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Research Paper

Lost in the glow: understanding the impact of light pollution on storm-petrels

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ABSTRACT. Seabirds are highly susceptible to human-induced threats such as light pollution, which alters their behavior and leads to increased mortality rates. Reports of storm-petrels (Hydrobatidae) affected by light pollution exist worldwide, yet the population-level response of this diverse and globally distributed family remains severely understudied. Therefore, we aim to uncover, through an extensive literature review, the current state of evidence regarding the effects of light pollution on seabird populations of the Hydrobatidae family. We conducted a scoping review on Scopus and Web of Science academic platforms and obtained 12 articles that met our search criteria. Our results indicate storm-petrels' groundings were recorded for almost all Hydrobatidae genera. Although inshore and offshore light pollution sources can lead to storm-petrel disorientation, the artificial light source characteristics (e.g., intensity, spectrum) were generally not quantified. Susceptibility to light pollution is associated with environmental factors (e.g., moon phase) and the storm-petrels' age, as fallout occurs primarily in fledglings during their first flight leaving the colony. While a limited number of studies assessing light-induced storm-petrel mortality at a population level suggest that it may not be high enough to be deemed as a substantial threat, further research is required to fully understand the extent of light pollution as a potential danger and develop effective conservation measures.

Le danger des lumières artificielles : comprendre l'impact de la pollution lumineuse sur les pétrels-tempête

RÉSUMÉ. Les oiseaux marins sont très sensibles aux menaces d'origine humaine, notamment à la pollution lumineuse. Celle-ci modifie leur comportement et entraîne une augmentation de leur taux de mortalité. Nombre de rapports étudient les conséquences de la pollution lumineuse sur les pétrels-tempête (Hydrobatidae) du monde entier. Toutefois, l'impact sur les populations de cette famille d'oiseaux diversifiée et répartie partout sur le globe reste très insuffisamment étudié. Par conséquent, nous proposons d'analyser méticuleusement la littérature scientifique à la recherche de preuves concernant les effets de la pollution lumineuse sur les populations d'oiseaux marins de la famille des Hydrobatidae. Ainsi, nous avons procédé à une analyse exhaustive des plateformes universitaires Scopus et Web of Science et nous avons sélectionné 12 articles répondant à nos critères de recherche. Nos résultats indiquent que les échouages de pétrels-tempête ont été enregistrés pour presque tous les genres d'Hydrobatidae. Bien que les sources côtières et hauturières de pollution lumineuse puissent entraîner la désorientation des pétrels-tempête, les caractéristiques de ces sources de lumière artificielle (p. ex. : intensité, spectre) n'ont généralement jamais été quantifiées. La sensibilité à la pollution lumineuse est associée à des facteurs environnementaux (p. ex. : les phases lunaires) et à l'âge des pétrels-tempête, car les échouages se produisent principalement chez les oisillons au cours de leur premier vol, au moment de quitter la colonie. Un nombre limité d'études évaluent l'impact des sources de lumière artificielle sur les populations de pétrels-tempête et suggèrent que cette mortalité n'atteint pas des niveaux suffisamment élevés pour constituer une menace substantielle. Toutefois, des recherches supplémentaires sont nécessaires pour comprendre l'étendue et la dangerosité potentielle de la pollution lumineuse et pour développer des mesures de conservation efficaces.

Key Words: *ALAN; conservation; fallout; Hydrobatidae; seabirds*

INTRODUCTION

The order Procellariiformes is among the most endangered seabird groups with the highest number of threatened species of marine birds globally (Croxall et al. 2012, as cited in Rodríguez et al. 2019, Norambuena et al. 2021). Procellariiformes, in general, are highly adapted to the marine environment and spend most of their lives in the open oceans (Rodríguez et al. 2019). They travel long distances for foraging, migration, and dispersal, mostly returning to land only for breeding or at night (Silva et al. 2016, Sausner et al. 2016, Rodríguez et al. 2019).

Within the Procellariiformes order, storm-petrels (Hydrobatidae family) are among the most poorly-known seabird groups (Rodríguez et al. 2019). The limited knowledge of the biology and ecology of storm-petrels, combined with the absence of accurate population estimates, is largely due to their nocturnal, cryptic, and burrow-nesting behavior, as well as the unknown or inaccessible locations of their colonies, which are often found on cliffs or remote islands (Rodríguez et al. 2017, 2019). Of the 22 identified species within the Hydrobatidae family (Nunn and Stanley 1998, Tree of Life Web Project 2008), 12 have declining population trends, and four prove to be Data Deficient (IUCN

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2022). Thus, it is important to identify threats and their impact on storm-petrel populations (Norambuena et al. 2021).

Among the documented land-based and marine threats for storm-petrels (e.g. invasive alien species, human disturbance, residential and community development, pollution, mining, and energy farms; Dias et al. 2019; Norambuena et al. 2021), one of the globally increasing threats is light pollution (Kyba et al. 2017). Light pollution is defined as the use of artificial illumination that disrupts natural darkness and the visibility of the night sky (Gaston et al. 2013, Falchi et al. 2016). With the global rise in artificial light due to expanding human settlements driven by population growth (Kyba et al. 2017, United Nations 2019), the ongoing expansion of population centers is expected to escalate light pollution and its effects on storm-petrel populations.

