastal waters of the southern Gulf of Mexico driven by the Grijalva-Usumacinta River discharges. *Marine Pollution Bulletin*. https://doi.org/10.1016/j.marpolbul.2022.113584.

Casado Izquierdo, J.M. 2021. De crisis sanitaria a crisis económica y laboral: Patrones espaciales del impacto de la COVID-19 en el empleo formal de México. *Investigaciones Geográficas*. https://doi.org/10.14350/rig.60212.

Celis-Hernandez, O., M.P. Giron-Garcia, J.F. Ontiveros-Cuadras, J.C. Canales-Delgadillo, R.Y. Pérez-Ceballos, R.D. Ward, O. Acevedo-Gonzales, J.S. Armstrong-Altrin, and M. Merino-Ibarra. 2020. Environmental risk of trace elements in mangrove ecosystems: An assessment of natural vs oil and urban inputs. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.138643.

Chethan, B.K. 2020. Abundance and distribution of bird species in lockdown and post-lockdown periods of Mysuru City, Karnataka. *Journal of Global Biosciences* 9: 8188–8198.

CONAGUA, Gerencia de meteorología y climatología. 2020. Ciclones tropicales 2020. Comisión Nacional del Agua. https://smn.conagua.gob.mx/tools/DATA/Ciclones%20Tropicales/Ciclones/2020-Cristobal%20.pdf. Accessed 01 March 2023.

Costanza, R., R. D'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, et al. 1997. The value of the world's ecosystem services and natural capital. *Nature*. https://doi.org/10.1038/387253a0.

Crooks, K.R., C.L. Burdett, D.M. Theobald, S.R.B. King, M. Di Marco, C. Rondinini, and L. Boitani. 2017. Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1705769114.

Cuevas-Gómez, G.A., J.C. Pérez-Jiménez, I. Méndez-Loeza, M. Carrera-Fernández, and J.L. Castillo-Géniz. 2020. Identification of a nursery area for the critically endangered hammerhead shark (*Sphyrna lewini*) amid intense fisheries in the southern Gulf of Mexico. *Journal of Fish Biology*. https://doi.org/10.1111/jfb.14471.

Cuevas, E., A. Uribe-Martínez, S.M. Morales-Ojeda, P.A. Gómez-Ruíz, E. Núñez-Lara, C. Teutli-Hernández, and J.A. Herrera-Silveira. 2021. Spatial configuration of seagrass community attributes in a stressed coastal lagoon, southeastern Gulf of Mexico. *Regional Studies in Marine Science*. https://doi.org/10.1016/j.rsma.2021.102049.

Darrah, A.J. 2020. Mixed evidence for effects of stewardship on Least Tern reproductive success in coastal Mississippi. *The Condor*. https://doi.org/10.1093/condor/duaa050.

Deo, S.V., V. Deo, and V. Sundaram. 2021. Survival analysis—part 2: Cox proportional hazards model. *Indian Journal of Thoracic and Cardiovascular Surgery*. https://doi.org/10.1007/s12055-020-01108-7.

Derryberry, E.P., J.N. Phillips, G.E. Derryberry, M.J. Blum, and D. Luther. 2020. Singing in a silent spring: Birds respond to a half-century soundscape reversion during the COVID-19 shutdown. *Science*. https://doi.org/10.1126/science.abd5777.

Diamond, A.W., and C.M. Devlin. 2003. Seabirds as indicators of changes in marine ecosystems: Ecological monitoring on Machias Seal island. *Environmental Monitoring and Assessment*. https://doi.org/10.1023/A:1025560805788.

Estela, F.A., C.E. Sánchez-Sarria, E. Arbeláez-Cortés, D. Ocampo, M. García-Arroyo, A. Perlaza-Gamboa, C.M. Wagner-Wagner, and I. MacGregor-Fors. 2021. Changes in the nocturnal activity of birds during the COVID–19 pandemic lockdown in a neotropical city. *Animal Biodiversity and Conservation*. https://doi.org/10.32800/abc.2021.44.0213.

Fraixedas, S., A. Lindén, M. Piha, M. Cabeza, R. Gregory, and A. Lehikoinen. 2020. A state-of-the-art review on birds as indicators of biodiversity: Advances, challenges, and future directions. *Ecological Indicators*. https://doi.org/10.1016/j.ecolind.2020.106728.

