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Light-induced Petrel Groundings in New Caledonia

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This study aims to identify the petrel species affected by artificial light pollution in New Caledonia, describe the spatial and temporal patterns of light-induced groundings, and infer the factors involved. The study took place across Grande Terre (New Caledonia's main island) from 2007 to 2009. A network of concerned citizens reported grounded seabirds. Live grounded birds were rescued and released when possible, or euthanized. Groundings were mapped at the scales of both Grande Terre and Nouméa, the main city. Negative binomial regression was used to analyze the effects of light intensity and proximity to shore on the number of groundings. Of the 523 grounded seabirds recorded between 2007 and 2009, 80.2% were wedge-tailed shearwaters (*Ardenna pacifica*), 14.2% were Gould's petrels (Pterodroma leucoptera), and 5.4% were Tahiti petrels (*Pseudobulweria rostrata*). Combining all three species, an estimated 64.9% of grounded individuals were fledglings. Groundings of Gould's petrels and wedge-tailed shearwaters peaked during their respective fledging seasons (April and May). The number of lights and the proximity to shore were identified as highly significant positive factors explaining the number of groundings. Groundings were particularly numerous at industrial sites and airports. Mortality upon discovery or within days after exceeded 47.8% in the wedge-tailed shearwater, 35% in Gould's petrel, and 23% in the Tahiti petrel. The results highlight the detrimental impact of outdoor artificial lighting on three petrel species breeding on Grande Terre, including the threatened Gould's petrel and the near-threatened Tahiti petrel. They provide evidence to support the urgent implementation of artificial light reduction policies at the periphery of Nouméa, around industrial sites, and near airports especially during the fledging periods.

Key words: Outdoor artificial lighting, Urbanization; industrial mining, Wedge-tailed shearwater, Gould's petrel, Tahiti petrel, Conservation, Citizen science

BACKGROUND

The global expansion of urban areas is accompanied by rapid and massive artificial lighting, which considerably alters the nocturnal environment (Gaston et al. 2013). Strong, negative impacts of artificial lighting on biodiversity have been documented, including the disorientation and mortality of insects, sea turtles and seabirds (Hölker et al. 2010; Gaston et al. 2013; Rodríguez et al. 2017b; Sanders et al. 2021). Artificial-light pollution (Cinzano et al. 2001; Longcore and Rich 2004; Gallaway et al. 2010; Hölker et al. 2010) represents a substantial part of the ongoing threats to seabirds, impacting 7.5% of the species (Dias et al. 2019). Seabirds of the order Procellariiformes are the most impacted: at least 48 species of the family

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Procellariidae (petrels), and 14 species of the families Hydrobatidae and Oceanitidae (storm petrels) have been recorded as vulnerable to artificial-light pollution (Croxall et al. 2012; Rodriguez et al. 2014 2022; Dias et al. 2019; Silva et al. 2020; Gilmour et al. 2023).

Petrels mainly commute between the sea and their breeding colonies at night, which makes them particularly vulnerable to light pollution. Both fledgling and adult petrels may be attracted to lights because in their natural environment light signals prey (Imber 1975), or simply because of an innate attraction to light at night (Telfer et al. 1987; Montevecchi 2006). Fledglings are particularly impacted by light pollution, presumably because they are inexperienced and are more easily to be disoriented by artificial lights compared to adults (Atchoi et al. 2020). The disoriented birds may end up hitting poles, electric lines, trees, buildings, antennas, guy wires and other hard superstructures (Telfer et al. 1987). Grounded petrels may die from injury or become easy prey to urban predators such as dogs and cats; they may also be trapped, unable to take off again, run over by cars or may otherwise die from dehydration and exhaustion (Rodríguez et al. 2017b; Gjerdrum et al. 2021).

The New Caledonian archipelago in the Coral Sea hosts at least 24 breeding seabird species (de Naurois 1978; de Naurois and Rancurel 1978; Hannecart and Létocart 1980; Pandolfi-Benoit and Bretagnolle 2002; Borsa and Vidal 2018) including five petrel species: the Herald petrel *Pterodroma heraldica*, Gould's petrel *P. leucoptera*, the black-winged petrel *P. nigripennis*, the Tahiti petrel *Pseudobulweria rostrata* and the wedge-tailed shearwater *Ardenna pacifica*, and at least one storm petrel species, the New Caledonian storm petrel *Fregetta lineata* (Bretagnolle et al. 2022). New Caledonia's main island ("Grande Terre") has undergone considerable industrial development in the last decades (Bonvallot and Lardy 2014; Gay 2014; Grenon 2014; Kowasch and Merlin 2024), associated with an influx of immigrants causing rapid demographic increase and urbanization (Gay 2014; Pestaña 2014). The problem of petrel groundings on New Caledonia's Grande Terre is well known to local ornithologists as it occurs massively in April and May each year, at the end of the breeding seasons of Gould's petrel and wedge-tailed shearwater (Baby 2011; Renaudet 2014; Cunéo 2019). However, apart from the brief mention of artificial-light induced Gould's petrel groundings (Croxall et al. 2012; Bretagnolle et al. 2021), no dedicated analysis of this phenomenon has been published for this region of the world.

This study aims to address this knowledge gap by analyzing seabird grounding data collected over three consecutive years by a network of concerned citizens in New Caledonia. We investigate: (i) which are the affected seabird species; (ii) the proportions of fledglings and adults in the groundings; (iii) the spatial and temporal patterns of groundings; and (iv) the evidence linking these groundings to artificial-light pollution. Understanding these patterns is crucial for developing strategies to mitigate light-induced mortality and for conserving vulnerable seabird populations in New Caledonia.