The presence of Artificial Lights at Night (ALAN) may result in the light-induced disorientation of seabirds (i.e., "fallout"), particularly among the youngest. On their first flight away from the colony, fledglings become disoriented by the presence of anthropogenic sources of light (Miles et al. 2010, Wilhelm et al. 2021). As fledglings approach and fly over light sources, they can fall to the ground due to physical exhaustion or collision with man-made structures (Troy et al. 2011), hereby referred to as "grounding." Storm-petrel fledglings that survive the fall may still die due to an increased risk of predation, starvation, dehydration, drowning, or even collisions with motorized vehicles (Rodríguez et al. 2012, Rodríguez et al. 2014, Rodríguez et al. 2017). Although fallout is considered an important source of mortality for storm-petrel populations (Rodríguez et al. 2017), its mechanism is still unknown. The main hypothesis is that light pollution may outshine natural celestial cues, interfering with storm-petrel navigation systems (Rodríguez et al. 2017). Additional hypotheses like foraging inexperience and an immature visual system have been formulated, but the information is scarce and inconclusive (Imber et al. 1975, Atchoi 2020).

Given the scarce information on the impacts of light pollution on storm-petrel populations, we conducted a scoping review to determine the main impacts of light pollution in the Hydrobatidae family. Through the scoping review, we aim to answer the following research question: What is the current state of evidence on the effects of light pollution on bird populations of the Hydrobatidae family? We expect this review will contribute to the inputs required for the development of adequate management and conservation plans for storm-petrels.

METHODS

For the scoping review, we limited our efforts to two academic platforms, Scopus and Web of Science. These platforms contain a wide array of scientific content on the selected subject.

Keyword selection and identification of relevant articles

We limited our search to keywords in two categories: (1) storm-petrel taxa, according to the Tree of Life Project (Nunn and Stanley 1998, Tree of Life Web Project 2008; Appendix 1), and (2) Light pollution (Table 1). All searches were conducted in English, considering that a first exploratory search in Spanish using the SciELO library catalog returned no results. During our search, only one full-text article (Silva et al. 2020) was found in

Table 1. Keywords (with synonyms) and syntax used for literature search in Scopus and Web of Science.

#1: Storm-petrel taxa	#2: Light pollution	Search terms[†]
("hydrobatidae" OR "oceanodroma" OR "hydrobates" OR "oceanites" OR "pelagodroma" OR "fregetta" OR "nesofregetta" OR "garrodia" OR "storm petrel" OR "storm-petrel")	("light pollution" OR "artificial light" OR "skylight" OR "sky glow)	#1 AND #2
("hydrobatidae" OR "oceanodroma" OR "hydrobates" OR "oceanites" OR "pelagodroma" OR "fregetta" OR "nesofregetta" OR "garrodia" OR "golondrina de mar" OR "paiño" OR "golondrina de tempestad")	("contaminación lumínica" OR "luz artificial" OR "fotopolución" OR "contaminación luminosa")	#1 AND #2

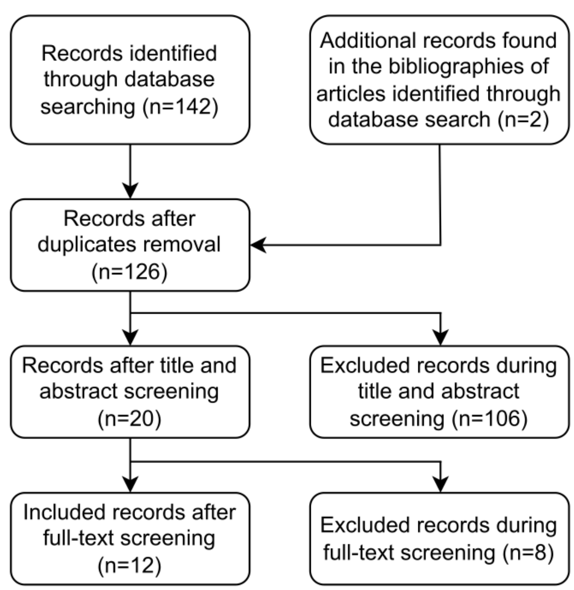
[†] The search syntax was adapted to the format used on each platform.

Spanish, although its information in the library catalog was obtained in English. No restrictions were applied on geographical location.

Article selection process and eligibility criteria

We carried out the literature search on February 16, 2023. Articles published between 01/01/2000 and 31/12/2022 were compiled and uploaded to the Rayyan reference manager (Mourad et al. 2016) for duplicate detection. Articles labeled as duplicates (by the default setting in Rayyan) were individually reviewed by two authors (PS, RM) and removed from the analysis. Article titles and abstracts were screened and excluded if they did not explicitly include light pollution and its effects on Hydrobatidae species or only mentioned unspecified seabirds (Fig. 1). This first screening process was executed by two authors (PS, RM), although in case of discrepancies, all authors discussed whether to exclude or include the article in the next exclusion stage.

Fig. 1. Flowchart of the article selection process.



The full-text screening was performed using the Zotero reference manager version 6.0.4 (Zotero n.d.). Original research papers that included both light pollution and its effects on Hydrobatidae species were included. Review articles were excluded in this process, except for Silva et al. (2020), as some of their information was published for the first time. At this stage, we also incorporated relevant articles identified within the bibliographies of the originally identified articles. We selected articles from the bibliographies based on title, abstract, and full-text screenings. All studies included in this stage were used for the analysis and literature synthesis presented in the results section.