Francis, C.D., C.P. Ortega, and A. Cruz. 2009. Noise pollution changes avian communities and species interactions. *Current Biology*. https://doi.org/10.1016/j.cub.2009.06.052.

Gochfeld, M. 1983. Colony site selection by Least Terns: Physical attributes of sites. *Colonial Waterbirds* 6: 205–213.

Gold, K., P. León-Lobos, and M. Way. 2004. Manual de recolección de semillas de plantas silvestres para conservación a largo plazo y restauración ecológica. La Serena, Chile: Boletín INIA - Instituto de Investigaciones Agropecuarias. https://hdl.handle.net/20.500.14001/7000. Accessed 27 October 2022.

Gómez-Ponce, M.A., E. Coria-Monter, C. Flores-Coto, J.C. Canales-Delgadillo, J.G. Cardoso-Mohedano, and E. Durán-Campos. 2021. Seasonal and interannual variability in the density of the postlarvae of *Litopenaeus setiferus* and *Farfantepenaeus duorarum* in Términos Lagoon, Gulf of Mexico. *Crustaceana* https://doi.org/10.1163/15685403-bja10154.

Gordo, O., L. Brotons, S. Herrando, and G. Gargallo. 2021. Rapid behavioural response of urban birds to COVID-19 lockdown. *Proceedings of the Royal Society b: Biological Sciences*. https://doi.org/10.1098/rspb.2020.2513.

Escudero, M., R. Silva, and E. Mendoza. 2014. Beach erosion driven by natural and human activity at Isla del Carmen barrier island, Mexico. *Journal of Coastal Research*. https://doi.org/10.2112/SI71-008.1.

Haldar, S.K. 2013. Photogeology, remote sensing and geographic information system in mineral exploration. *Mineral Exploration*. https://doi.org/10.1016/B978-0-12-416005-7.00006-4.

Hall, M. 2015. Loving nature to death: tourism consumption, biodiversity loss and the Anthropocene. In Gren, M., and E. H. Huijbens (eds). *Routledge*, 52–73. London. https://doi.org/10.4324/9781315747361.

Hensel, T. G., and D. Barkemeyer. 2021. weibulltools: statistical methods for life data analysis. R package version 2.0.0. https://CRAN.R-project.org/package=weibulltools

Hillman, M.D. 2012. *Evaluating the impacts of military and civilian overflights and human recreation on least terns, common terns, gull-billed terns, and black skimmers at Cape Lookout National Seashore*. North Carolina: Virginia State University.

Holyoak, M., R.J. Meese, and E.E. Graves. 2014. Combining site occupancy, breeding population sizes and reproductive success to calculate time-averaged reproductive output of different habitat types: An application to tricolored blackbirds. *PLoS ONE*. https://doi.org/10.1371/JOURNAL.PONE.0096980.

IUCN. 2022. IUCN Red List of threatened species version 2021–3. https://www.iucnredlist.org/. Accesed 27 October 2022.

Landes, J., S.C. Engelhardt, and F. Pelletier. 2020. An introduction to event history analyses for ecologists. *Ecosphere*. https://doi.org/10.1001/ecs2.3238.

LeTourneux, F., T. Grandmont, F. Dulude-de Broin, M.C. Martin, J. Lefebvre, A. Kato, J. Bêty, G. Gauthier, and P. Legagneux. 2021. COVID19-induced reduction in human disturbance enhances fattening of an overabundant goose species. *Biological Conservation*. https://doi.org/10.1016/J.BIOCON.2021.108968.

Lewinson, R. L., and D. H. Deutschman. 2014. Long-term analysis of California Least Tern data. San Diego, CA. State of California Fish and Wildlife.

Lewis, J., J. Collison, and D. Pillay. 2022. Effects of COVID-19 lockdowns on shorebird assemblages in an urban South African sandy beach ecosystem. *Scientific Reports*. https://doi.org/10.1038/s41598-022-09099-8.

Louvrier, J.L.P., A. Planillo, M. Stillfried, R. Hagen, K. Börner, S. Kimmig, S. Ortmann, A. Schumann, M. Brandt, and S. Kramer-Schadt. 2022. Spatiotemporal interactions of a novel mesocarnivore community in an urban environment before and during SARS-CoV-2 lockdown. *Journal of Animal Ecology*. https://doi.org/10.1111/1365-2656.13635.