MATERIALS AND METHODS

Study area

Three spatial scales were considered: New Caledonia's main island (Grande Terre), its main city (Nouméa) and the district scale within this city. Grande Terre is situated in the eastern half of the Coral Sea. It has an area of 16,660 km^2 and is nearly 400 km in length from its northwestern extremity (20.08°S, 167.03°E) to its southeastern extremity (22.40°S, 164.00°E), and up to 70 km in width. It is dominated over its entire length by a mountain range reaching 1628 meters above sea level. Nouméa is spread over a peninsula 10 km long and up to 11 km wide protruding into a ca. 4000-km^2 wide coral-reef lagoon, and indented by deeply penetrating bays. The population of Grande Terre reached ca. 228 000 inhabitants in 2009 (Fillon et al. 2010). Rampant urbanization mostly concerned coastal cities, principally Nouméa, and the adjacent cities of Païta, Dumbéa and Mont-Dore which together with Nouméa formed a conurbation of 164 000 inhabitants in 2009 (Fillon et al. 2010; Dumas 2014). Major nickel mining projects have been developed in the north and south of Grande Terre in the years 2000, including open-pit mines with associated ore-processing factories in Goro and Vavouto-Koné (Bonvallot and Lardy 2014; Gay 2014; Grenon 2014). Other nickel-mining projects scattered along Grande Terre have remained active during that period (Marini et al. 2014). Toutouta is the site of New Caledonia's international airport; a smaller, domestic airport is situated in the Magenta district in Nouméa (https://www.aeroports.cci.nc/fr; page consulted 19 Aug. 2023). The light pollution map of New Caledonia's Grande Terre (Fig. 1B) illustrates the spatial distribution of artificial lights and shows a main luminous area over the Païta-Dumbéa-Nouméa-Mont Dore conurbation and two other main areas corresponding to the Goro and Vavouto-Koné industrial zones.

Petrel species breeding on Grande Terre and adjacent islets

Gould's petrel is represented in New Caledonia by an endemic subspecies, *Petrodroma leucoptera caledonica*. Breeding colonies have been localized in the mountainous valleys along streams or on slopes near ridges of the Dzumac mountains (22.08°S, 166.44°E) ca. 20 km north of Nouméa; total population size in New Caledonia is estimated at 5000–7000 breeding pairs (Bretagnolle et al. 2022). The black-winged petrel breeds in small numbers along the shore of Grande Terre and on coral reef islets in the southern lagoon; its total population size in the southern lagoon may be as low as ca. 1000 pairs (Hannecart and Létocart 1980; Pandolfi-Benoit and Bretagnolle 2002; Borsa et al. 2017). The Tahiti petrel breeds in loose colonies mostly in the mountains of Grande Terre, including in areas earmarked as nickel-mining concessions (Pagenaud et al. 2022). Some nesting has been reported mixed with wedge-tailed shearwater and black-winged petrel along the shore and on coral-reef and rocky islets of the New Caledonian lagoon (Hannecart and Létocart 1980; Pandolfi-Benoit and Bretagnolle 2002; Villard et al. 2006; Ravache 2021; Pagenaud et al. 2022). Its population size is estimated between 1000 and 5000 breeding pairs along the mountains of Grande Terre (Villard et al. 2006) to perhaps as many as 15,000 pairs based on transects at sea (Borsa 2008). The wedge-tailed shearwater is an oceanic species with a wide Indo-Pacific distribution (Brooke 2004). Its dense colonies on Grande Terre and Île des Pins, on all forested islets in the southern, northern and eastern New Caledonian lagoons, and on remote islands and reefs in the New Caledonian EEZ each comprise several hundred to several tens of thousands of breeding pairs (Pandolfi-Benoit and Bretagnolle 2002; Borsa 2021; Borsa et al. 2021). Its total population size on Grande Terre and in the adjacent lagoon may well exceed 500,000 pairs (Pandolfi-Benoit and Bretagnolle 2002; Receveur et al. 2022). At sea, flocks of several tens of thousands of individuals have been reported, both close to shore and off the barrier reef surrounding Grande Terre (Borsa and Baudat-Franceschi 2009). Only two large colonies of the wedge-tailed shearwater are known on Grande Terre. Both are located in remote areas with surviving patches of dry forest along the western shore of the island: in Gouaro Deva (up to 25,000 breeding pairs; Bège 2016) and in Pindaï (up to 26,000 pairs; Le Bouteiller and Borsa 2024). Little is known of the New Caledonian storm petrel. Its total population size might be only a few hundred pairs; breeding colonies have not yet been located (Bretagnolle et al. 2022). Overall, there are still important knowledge gaps on basic aspects such as the population sizes and the spatial distribution of the colonies of the petrel species breeding in New