Data management and result summarizing

A Microsoft Excel version 16.0. spreadsheet (Microsoft Corporation 2021) was created with all the articles in Zotero after duplicate removal (Appendix 2). Information presented for each article includes publication year, title, journal, DOI, abstract, volume, issue, pages, library catalog, link attachment, status, exclusion stage, and exclusion criteria. Table 2 presents a summary of the relevant content of the included articles.

RESULTS

Literature profile and article characteristics

A total of 144 records were identified; 142 were from the database search, and two were added from the bibliographies of articles found in the original search (Appendix 3). After screening titles and abstracts, 20 articles were reviewed in full. Of these, 12 articles published between 2005 and 2022 were included in the final analysis, with half published between 2020 and 2022. Of the 12 articles, six presented data from the southern hemisphere and six from the northern hemisphere. All articles extracted data from locations in the Atlantic Ocean, with only four exceptions: one article from the Mediterranean Sea and three articles from the Pacific Ocean. Most articles included data recovered before the year 2013 (Table 2). In six of the included articles, data collection spanned short periods (< 4 years), while six articles had a more extended data collection period (> 4 years).

Only four articles explicitly focused on Hydrobatidae species; the rest focused on seabirds in general. In these last articles, the percentage of Hydrobatidae species representation was below 45% of all recorded seabird groups. Only two articles used a systematic methodology for data collection (Miles et al. 2010, Wilhelm et al. 2021), while four articles used citizen science (Rodríguez and Rodríguez 2009, Murillo et al. 2013, Rodríguez et al. 2015), and three collected their data from records by vessel crew (Black 2005, Glass and Ryan 2013, Ryan et al. 2021). The remaining articles used previous reports from multiple sources (Silva et al. 2020) or from wildlife centers (Montesdeoca et al. 2017, Gjerdrum et al. 2021, Heswall et al. 2022).

Regarding light pollution, eight articles identified sources of light pollution as inshore, offshore sources, or both. Inshore sources of artificial lights were mentioned in four articles (Miles et al. 2010, Murillo et al. 2013, Wilhelm et al. 2021, Heswall et al. 2022), offshore sources were considered in three articles (Black 2005, Glass and Ryan 2013, Ryan et al. 2021), and only one article included both (Gjerdrum et al. 2021). Merely three articles quantified light pollution levels, two used VIIRS satellite data (Rodríguez et al. 2015, Gjerdrum et al. 2021), while Heswall et al. (2022) used previously measured natural sky brightness in the study area. Additional variables on light pollution effects were evaluated in 9 articles; the remaining articles recorded grounding data (location and date). Environmental variables, such as moon phase and wind, were considered in four (Miles et al. 2010, Murillo et al. 2013, Wilhelm et al. 2021, Gjerdrum et al. 2021) and one article (Wilhelm et al. 2021) respectively. Body condition was assessed in five articles (Black 2005, Murillo et al. 2013, Rodríguez et al. 2015, Wilhelm et al. 2021, Gjerdrum et al. 2021), including body mass, wing length, and plumage condition. Storm-petrel´s age class was recorded in six articles (Rodríguez and Rodríguez 2009, Miles et al. 2010, Rodríguez et al. 2015, Silva et al. 2020, Wilhelm et al. 2021, Heswall et al. 2022), while sex was only determined in 2 (Black 2005, Montesdeoca et al. 2017).

Article content

Grounding records

Grounding records were found for all Hydrobatidae genera except for *Nesofregetta.* Out of the 22 species of the Hydrobatidae family (Tree of Life Web Project 2008, Nunn and Stanley 1998), grounding was recorded in 12 species (Table 3). *O. leucorhoa* and *P. marina* were the most frequently mentioned species, followed by *H. pelagicus*.

Age class

Storm-petrel fallout occurs primarily in fledglings during their first flight leaving the colony. Of the articles that included age class in their analysis, five concluded that fledglings comprised a higher percentage of grounding records in comparison with adult storm-petrels (Miles et al. 2010, Rodríguez et al. 2015, Silva et al. 2020, Wilhelm et al. 2021, Heswall et al. 2022). According to a study (Wilhelm et al. 2021), over 99% of all grounded *O. leucorhoa* were fledglings. These results coincide with Silva et al. (2020), in which fledglings account for the majority of grounded individuals of *O. oceanicus*, *O. markhami,* and *G. nereis*. Fledgling fallout rates present seasonal variation and coincide with the storm-petrel´s reproductive season, as found by Rodríguez et al. (2015) and Heswall et al. (2022). Contrary to previously described articles, the publication by Rodríguez and Rodríguez (2009) indicated that 84% of grounded *O. castro* individuals and all of *O. leucorhoa*, *P. marina,* and *H. pelagicus* individuals were adults.

Light pollution and additional variables

Storm-petrels can be attracted to terrestrial or marine light pollution sources. Eight articles registered grounding events inshore, but only four mention the inshore light pollution source (Miles et al. 2010, Murillo et al. 2013, Wilhelm et al. 2021, Heswall et al. 2022). Of these, only Wilhelm et al. (2021) specified the type of property where stranded birds were found (e.g., residential, industry, road, highway, business), and Heswall et al. (2022) made a distinction between urban and rural areas. Three articles (Black 2005, Glass and Ryan 2013, Ryan et al. 2021) assessed bird strike events caused by offshore light pollution sources, mainly fishing vessels' deck lights. Only Gjerdrum et al. (2021) considered offshore and inshore light pollution sources, including oil and gas platforms, vessels, construction sites, and municipalities.