Mallory, M.L. 2016. Reactions of ground-nesting marine birds to human disturbance in the Canadian Arctic. *Arctic Science*. https://doi.org/10.1139/as-2015-0029.

Manenti, R., E. Mori, V. Di Canio, S. Mercurio, M. Picone, M. Caffi, M. Brambilla, G.F. Ficetola, and D. Rubolini. 2020. The good, the bad and the ugly of COVID-19 lockdown effects on wildlife conservation: Insights from the first European locked down country. *Biological Conservation*. https://doi.org/10.1016/j.biocon.2020.108728.

Martínez, M.L., G. Mendoza-González, R. Silva-Casarín, and E. Mendoza-Baldwin. 2014. Land use changes and sea level rise may induce a "coastal squeeze" on the coasts of Veracruz, Mexico. *Global Environmental Change*. https://doi.org/10.1016/J.GLOENVCHA.2014.09.009.

Maslo, B., K. Leu, T. Pover, M.A. Weston, and T.A. Schlacher. 2018. Managing birds of conservation concern on sandy shores: How much room for future conservation actions is there? *Ecology and Evolution*. https://doi.org/10.1002/ECE3.4564.

Mendoza-González, G., M.L. Martínez, D. Lithgow, O. Pérez-Maqueo, and P. Simonin. 2012. Land use change and its effects on the value of ecosystem services along the coast of the Gulf of Mexico. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2012.07.018.

Mishra, A., S. Das, D. Singh, and A.K. Maurya. 2021. Effect of COVID-19 lockdown on noise pollution levels in an Indian city: A case study of Kanpur. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-021-13872-z.

Nefas, S.M., K.L. Hunt, J.D. Fraser, S.M. Karpanty, and D.H. Catlin. 2018. Least Tern (*Sternula antillarum*) nest success and chick survival on the Missouri River following historic flooding. *The Wilson Journal of Ornithology*. https://doi.org/10.1676/16-210.1.

Ogden, J.C., J.D. Baldwin, O.L. Bass, J.A. Browder, M.I. Cook, P.C. Frederick, P.E. Frezza, et al. 2014. Waterbirds as indicators of ecosystem health in the coastal marine habitats of Southern Florida:

2. Conceptual ecological models. *Ecological Indicators*. https://doi.org/10.1016/j.ecolind.2014.03.008.

Oksanen, J., F. Guillaume-Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P. R. Minchin, et al. 2022. vegan: community ecology package. CRAN R-Project R package version 2.6–2. https://CRAN.R-project.org/package=vegan.

Paz-Ríos, C., A. Sosa-López, Y. Torres-Rojas, J. Ramos-Miranda, and R. del Río-Rodríguez. 2021. Fish species richness in the Terminos Lagoon: An occurrence data compilation of four sampling campaigns along a multidecadal series. *Biodiversity Data Journal*. https://doi.org/10.3897/BDJ.9.e65317.

Power, T.J., H. Paynter, M. Silva-Opps, and P.A. Quijón. 2022. The coastal breeding habitat of Bank Swallows (*Riparia riparia*) in an Atlantic Canada National Park: Assessing habitat use in relation to availability. *Canadian Journal of Zoology*. https://doi.org/10.1139/cjz-2021-0216.

R Development Core Team. 2023. R Development Core Team. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing , Vienna, Austria. https://www.R-project.org/.

Ramos, J. A., and R. W. Furness. 2022. Seabirds as indicators of forage fish stocks. In *Seabird Biodiversity and Human Activities*, ed. Ramos, J., and L. Pereira. Boca Raton FL, CRC Press. https://doi.org/10.1201/9781003047520-12.

Ruiz-Fernández, A.C., J.-A. Sanchez-Cabeza, T. Cuéllar-Martínez, L.H. Pérez-Bernal, V. Carnero-Bravo, E. Ávila, and J.G. Cardoso-Mohedano. 2020. Increasing salinization and organic carbon burial rates in seagrass meadows from an anthropogenically-modified coastal lagoon in southern Gulf of Mexico. *Estuarine, Coastal and Shelf Science*. https://doi.org/10.1016/j.ecss.2020.106843.

Samia, D.S.M., S. Nakagawa, F. Nomura, T.F. Rangel, and D.T. Blumstein. 2015. Increased tolerance to humans among disturbed wildlife. *Nature Communications*. https://doi.org/10.1038/ncomms9877.