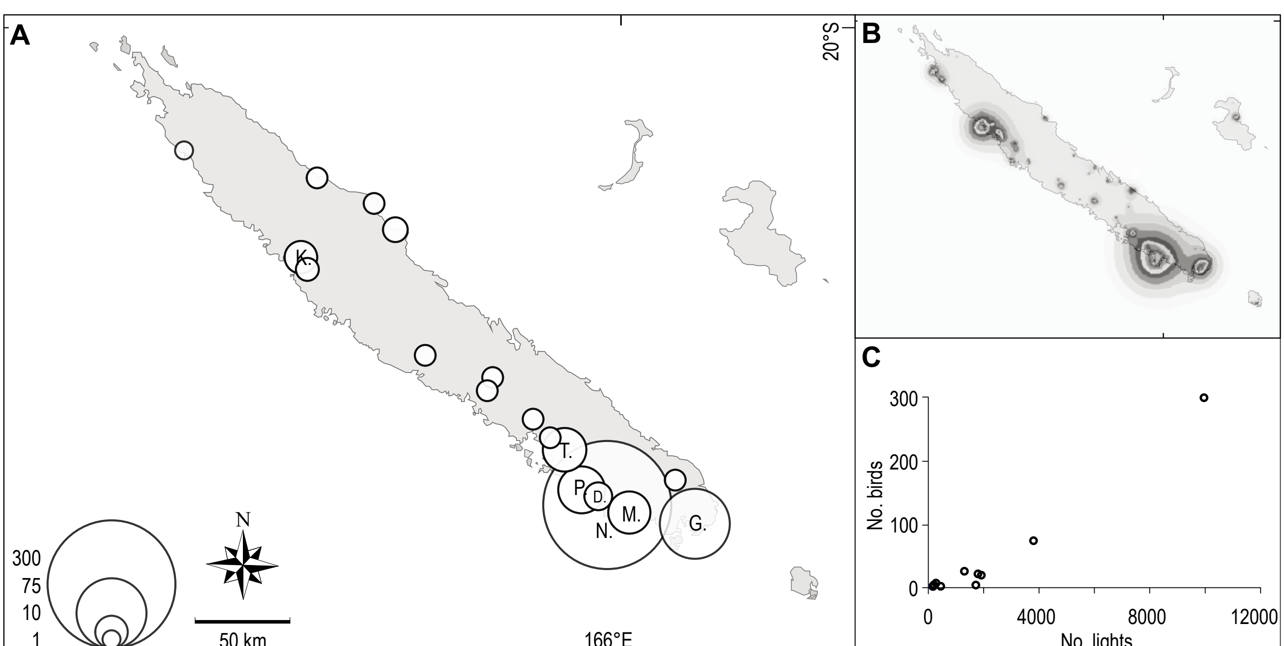

Fig. 1. Petrel groundings in the towns and cities across New Caledonia's main island. A, Total number of petrels reported by locality through years 2007–2009, represented by circles. Main petrel-grounding localities: *D.* Dumbéa (*N* = 6); *G.* Goro nickel plant (*N* = 78); *K.* Koné (*N* = 10); *M.* Mont Dore (*N* = 21); *N.* Nouméa (*N* = 301); *P.* Païta (*N* = 28); *T.* Tontouta airport (*N* = 23). B, Light pollution map, image taken on 14 December 2015 (Falchi et al. 2016). C, Number of grounded petrels plotted against the number of artificial lights, by town or city.

Caledonia. The fact that the largest wedge-tailed shearwater breeding colony ever discovered in the southwestern lagoon of New Caledonia was mentioned for the first time only very recently (Le Bouteiller and Borsa 2022) is an illustration.

Collection of seabird-grounding data

Seabird-grounding information over New Caledonia's Grande Terre was produced from 2007 to 2009 by the seabird-rescue campaign called "SOS Pétrels" (Anonymous 2009) initiated in 2007 by the Nouméa-based ornithological association, the Société calédonienne d'ornithologie (SCO), to help rescue grounded seabirds. The citizens of New Caledonia were encouraged through local news media to report to SCO or to the local zoo any grounded seabird found by calling dedicated telephone lines (Anonymous 2007; de Kermoysan 2007; Girard 2008a b; Wibart 2009). The date and place of each grounding were recorded, as well as the condition of the seabird, *i.e.*, dead or alive and in the latter case, whether injuries were visible. Seabirds found dead were identified to species by a benevolent SCO member, either from its description by telephone, or from photographs, or from de visu examination. Seabirds reported alive were collected by benevolent SCO members, examined, cared for and released when possible. Seabirds with unsustainable injuries including broken bones or an advanced stage of dehydration were euthanized by a professional veterinarian. In 2007, rescue effort focused on Gould's petrel and the Tahiti petrel (de Kermoysan 2007).

Details on the condition of grounded seabirds upon discovery, when available, are presented in a companion report (Mareschal et al. 2024). Among the grounded birds discovered alive, a proportion exhibited deadly injuries: broken wings, legs, pelvic bones, backbone and bill, punctured eye, ataxis, hemiplegy. Severe dehydration was evident in a proportion of birds.

Age determination

Grounded seabirds were classed into either of two age categories, fledgling or adult. Fledglings were distinguished from adults by their intact plumage and by the weak ossification of their nasal tubes, such that mild pressure with a finger or a caliper would flatten them (V. Bretagnolle, pers. comm.). Some fledglings retained remains of down, a characteristic which allowed them to be identified without doubt. An adult individual had more or less worn plumage, and its nasal tubes were calcified, such that it was not possible to flatten them with mild pressure.