Evidence suggests a potential relationship between moon phases and grounding registers (Miles et al. 2010, Murillo et al. 2013, Gjerdrum et al. 2021, Wilhelm et al. 2021). As established by Wilhelm et al. (2021), during the new moon (lowest moon visibility), *O. leucorhoa* had the highest grounding rates. On the

Table 2. Summary of included articles.

Citation[†]	Location	Methods	Light pollution	Main findings
Wilhelm et al. 2021	The Witless Bay Ecological Reserve, Newfoundland and Labrador, CA	Systematic collection	Evaluated qualitatively	There were 1156 reports of stranded *Oceanodroma leucorhoa* storm-petrels in 2018 and 747 in 2019, and the proportion of stranded birds found alive was 40% and 60%, respectively. Of the 686 stranded *O. leucorhoa* examined, all but five were aged as recently fledged birds. Most strandings were reported on industry properties, followed by business properties and roads or highways, and the highest strandings occurred around the new moon.
Ryan et al. 2021	Tristan da Cunha, UK	Vessel data	Not evaluated	In total, 1823 birds were reported coming aboard the ship on 118 nights, all at the uninhabited islands. Petrels, shearwaters, and storm-petrels were reported coming aboard the vessel at night. Prions were the most common taxon, followed by two species of *Fregetta* storm-petrels, *Pelagodroma marina* storm-petrels, and Subantarctic Shearwaters *Puffinus elegans*. Birds were killed on 3% of fishing nights, with at least 70 birds found dead overall, most of which were prions, followed by *Fregetta* storm-petrels, Subantarctic Shearwaters, and *P. marina* storm-petrels.
Gjerdrum et al. 2021	Atlantic Canada	Previous reports by wildlife centers	Evaluated quantitatively	A total of 7922 reported stranded birds represented 108 species and 32 families. The majority (87.4%) were storm-petrels, most of them identified as *Oceanodroma leucorhoa* storm-petrels. Many of the strandings were reported in offshore production platforms and support vessels, followed by onshore refinery and construction facilities, and offshore seismic vessels. The frequency of large stranding events was significantly related to moon phase, as the largest stranding events occurred when the moon was less than 20% illuminated.
Montesdeoca et al. 2017	Gran Canaria Island, ES	Previous reports by wildlife centers	Not evaluated	A total of 1956 seabirds belonging to the Orders Procellariiformes, Suliformes, and Charadriiformes were included in this study. Light pollution (fallout) was the most frequent cause of admission into the Tafira Wildlife Rehabilitation Center (TWRC), mainly among Procellariiformes species, and *Pelagodroma marina* storm-petrel (the fourth species most frequently admitted) had the highest risk of fallout. Light pollution admissions were concentrated around the fledgling periods of the different species affected.
Rodríguez et al. 2015	Balearic Islands, ES	Citizen science	Evaluated quantitatively	A total of 304 fledgling birds were found stranded due to attraction to artificial lights, but only 26 were fatally affected by lights. The Scopoli's Shearwater was the most abundant species found, followed by the Balearic shearwater and the *Hydrobates pelagicus* storm-petrel. In general, colonies for all species showed low mean light pollution levels, and the percentage of the population fledglings grounded by artificial lights was lower than 1%.
Glass and Ryan 2013	Tristan da Cunha, UK	Vessel data	Not evaluated	Over three fishing seasons 723 seabird strikes were recorded, of which 36% were storm-petrels (*Pelagodroma marina, Fregetta grallaria, Fregetta tropica*). The mortality rate varied among species, with recorded storm-petrels exhibiting a lower mortality rate (5%) compared to other procellariids.
Miles et al. 2010	St Kilda archipelago, GB-SCT	Systematic collection	Evaluated qualitatively	Over four years 45 *Oceanodroma leucorhoa* and one *Hydrobates pelagicus* were collected. No storm-petrels were found when light reduction methods were applied. Moon phase had an effect on attraction to artificial lights, nights with low moon visibility led to higher storm-petrel grounding records.
Rodríguez and Rodríguez 2009	The Canary Islands, ES	Citizen science	Evaluated qualitatively	During a nine-year study, four species of storm-petrels were recorded as grounded, including *Oceanodroma castro*, *Oceanodroma leucorhoa*, *Pelagodroma marina*, and *Hydrobates pelagicus*. Almost 94% of all grounded seabirds were fledglings. The number of grounding records varied based on the breeding phenologies of the different species.
Heswall et al. 2022	Auckland, NZ	Citizen science and previous reports by wildlife centers	Evaluated quantitatively	The wildlife rehabilitation center received 356 seabirds of eight different species, out of which seven were *Pelagodroma marina*, and these experienced a 29% mortality rate. The grounded *P. marina* storm-petrels were found between November to March, which aligns with the fledgling months of the storm-petrel population in Auckland. Areas with higher levels of light pollution (indicated by lower values of maximum natural night sky brightness) had more seabird groundings, with the majority occurring in those areas.
Black 2005	South Georgia Maritime Zone, UK	Vessel data	Not evaluated	A total of 899 seabird strikes were recorded, of which 59 belong to *Oceanites oceanicus*, 13 to *Fregetta tropica*, and two to *Garrodia nereis.*
Murillo et al. 2013	Lima, PE	Citizen science	Not evaluated	A total of 62 groundings of *Oceanodroma hornbyi* storm-petrels were recorded. The majority of these groundings occurred in June, and there was a higher frequency of groundings during the waxing gibbous and new moon phases. Although the sex of the storm-petrels was evaluated, no statistically significant effect on the frequency of groundings was found.