Santander-Monsalvo, J., I. Espejel, and L. Ortiz-Lozano. 2018. Distribution, uses, and anthropic pressures on reef ecosystems of Mexico. *Ocean & Coastal Management*. https://doi.org/10.1016/j.ocecoaman.2018.08.014.

Schrimpf, M. B., P. G. Des Brisay, A. Johnston, A. C. Smith, J. Sánchez-Jasso, B. G. Robinson, M. H. Warrington, et al. 2021. Reduced human activity during COVID-19 alters avian land use across North America. *Science Advances.* 5073–5095. https://doi.org/10.1126/sciadv.abf5073.

Schofield, G., L.C.D. Dickson, L. Westover, A.M. Dujon, and K.A. Katselidis. 2021. COVID-19 disruption reveals mass-tourism pressure on nearshore sea turtle distributions and access to optimal breeding habitat. *Evolutionary Applications*. https://doi.org/10.1111/EVA.13277.

SEMARNAT. 2010. NOM-059-SEMARNAT-2010 Protección ambiental, especies nativas de México de flora y fauna silvestres, categorías de riesgo y especificaciones para su inclusión, exclusión o cambio. Lista de especies en riesgo. Diario Oficial de la Federación. México.

Sordello, R., O. Ratel, F.F. de Lachapelle, C. Leger, A. Dambry, and S. Vanpeene. 2020. Evidence of the impact of noise pollution on biodiversity: A systematic map. *Environmental Evidence*. https://doi.org/10.1186/S13750-020-00202-y.

Soto, E.H., C.M. Botero, C.B. Milanés, A. Rodríguez-Santiago, M. Palacios-Moreno, E. Díaz-Ferguson, Y.R. Velázquez, et al. 2021. How does the beach ecosystem change without tourists during COVID-19 lockdown? *Biological Conservation*. https://doi.org/10.1016/j.biocon.2021.108972.

Sovilla, B., E. Gómez-Ramírez, and M. Sánchez-Pérez. 2021. La reforma energética y el problema petrolero en México. *Revista CEA*. https://doi.org/10.22430/24223182.1631.

Steibl, S., J. Franke, and C. Laforsch. 2021. Tourism and urban development as drivers for invertebrate diversity loss on tropical islands. *Royal Society Open Science*. https://doi.org/10.1098/rsos.210411.

Terry, C., M. Rothendler, L. Zipf, M.C. Dietze, and R.B. Primack. 2021. Effects of the COVID-19 pandemic on noise pollution in three protected areas in metropolitan Boston (USA). *Biological Conservation*. https://doi.org/10.1016/j.biocon.2021.109039.

Therneau, T. M. 2022. A package for survival analysis in R. R package version 3.3–1. https://CRAN.R-project.org/package=survival.

Thompson, B. C., J. A. Jackson, J. Burger, L. A. Hill, E. M. Kirsch, and J. L. Atwood. 2020. Least Tern (Sternula antillarum). In Birds of the World, ed. A. F. Poole and F. B. Gill. Cornell Lab of Ornithology. https://doi.org/10.2173/bow.leater1.01.

Thurstan, R.H., K.J. Hockings, J.S.U. Hedlund, E. Bersacola, C. Collins, R. Early, Y. Ermiasi, et al. 2021. Envisioning a resilient future for biodiversity conservation in the wake of the COVID-19 pandemic. *People and Nature*. https://doi.org/10.1002/pan3.10262.

Verma, S.K., and T.D. Murmu. 2015. *Impact of environmental and disturbance variables on avian community structure along a gradient of urbanization in Jamshedpur*. India: PLOS ONE. https://doi.org/10.1371/journal.pone.0133383.

Williams, D.R., C. Rondinini, and D. Tilman. 2022. Global protected areas seem insufficient to safeguard half of the world's mammals from human-induced extinction. *PNAS*. https://doi.org/10.1073/pnas.2200118119.

Zuarth, C.G., A. Vallarino, and A.V. Botello. 2016. Breeding biology of the Atlantic Least Tern (*Sternula antillarum antillarum*) in a colony of the south of the Gulf of Mexico: New perspectives for its threat status. *Revista Brasileira De Ornitologia*. https://doi.org/10.1007/BF03544361.