Characterization of grounding sites

The number of light points in a town or city (as of 2009) was communicated to us by Électricité et Eau de Calédonie (EEC, Nouméa) which is one of the two main energy suppliers in New Caledonia. The towns and cities concerned (N = 14) were Boulouparis, Dumbéa, Goro, Hienghène, Koné, Mont-Dore, La Foa, Nouméa, Païta, Poindimié, Pouembout, Sarraméa, Tontouta and Yaté. Equivalent information was provided for each district in Nouméa. These districts (N = 36) were Aérodrome, Anse Vata, Artillerie, Baie des Citrons, Centre Ville, Doniambo, Ducos, Ducos industriel, Faubourg Blanchot, Haut Magenta, Kaméré, Km 4, Km 6, Km 7, Logicoop, Magenta, Montagne coupée, Montravel, Motor Pool, N'Géa, Normandie, Nouville, Numbo-Koumourou, Orphelinat, Ouémo, Portes de Fer, Quartier latin, Receiving, Rivière salée, Tina, Tindu, Trianon, Vallée des Colons, Vallée du Génie, Vallée du Tir and Val Plaisance. The number of outdoor artificial lights in towns, cities, and Noumea's districts is given in Mareschal et al. (2024). The number of outdoor artificial light sources at petrel-grounding sites in Nouméa was counted within a radius of 50 meters around the precise point where a grounded seabird was found. These light sources were categorized as either spotlight, street-light pole, globe-light pole, neon light, billboard, recessed floor light, wall light, pathway light, or "other". Light illuminance was measured with an accuracy of 0.1 lux ca. 1.20 meter above ground using a handheld MS-1500 luxmeter (Voltcraft, Hirschau) photometric head oriented towards the zenith. The outdoor lighting characteristics of these petrel-grounding sites were compared with those of a similar number of other sites which coordinates were randomly chosen within the same districts of Nouméa. When the randomly chosen site was located in a private property, the nearest accessible point outside it was chosen. Petrel-grounding sites (N = 54) and randomly chosen sites (N = 47) were characterized by their illuminance and their number of lights and compared. Geographical coordinates of a site were taken using a GPS 72 (Garmin, Olathe KS) GPS receiver and the WGS84 coordinates system in the UTM longitude zone of reference no. 58S (Hofmann-Wellenhof et al. 1992).

Statistical analyses

For the 14 cities where the number of lights was available, the number of recorded petrel groundings was first regressed on the number of lights using a Poisson model, using the *glm()* function of the stats package implemented in R v. 4.3.2 (https://www.R-project.org/; R Core Team 2023). A Poisson regression model was similarly used to apportion the contribution of factors possibly affecting the number of grounded petrel records in a district in Nouméa, namely its proximity to the sea (encoded as 1 when the district was adjacent to the shoreline, or 0 when it was located inland) and the number of lights. In the first Poisson regression (Grande Terre), residual deviance was 112.9 for 12 degrees of freedom. The rule of thumb is that the ratio of deviance to the number of degrees of freedom should be equal to 1 (Dormann 2016). The ratio observed with our preliminary regression (9.4) indicated overdispersion, *i.e.*, more variation than expected from a Poisson process. In the second Poisson regression (Nouméa), this ratio was 8.6, similarly indicating overdispersion. Negative binomial models were thus chosen instead of the Poisson model (Dormann 2016). For this, we used the mass package (Venables and Ripley 2002) in R 4.3.2.

The null hypothesis of random petrel grounding among districts in Nouméa was tested by comparing the number of groundings of a district to the number of groundings expected according to the district's surface, using the χ^2 statistic. The *t*-test (Sokal and Rohlf 1969) was used for comparing the illuminance characteristics of grounding sites with randomly chosen sites. Fisher's combined probability test (Sokal and Rohlf 1969) was used to test the null hypothesis of no correlation between the number of lights and the number of petrel groundings, whatever the geographic scale addressed. The number of petrel groundings of each town or city, or each district within Nouméa was represented in the form of bubble diagrams using the *ggplot2* package (Wickham 2016) under R, superimposed on the maps of New Caledonia and Nouméa drawn under Illustrator (Smith 2010).

RESULTS

Grounded bird statistics

In total, 523 grounded individuals representing six seabird species were recorded on New Caledonia's Grande Terre during the study period (2007–2009). The near-totality ($N = 521$) of grounded seabirds belonged to the family Procellariidae or petrels. The petrel species recorded were the wege-tailed shearwater (80.2% of all grounded petrels), Gould's petrel (14.2%), the Tahiti petrel (5.4%), and a single individual of Buller's shearwater *A. bulleri* (0.2%). In addition, one bridled tern *Onychoprion anaethetus* and one black noddy *Anous minutus* were reported grounded in the vicinity of moored sailboats, both with a broken wing.

Among the grounded petrels whose age was estimated, the proportion of fledglings reached 88.5% (0.95 confidence interval: 83.5%–92.0%) in the wedge-tailed shearwater, 65% (52%–76%) in Gould's petrel, and 47% (25%–70%) in the Tahiti petrel. The mortality of grounded birds at the time of their discovery or within days after (including those euthanized) was ≥ 47.8% for the wedge-tailed shearwater ($N = 418$), ≥ 35% for Gould's petrel ($N = 74$) and ≥ 23% for the Tahiti petrel ($N = 28$); rescued wedge-tailed shearwaters, Gould's petrels and Tahiti petrels still in weak condition at the time of their release represented, respectively, 17.4%, 23% and 65% of the survivors and the proportion of those released in apparently good condition was 41.2%, 45% and 19%, respectively (Table 1).