[†] Silva et al. 2020 was not considered, as it does not present the necessary information.

other hand, there are few stranding records during the full moon. This lack of records is supported by findings made by Gjerdrum et al. (2021), Miles et al. (2010), and Murillo et al. (2013) in which the largest stranding events of *O. leucorhoa* (Miles et al. 2010, Gjerdrum et al. 2021) and *O. oceanicus* (Gjerdrum et al. 2021) occurred during the moon's low illumination phase and most of *O. hornbyi* fallouts (Murillo et al. 2013) occurred during the first quarter of the moon or new moon. In addition, Miles et al. (2010) considered the percentage of the night that the moon was above the horizon but found no interactions with the moon phase in the analysis of *O. leucorhoa* grounding rates. Although these articles suggest a potential association between moon phase and groundings, the possibility of a causal link requires further evaluation and is beyond the scope of this study.

Population-level impacts and species' threat status

According to IUCN (2022), among the 12 storm-petrel species mentioned in the articles included in this study, nine have decreasing population trends, two have unknown statuses, and only one is considered stable. Additionally, *O. hornbyi* and *O.*

Table 3. Light pollution data sorted by species. This table summarizes the storm-petrel grounding information collected in all included papers, represented in the table by numbered superscripts. Wilhelm et al. (2021),[1] Ryan et al. (2021),[2] Gjerdrum et al. (2021),[3] Silva et al. (2020),[4] Montesdeoca et al. (2017),[5] Rodríguez et al. (2015),[6] Glass and Ryan (2013),[7] Miles et al. (2010),[8] Rodríguez and Rodríguez (2009),[9] Heswall et al. (2022),[10] Black (2009),[11] and Murillo et al. (2013).[12] Not all included articles specified the information displayed in the table.

Species	Data collection period[†,‡]	Light pollution source	Assessed variables	Effect on population
Oceanodroma leucorhoa (Vieillot, 1818)	1998–2006[9]; 1998–2018[3]; 2003–2013[5]; 2005–2008[8]; 2018–2019[1]	Industry properties, business properties, roads or highways, airports, outdoor recreational sites, public buildings, residential,[1] oil and gas platforms, support vessels, drillships, seismic vessels, refineries, construction sites, municipalities,[3] Village of Hirta[8]	Lunar influence or moon phase,[1,3,8] gender, age locality,[5,9] body mass, wing length, wind direction and speed,[1] length of time that the moon was above the horizon at night,[8] distribution of groundings.[9]	The total number of fallouts was low compared to the colonies' estimated breeding population.[8]
Oceanodroma markhami (Salvin, 1883)	N.A.	Arica city, Carlos Dittborn stadium, mining industry, salt mines, Iquique city, Antofagasta city[4]	N.A.	N.A.
Oceanodroma tethys (Bonaparte, 1852)	N.A.	Luminaries in Iquique[4]	N.A.	Unknown[4]
Oceanodroma hornbyi (G. R. Gray, 1864)	2009–2012[12]	Center and South Peru, Arica city, Iquique city, Alto Hospicio commune, Antofagasta region, Tocopilla, Michilla, Baquedano, Sierra Gorda, industry sector La Negra,[4] Lima city[11]	Date of encounter moon phase, body weight, plumage condition, and additional biometric data (folded wing length, tarsus, culmen and head length)[11]	N.A.
Oceanodroma castro (Harcourt, 1851)	1998–2006[9]; 2003–2013[5]	Urban areas[5]	Date, location, age, seasonality,[5,9] gender,[5] distribution of grounded birds[9]	The percentage of grounded fledglings and adults represents 0.6% of the fledglings produced by the population and 0.9% of the adult population, respectively.[5]
Pelagodroma marina (Latham, 1790)	1998–2006[9]; 2003–2013[5]; 2010–2013[7]; 2013–2021[2]; 2018–2021[10]	Fishing vessel,[2,7] urban and rural areas[10]	Seasonality,[2,5,9,10] date, location, age,[5,9] gender,[5] distribution of grounded birds[9,10]	The number of individuals killed per year is <0.1% of the island population.[2] According to Glass and Ryan (2013), "it is unlikely that the numbers killed currently are significant at the population level."[7]
Oceanites oceanicus (Kuhl, 1820)	1998–2018[3]; 2004[11]	Fishing vessel[11]	Location,[3] weight, sex, stomach samples[11]	Unknown[4]
Oceanites gracilis (Elliot, 1859)	N.A.	Iquique city and Antofagasta city[4]	N.A.	N.A.
Garrodia nereis (Gould, 1841)	2004[11]	Meteorological station,[4] fishing vessel[11]	Weight, sex, stomach samples[11]	N.A.
Fregetta grallaria (Vieillot, 1817)	2010-2013[7]; 2013–2021[2]	Fishing vessel[2,7]	Seasonality[2]	The number of individuals in each species killed per year is <0.1% of the island population.[2]
Hydrobates pelagicus (Linnaeus, 1758)	1998–2006[9]; 1999–2013[6]; 2003–2013[5]; 2005–2008[8]	Village of Hirta[8]	Age, location, seasonality,[5,9] date,[5,6,9] gender, annual variation,[5] body mass, distance from rescue location to colony,[6] moon phase, length of time that the moon was above the horizon,[8] distribution[9]	The percentage of fledglings grounded by artificial lights was lower than 1% (between 0.13 and 0.18%) of the fledglings produced annually.[6] There are low fallout numbers compared to the colonies' estimated breeding population.[8] The percentage of grounded adults represents only 0.4% of the adult population.[9]
Fregetta tropica (Gould, 1844)	2004[11]; 2013–2021[2]; 2012–2013[7]	Fishing vessel[2,7,11]	Seasonality,[2] weight, sex, stomach samples[11]	The number of individuals in each species killed per year is <0.1% of the island population.[2]

† Years of data collection from Silva et al. 2020 were not considered, as it was not specified for most cases.
‡ Years stated in this column do not imply that data was recorded during the entire year in question.

markhami are assessed in the Red List as Near Threatened, *O. leucorhoa* as Vulnerable (*O. leucorhoa*), and *O. gracilis* as Data Deficient. However, the effect of light-induced groundings as a threat to storm-petrel populations is rarely assessed.