Table 1. Fate of grounded petrels on New Caledonia's Grande Terre, 2007–2009. *Total* is the sum of the numbers of dead and live individuals

Species,	Condition upon discovery		Fate of birds discovered alive				Total
Year	Dead	Alive	Dead within days	Released in weak condition	Released in good condition	Unknown	
A. pacifica							
2007	2	8	2	1	5	-	10
2008	47	99	21	8	30	40	146
2009	58	204	23	29	99	53	262
P. leucoptera							
2007	1	9	3	3	3	-	10
2008	1	14	6	3	5	-	15
2009	9	40	5	8	24	3	49
P. rostrata							
2007	1	8	1	5	1	1	9
2008	1	10	-	8	1	1	11
2009	1	7	2	2	3	-	8

Spatial distribution of groundings

Grounded petrels were recorded from all over New Caledonia's Grande Terre (Fig. 1A). The highest number of grounded petrels was scored in Nouméa (N = 301, *i.e.*, 57.8% of the total). The nickel-ore processing plant at Goro ranked second (N = 78; 15.0%). Païta, a widespread town adjacent to Nouméa ranked third (N = 28; 5.4%). The international Tontouta airport ranked fourth (N = 23; 4.4%). The number of grounded seabirds was correlated with the number of outdoor artificial lights at the scale of New Caledonia's Grande Terre (Fig. 1C; Table 2). Over 40% of grounded Gould's petrels were recorded at the Tontouta airport site.

Petrel groundings were recorded in a proportion of Nouméa districts (Fig. 2). Taking the area of a district into account, the number of groundings per district differed from that expected by chance (χ^2 = 612.49, *d.f.* = 35; P < 0.001). Proximity to shore was identified as the main factor affecting the number of grounded petrels while the effect of the number of lights was not significant at this scale (Table 2). The distribution of residues highlighted the Numbo-Koumourou district as an outlier, where 17% of all petrel groundings recorded in Nouméa occurred. The petrel-grounding hotspot in this district was the densely-lit industrial oil-and-

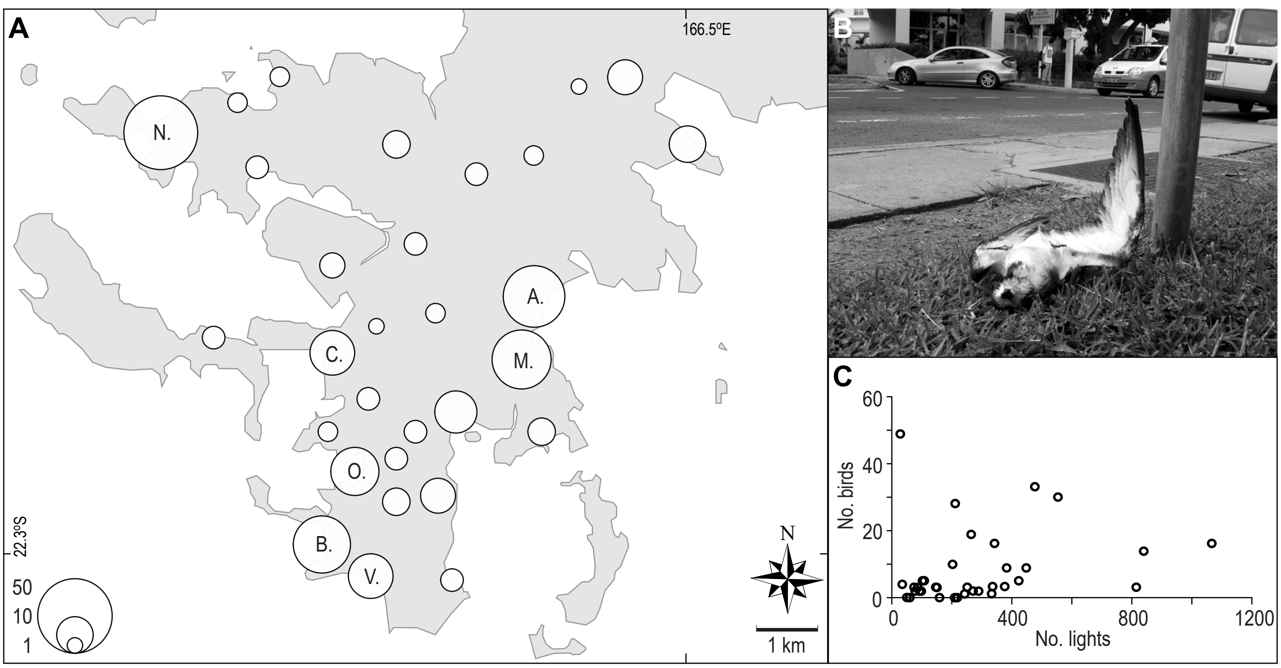

Fig. 2. Petrel groundings in Nouméa, New Caledonia. A, Number of petrels reported by district through years 2007–2009 (total N = 288) [*A.* Aérodrome (N = 33). *B.* Baie des Citrons (N = 28); *C.* Centre Ville (N = 16); *M.* Magenta (N = 30); *N.* Numbo (N = 49); *O.* Orphelinat (N = 19); *V.* Anse Vata (N = 16)]. B, Dead Gould's petrel *Pterodroma leucoptera* grounded in the Anse-Vata district, Nouméa, New Caledonia (early morning, 15 March 2008). The bird showed injuries to the neck, with punctures possibly inflicted by the canine teeth of a dog or a cat. C, Number of grounded petrels plotted against the number of artificial lights, by district.