Out of the 12 articles included, only five considered the population impact of light pollution (Appendix 3). The articles by Rodríguez and Rodríguez (2009), Ryan et al. (2021), and Rodríguez et al. (2015) found that the percentage of individuals killed annually by fallout is less than 1% of the respective species' population. According to Miles et al. (2010), the number of grounded *O. leucorhoa* and *H. pelagicus* is low compared to their breeding population, and Glass and Ryan (2013) stated that it is unlikely that grounding records of *P. marina* and *Fregetta spp.* have a significant effect at a population level.

DISCUSSION

This scoping review provides an overview of the state of evidence on the effects of light pollution on storm-petrel (Hydrobatidae) populations worldwide. We discuss the most relevant findings recovered from the analyzed scientific literature, which include (1) the spatial and temporal distribution patterns of light-induced grounding, (2) the implications of these results for future research on light pollution, (3) the knowledge gaps in the reviewed literature, and (4) the limitations encountered during this review.

Relevance of findings for scientific research and literature

This article is the first global review to focus on light pollution effects on the members of the Hydrobatidae family, aside from broader reviews that include other seabird taxa (Rodríguez et al.

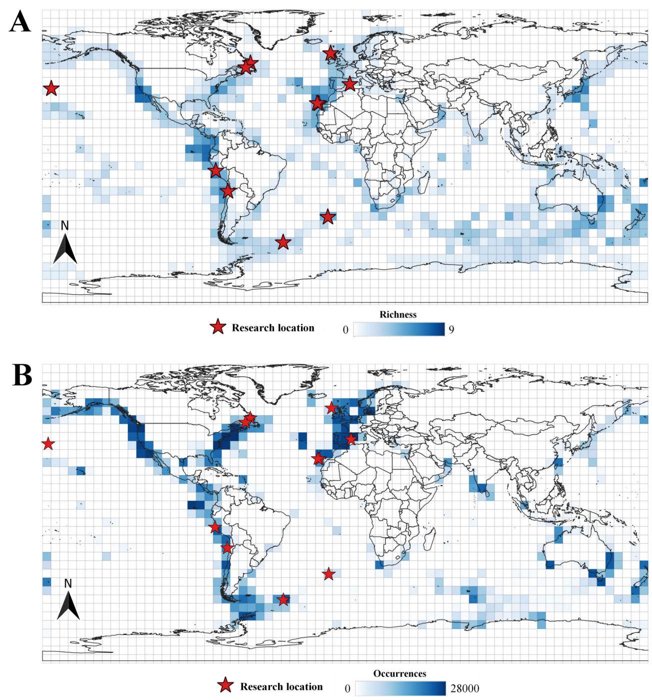
2017, Rodríguez et al. 2019, Dias et al. 2019, Silva et al. 2020). Data for storm-petrels on this subject is scarce, with only twelve scientific articles included in the final analysis of this study. Although there is a trend of increasing research on the effects of light pollution on storm-petrels, most articles used data recovered before 2013, which may be outdated information on light pollution and storm-petrel populations. Furthermore, few articles focused specifically on studying the effects of light pollution on storm-petrels. Most articles treated seabirds as a single group, probably due to methodological limitations or difficulty related to the taxonomic identification of closely related storm-petrel species. Given the specific focus of this scoping review on Hydrobatidae, research articles on light pollution effects on other Procellariiformes (i.e., Procellariidae, Diomedeidae, Pelecanoididae) were not included.

Storm-petrel records are limited mainly to the North American and European coastlines (Fig. 2), even though the eastern Pacific Ocean has the highest storm-petrel diversity due to phylogenetic radiation in the late Miocene (Warheit 1992). This pattern is also noticeable in the number of studies assessing light pollution effects on genera and species. *Oceanodroma*, the most diverse genus within Hydrobatidae, with 13 species out of 22 (Tree of Life Web Project 2008), was evaluated in seven articles. Within this genus, *O. tethys and O. markhami*, present in South America, were the least studied. The limited research on the effects of light pollution on storm-petrels found primarily in the southern hemisphere, and the distribution pattern record centered in the northern hemisphere may be another case of the identified trends of research limitations in the Global South (Dados and Connell 2012, Collyer 2018). This pattern, however, could also be influenced by the elevated levels of light pollution in regions of the northern hemisphere, such as the coastlines of Europe and North America (Falchi et al. 2016).