Table 2. Results of negative binomial regressions to explain the number of grounded petrels at two geographic scales in New Caledonia (Figs. 1A, 2A). Data compiled for three petrel species over years 2007–2009

Geographic scale, Parameter	Estimate	Std. error	z value	*P*
Grande Terre				
(Intercept)	1.641	0.252	6.509	7.59e-11
Lights	5.165e-04	7.645e-05	6.756	1.42e-11
Nouméa				
(Intercept)	0.199	0.399	0.500	0.617
Shore	2.003	0.429	4.672	2.99e-06
Lights	0.001	0.001	0.889	0.374

gas warehouse, which is located in the pass between the Koumourou peninsula and the mainland. Petrel-grounding sites across Nouméa were characterized by two times more lights and a four-times higher illuminance than randomly chosen sites (Table 3); and on the average they had a higher number of street light poles and pathway lights than random sites in the same districts (Table 3).

Overall, the number of petrel groundings was correlated with the number of outdoor artificial lights (Fisher's combined probability test: $P < 0.001$).

Temporal distribution of groundings

Wedge-tailed shearwater groundings were recorded between 03 January and 12 June with a well-identified peak on 19–20 May in both years 2008 and 2009. During the peak month (May), an estimated 94.0% (0.95 confidence interval: 90%–97%) of grounded wedge-tailed shearwaters were fledglings. Gould's petrel groundings, of both adults and fledglings, were recorded from December to early May, with a well-identified peak in the very last days of April in year 2009. During the peak month (April), an estimated 90% (0.95 confidence interval: 74%–97%) of grounded Gould's petrels were fledglings. Groundings of Tahiti petrels, both adults and fledglings, were recorded from January to November, with no apparent peak period.

DISCUSSION

This is the first dedicated survey of the seabird-grounding phenomenon in New Caledonia. Nearly all of the grounded seabirds belonged to the petrel family. The wedge-tailed shearwater dominated the records. Gould's petrel ranked second with a ratio to wedge-tailed shearwater of ca. 1/7, and the Tahiti petrel ranked third with a ratio to wedge-tailed shearwater of ca. 1/20. All three species breed on New Caledonia's Grande Terre and adjacent islets. The highly significant effect of the number of lights in the regression model makes this factor a highly likely cause of petrel groundings in New Caledonia, consistent with previous research (Rodriguez et al. 2014; Heswall et al. 2022). We observed high numbers of grounded seabirds in some areas, such as Tontouta and Goro, with low human population density but high luminance levels (Falchi et al. 2016). This finding helps to rule out human population density per se as a factor to explain spatial variation in petrel grounding. Petrel groundings were mostly recorded in towns and cities, and at industrial sites including nickel-mining sites, a gas-and-oil terminal, and commercial airports. Our results also point the proximity to the shore as a factor positively associated with petrel grounding. Thus, New Caledonia is confirmed as one of the world's artificial-light induced petrel-grounding hotspots, which also include Hawaii, Phillip Island, the Canary Islands, Reunion Island, the Arica and Iquique regions of Chile, Auckland, and other localities (Rodriguez and Rodriguez 2009; Rodriguez et al. 2014 2015 2017b; Silva et al. 2020; Heswall et al. 2022; Friswold et al. 2023).

Characteristics of seabird grounding phenomenon in New Caledonia

Most wedge-tailed shearwater groundings were recorded in the Païta-Dumbéa-Nouméa-Mont Dore conurbation. The largest wedge-tailed shearwater

Table 3. Characteristics of petrel-grounding sites ($N = 54$) compared with randomly chosen sites ($N = 47$) in Nouméa, 2007–2009. Number of lights of each category within a 100-m wide circle centered on grounding (or random) location

Light category	Petrel–grounding sites		Randomly chosen sites		*t*–statistic
	Mean ± SD	Min-Max	Mean ± SD	Min–Max	
Illuminance (lux)	16.09 ± 33.92	0.0–241.2	4.00 ± 5.54	0.0–24.7	2.579 **
All light types	22.11 ± 19.86	3–108	10.17 ± 7.03	0–32	4.132 ***
Spotlight	3.13 ± 6.72	0–32	0.83 ± 1.82	0–9	1.499
Street light pole	8.56 ± 10.45	0–55	5.26 ± 3.69	0–12	2.098 *
Globe–light pole	3.69 ± 8.02	0–43	1.30 ± 2.88	0–13	1.839 †
Neon light	2.13 ± 5.30	0–26	1.17 ± 3.15	0–19	1.001
Billboard	0.67 ± 1.78	0–11	0.43 ± 1.10	0–6	-0.654
Recessed floor light	0.80 ± 3.80	0–26	0	0–0	-0.597
Wall light	1.13 ± 3.96	0–26	0.94 ± 1.88	0–9	0.851
Pathway light	0.83 ± 2.97	0–18	0.11 ± 0.73	0–5	2.303 *
Other	1.19 ± 3.98	0–25	0.15 ± 0.59	0–3	1.168

† $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

colonies in its vicinity are those of M'Ba and Signal islets in the southwestern lagoon respectively 25 km and 15 km from Nouméa, and of respectively 88,000 and 14,000 breeding pairs (Le Bouteiller and Borsa 2022). These two colonies may largely contribute to the groundings recorded in Nouméa and in adjacent cities. Indeed, grounded wedge-tailed shearwaters may originate from colonies distant up to tens of kilometres from the grounding site (Friswold et al. 2023). Dozens of other densely-populated wedge-tailed shearwater colonies scatter the southwestern lagoon (Pandolfi-Benoit and Bretagnolle 2002). However, evidence is needed to assess grounding locations in relation to colonies. For this, a banding programme designed to assign grounded fledglings to their native colony could be implemented (see Friswold et al. 2023). In complement, adults grounded and rescued in good condition could be fitted with light radio-transmitters (Wilson et al. 2009) or GPS/GSM trackers (Potiek and Duijns 2021; Raine et al. 2022), so as to uncover their flight paths and locate their colonies.