Implications for studying light pollution

To determine the extent of light pollution as a threat to the survival of storm-petrel populations, we must first understand which individuals are more susceptible to being disturbed by artificial light sources. One of the variables proven to be fundamental is the age group, as fledglings frequently get disoriented by artificial lights on their first flight toward the sea (Aubrecht et al. 2010, Rodríguez et al. 2017). Six of the evaluated articles considered this variable, and almost all found that storm-petrel fledglings were more frequently grounded by light pollution than adults. These results support evidence from previous studies (Le Corre et al. 2002, Rodríguez and Rodríguez 2009), suggesting that fledgling fallout and mortality may influence population decline (Troy et al. 2011). Even though the reason for fledgling disorientation and attraction toward artificial lights has not been fully established, four main hypotheses have been proposed: (i) inexperienced fledglings may confuse artificial lights with bioluminescent prey (Imber 1975), (ii) storm-petrel fledglings may associate light with a food source since the only light they encounter as nesting chicks is emitted from the burrow entrance used by parents to deliver food (Ainley, personal communication as cited in Rodríguez et al. 2017), (iii) the interplay between an undeveloped visual system and innate behavioral inexperience as fledglings (Atchoi et al. 2020), and (iv) artificial lights may limit their ability to use the moon and stars as navigation cues (Telfer

Fig. 2. Spatial Distribution of Storm-petrel Richness and Occurrence on a Global Scale. Hydrobatidae occurrence data was extracted from the Global Biodiversity Information Facility (GBIF) database, focusing on human observations recorded between January 1, 2000, and December 31, 2022. A 5x5 degree grid was employed to segment the global map adjusted to the Equirectangular projection, with the color gradient representing the diversity and number of records. Red stars on the map represent the location of data collection for the 12 articles included in the final literature analysis. A) Spatial distribution of storm-petrel richness. B) Spatial distribution of storm-petrel records.



et al. 1987). Understanding the mechanisms of fledgling attraction will allow the proposal of mitigation measures to reduce light pollution effects (Atchoi et al. 2020), particularly during fledgling periods in high-risk areas (Dias et al. 2019).

Among the environmental factors identified in numerous studies to affect storm-petrel susceptibility to light pollution (e.g., wind direction and speed, moon phase, length of time the moon was above the horizon), the moon phase is the most frequently mentioned. An association between grounded storm-petrels' body condition and subsequent mortality has been established by Wilhelm et al. (2021). However, standardization of data collection may reveal patterns that have remained undetected. Studies performed by Wilhelm et al. (2021), Gjerdrum et al. (2021), Miles et al. (2010), and Murillo et al. (2013) suggest that stranding records focus on nights with the lowest moon visibility, while there are fewer storm-petrel strandings during the full moon (i.e., high moon visibility). In a recent study, Rodríguez et al. (2023) argued that the reduction in strandings during full moon nights may be associated with a lower attraction effect of artificial light when overlapped with natural moonlight. Future studies focusing on storm-petrels' use of the moon as a navigational cue may reveal the mechanism of disorientation and attraction to artificial lights.

Knowledge gaps in the reviewed literature

One of the limitations of the current state of evidence on the effects of light pollution on the Hydrobatidae family is that only two of the articles from our study used a systematic methodology for data collection. The accuracy of storm-petrel grounding records depends on the search effort, so systematic searches by qualified personnel are needed to increase the proportion of dead birds found (Rodríguez et al. 2017). However, accurate information is difficult to obtain. Effective monitoring programs need to consider a wide array of factors such as the area of impact, the search area and intensity (Rodríguez et al. 2014, Rodríguez et al. 2017), the probability of a carcass to be found (e.g., due to size, carcass accessibility or time of day; Rodríguez et al. 2017, Malinarich et al. 2018 in Silva et al. 2020), light-induced grounding hotspots (Crymble et al. 2020), proximity to the colony, and how quickly a grounded storm-petrel may disappear due to predation or decay (Rodríguez et al. 2017).

Most data about the magnitude of fallout comes from rescue programs carried out by communities, not necessarily as part of systematic monitoring programs (Rodríguez et al. 2017). The success of rescue campaigns, usually conducted by volunteers, relies on public awareness and successful media campaigns (Crymble et al. 2020). These rescue programs allow the generation of conservation knowledge for rare or poorly-known species, which otherwise would be too expensive or intractable to acquire (Rodríguez et al. 2017). Yet, data obtained through rescue campaigns or volunteering programs generally go underreported and should be interpreted as minimum numbers since (1) some grounded birds could be found by people unaware of the light pollution-seabird problem and hence not be reported (Rodríguez et al. 2015), (2) grounded fledglings tend to hide in dense vegetation, holes or crevices, so an unknown number of grounded birds are never found (Reed et al. 1985), (3) the general public is biased toward the collection of live birds and usually do not report or collect dead birds (Rodríguez et al. 2014, Rodríguez et al. 2015, Crymble et al. 2020), and (4) the effort is inherently greater in highly trafficked areas, leading to a possible sampling bias (Burt et al. 2023). Improved data collection and analysis will arise from combining rescue program information with rigorous scientific methods (Rodríguez et al. 2017). These volunteer rescue campaigns, as part of a citizen science approach, provide the opportunity to gather information that, due to resource and time constraints, would not be possible through traditional scientific methods (Kobori et al. 2016), as it may help to monitor stranding events in a broader geographical scale (Burt et al. 2023). Despite the great potential that citizen science has to advance marine and coastal conservation (Cigliano et al. 2015), awareness and community rescue campaigns still need to be encouraged so that the general public understands the threat of light pollution to seabirds, becomes more involved with conservation efforts, and demands solutions from the local and national governments (Rodríguez and Rodríguez 2009, Burt et al. 2023).