The Noumea conurbation and Tontouta airport lie at the bottom of the Dzumac mountains where Gould's petrel colonies have been located so far (Bretagnolle et al. 2021), forming a dense light barrier between these colonies and the sea. The shortest path for Gould's petrels commuting from their known colonies to the Coral Sea and vice-versa thus crosses the most urbanized and illuminated part of the island, making each trip at night to and from the sea a perilous one. Using light radio transmitters or GPS/GSM trackers again may help locating more colonies of this species.

The absence of the black-winged petrel in the grounding record is likely related to its rarity, compared to the three other petrel species that breed on Grande Terre or on the surrounding islets. It is also possible that this species mainly attends colonies in daylight as observed elsewhere in the region (Borsa and Baudat-Franceschi 2023) and thus more likely escapes the risks associated with artificial light pollution. In addition, we cannot exclude that black-winged petrels had been reported to us as Gould's petrels, as shown in a report where the picture of a black-winged petrel rescued in the vicinity of the Goro nickel plant was mislabelled as Gould's petrel (Tehei and Lehoullier 2012). The absence of the New Caledonian storm petrels in the grounding record may be similarly explained by their rarity; nothing is known of the commuting behaviour of this species (Bretagnolle et al. 2022).

The differences in grounding frequency between the Tahiti petrel and the two other species could reflect differences in actual population size. Under this hypothesis, all other things being equal, the population size of the Tahiti petrel would be ca. 1/20 that of the wedge-tailed shearwater. Assuming a population size of 560 000 pairs for the latter on Grande Terre and adjacent islets (Receveur et al. 2022), the Tahiti petrel population size would be ca. 28,000 pairs. This estimate is nearly twice the rough estimate of 15,000 pairs proposed by Borsa (2008) based on transects at sea and nearly six times the upper figure of Villard et al.'s (2006) previous estimate. The 1/20 Tahiti-petrel to wedge-tailed shearwater ratio might be overestimated though, considering that wedge-tailed shearwaters were less a priority than the two other main petrel species in the first year of the rescue campaigns (de Kermoysan 2007).

Four out of five grounded wedge-tailed shearwaters were fledglings. This ratio was two thirds in Gould's petrel and it dropped to approximately one half in the Tahiti petrel. In addition, the only New Caledonian storm petrel reported grounded "presumably disoriented by onshore artificial lights" was a fledgling (Bretagnolle et al. 2022). In both the wedge-tailed shearwater and Gould's petrel, we identified a well-defined grounding peak, which presumably corresponds to the peak of fledgling departure from colony. Indeed, most of the grounded individuals during the peak periods were fledglings, as previously reported in several other petrel species (Telfer et al. 1987; Rodriguez et al. 2017b). This observation in turn points to a narrow fledging period in these two species in New Caledonia. The synchronization of fledglings departing the colony may be the consequence of the synchronization of adults stopping to attend their burrows to undertake their annual trans-oceanic migration (Priddel et al. 2014; Weimerskirch et al. 2020; Whittow 2020). Tahiti petrel groundings were reported all year round, without any particular peak, which is consistent with the absence of a defined breeding season for this species in New Caledonia (Villard et al. 2006).

Mortality estimates

In this study, mortality rates of grounded petrels (> 32% all species confounded) approached the extreme higher values of artificial-light induced mortality estimates in the literature: up to 43% mortality in grounded Newell's shearwater *Puffinus newelli* on Kaui, Hawai'i and 39% in the short-tailed shearwater *A. tenuirostris* on Phillip Island, Australia (reviewed in Rodriguez et al. 2017b). A possible explanation is that in our study, as in those studies where the mortality was highest, great effort was taken to record dead grounded petrels. However, as discussed in the following sub-section, this figure still might be underestimated.

Possible biases

Possible biases that may have distorted the results presented in this paper have to be mentioned. First, the present study relied on citizen reports of grounded seabirds. As the purpose of the "SOS petrels" campaign was to rescue petrels and shearwaters, it is likely that live grounded birds were more frequently reported than dead ones. Moreover, grounded birds attempting to take off are likely to attract human attention more than weak birds attempting to hide. Dead birds may even more likely remain unnoticed. In addition, a proportion of grounded birds may be run over by vehicles or taken away by predators without being noticed. Last, rescued birds still in weak condition at the time of their release may not have survived. On the other hand, a proportion of uninjured grounded seabirds may have been able to take off and escape at dawn, hence evade our grounding record.

Although grounded petrels were reported from all main areas of Grande Terre, it is possible that the higher density of the human population at urbanized sites both indirectly enhanced the risk of injury to seabirds and increased the likelihood of discovering grounded individuals. In other words, it is possible that grounded petrels in the Noumea conurbation had a higher chance of being reported to us, than those in less populated areas. Other factors may be involved, such as levels of awareness and sensitivity to the fate of grounded seabirds. Such biases that may have affected the outcome of the present study illustrate the limits of this type of citizen-science approach.