There is a considerable gap in the knowledge of light pollution effects on the Hydrobatidae family, which needs to be addressed to propose appropriate management conservation measures. Although some articles identify light pollution sources, the intensity, and spectrum are generally not quantified. This aspect of light pollution is relevant as the spectrum (wavelengths) and intensity of city lights at night are highly diverse, resulting in a mosaic-like distribution that can affect birds' responses in different magnitudes (Dominoni et al. 2013). Other essential factors to consider on light pollution effects are the temporality of light pollution sources (e.g., time of the day, duration, seasonality), the relationship between gender and incidence of light pollution attraction, and the distance between light pollution sources and the storm-petrel breeding populations or their flight paths (Troy et al. 2011, Silva et al. 2016; Rodríguez et al. 2017, Norambuena et al. 2021, Wilhelm et al. 2021). In fact, a recent study on Leach's storm-petrels found that even a partial reduction in ALAN resulted in a decrease in strandings of up to 57% (Burt et al. 2024). Understanding the potential relationship between the attributes of light pollution sources such as intensity and distance attracting storm-petrels, may allow to quantify the exposure of dark areas and colonies to light pollution (Rodríguez et al. 2017, Norambuena et al. 2021, Wilhelm et al. 2021, Ryan et al. 2021). These and other previously mentioned gaps in our understanding of the effects of light pollution on storm-petrels, particularly at a population level, need to be addressed in future research, as they hold significant implications for conservation management.

Limitations of this study

This scoping review has two main limitations. First, our literature search was conducted exclusively in English, with a prior search in Spanish that yielded no results. However, it is possible that relevant articles written in other languages may exist but were not accessible for inclusion in our analysis. Second, we focused exclusively on scientific articles indexed in Scopus and Web of Science platforms. Information from other web search tools, such as Google Scholar, ProQuest, ScienceDirect, and SciELO was not included. Since we also limited our analyses to scientific research papers published between 2000 and 2022, we acknowledge that important information from earlier research or found in the gray literature, such as government reports and environmental impact assessments, was not considered. Yet, focusing solely on academic scientific articles allowed us to identify relevant information gaps and biases in recent light pollution and storm-petrel research.

CONCLUSIONS AND FUTURE PERSPECTIVES

We identified a series of knowledge gaps that must be further studied to propose effective mitigation measures for light pollution effects on members of the Hydrobatidae family. Future research would benefit from focusing on (1) standardizing data collection of storm-petrel groundings and associated environmental variables, (2) prioritizing systematic collection of grounding data or increasing available information through citizen science programs, (3) assessing the impact of light pollution at a population level to comprehend the effect of light-induced mortality in the species population trends, and (4) characterizing light pollution sources.

As light pollution rapidly increases globally with the expansion of cities, we need to start prioritizing research to determine effects on wildlife and adequately propose management plans and mitigation measures to ensure the well-being of other-than-human beings.

Author Contributions:

R. A. Medina-Franco and P. Sangiorgi: conceptualization, data curation, analysis, writing of original draft, editing, and approval of the final manuscript; A. Valdés-Velásquez: conceptualization, supervision, editing, and approval of the final manuscript. The authors wish it to be known that, in their opinions, the first two authors should be regarded as joint first authors. As such, co-first authors can prioritize their names when adding this article's reference to their résumés.

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Species	Taxonomic authority	Common name
Garrodia nereis	(Gould, 1841)	Grey-backed storm-petrel
Pelagodroma marina	(Latham, 1790)	White-faced storm-petrel
Fregetta tropica	(Gould, 1844)	Black-bellied storm-petrel
Fregetta grallaria	(Vieillot, 1817)	White-bellied storm-petrel
Oceanites oceanicus	(Kuhl, 1820)	Wilson's storm-petrel
Oceanites maorianus	(Mathews, 1932)	New Zealand storm-petrel
Oceanites gracilis	(Elliot, 1859)	White-vented storm-petrel
Nesofregetta fuliginosa	(Gmelin, 1789)	Polynesian storm-petrel
Oceanodroma leucorhoa	(Vieillot, 1818)	Leach's storm-petrel
Oceanodroma tristrami	Salvin, 1896	Tristram's storm-petrel
Oceanodroma furcata	(Gmelin, 1789)	Fork-tailed storm-petrel
Hydrobates pelagicus	(Linnaeus, 1758)	European storm-petrel
Oceanodroma melania	(Bonaparte, 1854)	Black storm-petrel
Oceanodroma tethys	(Bonaparte, 1852)	Wedge-rumped storm-petrel
Oceanodroma microsoma	(Coues, 1864)	Least storm-petrel
Oceanodroma castro	(Harcourt, 1851)	Band-rumped storm-petrel
Oceanodroma monteiroi	Bolton et al. 2008	Monteiro's storm-petrel
Oceanodroma monorhis	(Swinhoe, 1867)	Swinhoe's storm-petrel
Oceanodroma markhami	(Salvin, 1883)	Markham's storm-petrel
Oceanodroma matsudairae	Kuroda, 1922	Matsudaira's storm-petrel
Oceanodroma homochroa	(Coues, 1864)	Ashy storm-petrel
Oceanodroma hornbyi	(G. R. Gray, 1864)	Hornby's storm-petrel

Appendix 2. Spreadsheet of articles obtained through database search after duplicate removal.

Please click here to download file 'appendix2.xlsx'.

Appendix 3. Data collection sheets.

Please click here to download file 'appendix3.xlsx'.