As the seabird-rescue campaigns were advertised in anticipation of the grounding peaks of April and May, where a majority of grounded individuals were fledglings, the estimate of the proportion of grounded fledglings in Gould's petrel and in the wedge-tailed shearwater might be biased. Under the presumption that the level of awareness of the public, hence the rescuing effort, was not evenly distributed throughout the period of their presence in New Caledonia (from October to May: Weimerskirch et al. 2020), the proportion of grounded adult wedge-tailed shearwaters might be underestimated. The same rationale would apply for Gould's petrel.

In the wedge-tailed shearwater, the visual perception spectrum is centred on blue wavelengths (Hart 2004). Because of their design focusing on the light wavelengths perceived by the human eye, standard luxmeters like the one used in this study can only measure part of the short wavelengths that petrels see (Tabaka and Wtorkiewicz 2022) and are mostly impacted by. Therefore, the illuminance levels that were measured underestimate the light intensity perceived by seabirds. It is likely that improving the measurement of illuminance by correcting for petrel wavelength perception spectrum would enforce the significance of the difference in light intensity between those sites where petrels grounded and randomly chosen sites.

Stakes and recommendations

Over 30% of all seabird species are globally threatened with extinction and almost 50% have declined within the last six decades (Paleczny et al. 2015; BirdLife International 2022), mostly petrels (Rodriguez et al. 2019). Of the three petrel species mostly impacted by artificial lights on Grande Terre, Gould's petrel is threatened with extinction and its populations continue to decrease (BirdLife International 2018d; Bretagnolle et al. 2021). The Tahiti petrel is also dramatically decreasing on Grande Terre because of introduced predators and the encroachment on breeding colonies of ever-expanding nickel mines. This species is assessed as near threatened (BirdLife International 2018c; Pagenaud et al. 2022). The wedge-tailed shearwater is not yet considered of conservation concern, although its global population has been suspected decreasing (Brooke 2004; BirdLife International 2018b). In addition, Buller's shearwater is listed as vulnerable (BirdLife International 2018a) and the New Caledonian storm petrel has been evaluated as "almost certainly globally threatened" (Bretagnolle et al. 2022). Artificial lighting is obviously a factor of overmortality and a threat to the populations of these petrel species in New Caledonia, but the actual magnitude of its impact on their demography remains to be evaluated. Minimizing the threat of light attraction for petrels in New Caledonia is of particular importance given the generally declining population trend in these petrels and the current conservation status of several of the species affected. For this, concrete steps should be taken to reduce coastal light pollution.

As the number of petrel groundings increases with the number of lights (Burt et al. 2024; present work), all other things being equal, suppressing unnecessary outdoor lighting and diminishing the number of lights should decrease the number of petrel groundings. As the number of petrels grounded was higher in locations with higher light intensity, diminishing light intensity similarly should have a mitigating effect. Other possible mitigation measures include channeling the light to the direction where it is needed (Reed et al. 1985), altering light signatures towards longer wavelengths to which petrels are less sensitive (Hart 2004; Rodriguez et al. 2017a), and turning off lights during the peak months of groundings (Burt et al. 2024). The few nights around the new moon are particularly critical for fledglings of several petrel species (Reed et al. 1985; Telfer et al. 1987; Rodriguez and Rodriguez 2009; Miles et al. 2010). The mitigation measures required to reduce the ecological impacts of light pollution on seabird populations have been the topic of a recent comprehensive review (Rodriguez 2023).

To the best of our knowledge, no mitigation measures of this type have been undertaken so far in New Caledonia. On the contrary, local authorities, relayed by the local press, continue to view an increase in outdoor artificial lighting as desirable (Hoffmann 2021; Pophillat 2021). In this context, local awareness campaigns directed towards the relevant services and the general public (Borawska 2017) should be implemented immediately. Support should also be allocated to rescue campaigns, to continue saving those grounded petrels that can be returned to the sea. A non-negligible benefit from such rescue campaigns is also to raise awareness among the population about the impact of light pollution on petrels and more generally about the threatened biodiversity of New Caledonia.

CONCLUSIONS

In this study, we characterized and analyzed seabird groundings in New Caledonia, listed three petrel species as the most impacted ones, and identified light pollution as a significant explanatory factor. Our study thus showed that the petrel-grounding phenomenon in New Caledonia, as elsewhere in the world, is intrinsically caused by the transformation of the natural environment by humans. The study also showed how the grounding data can be used to better understand the biology and ecology of the impacted petrel species. Beyond campaigns to rescue grounded birds, groundings will only decrease if light pollution is drastically reduced, particularly during the peak periods when fledglings depart from their colonies.

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Authors' contributions: All three authors participated in the "SOS Pétrels" rescue campaign between 2007 and 2009 and formulated the research goals and aims of the present study. JM did the field work, collected the data, and wrote a memoir which constituted a basis to the present paper. VC coordinated field work and provided resources. PB completed the analyses, produced the tables and figures, and wrote the paper. All three authors agreed with the form and content of the final version of the paper.

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Availability of data and materials: Detailed individual records of grounded seabirds have been compiled into a report deposited in the HAL-LARA archives (Daphy and Ha-Duong 2010), available from: https://hal-lara.archives-ouvertes.fr/hal-04728786 (Mareschal et al. 2024).

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