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Research Paper

Bird strandings and bright lights at coastal and offshore industrial sites in Atlantic Canada

Carina Gjerdrum [1], *Robert A. Ronconi* [1], *Kelley L. Turner* [2,3] and *Thomas E. Hamer* [2]
[1]Canadian Wildlife Service, Environment and Climate Change Canada, [2]Hamer Environmental, [3]Lummi Nation Natural Resources Department

ABSTRACT. Artificial lights can disorient birds and lead to injury or death. In Atlantic Canada, lights attract birds at sites along the coastline and offshore, but the relative impacts of lights on birds in this region are largely unknown. We summarized data on stranded bird encounters submitted annually to the Canadian Wildlife Service, Environment and Climate Change Canada, and quantified light radiance values at a selection of industrial sites in the region. Stranded birds were reported from offshore oil and gas production platforms, support vessels, and seismic ships, and from onshore oil and gas refineries and construction facilities. Leach's Storm-Petrel (*Hydrobates leucorhoa*) was the most abundant bird species to be stranded: most were found alive offshore Newfoundland and Labrador, and were subsequently released. Landbirds dominated the stranded bird reports from Nova Scotia. Offshore platforms in Newfoundland and Labrador were brighter than onshore sites, and were brighter than platforms located in Nova Scotia, particularly during the Leach's Storm-Petrel breeding season, in part due to flaring activity. Stranding events were more likely during nights with little or no moonlight, but systematic searches for stranded birds, with documentation of search effort by trained personnel, are needed to better understand how light characteristics, weather, and the location of sites influence strandings, and to monitor the effectiveness of light mitigation. Minimizing the threat of light attraction for declining populations of Leach's Storm-Petrels in the Atlantic is of particular importance given the species' current conservation status.

Échouement d'oiseaux et lumières artificielles sur des sites industriels côtiers et en mer dans le Canada atlantique

RÉSUMÉ. Les lumières artificielles peuvent désorienter les oiseaux et leur causer des blessures ou la mort. Au Canada atlantique, les lumières attirent les oiseaux à des sites répartis le long du littoral et en mer, mais les impacts relatifs des lumières sur les oiseaux dans cette région sont largement inconnus. Nous avons compilé les données sur les oiseaux échoués trouvés et soumis annuellement au Service canadien de la faune, Environnement et Changement climatique Canada, et quantifié les valeurs de radiance lumineuse sur une sélection de sites industriels de la région. Les oiseaux échoués ont été signalés à partir de plateformes de production de pétrole et de gaz en mer, de navires de soutien et de navires sismiques, ainsi qu'à des raffineries de pétrole et de gaz et des installations de construction continentales. L'Océanite cul-blanc (*Hydrobates leucorhoa*) est l'espèce d'oiseau à s'être le plus échouée : la plupart ont été retrouvés vivants au large de Terre-Neuve-et-Labrador et ont ensuite été relâchés. Les oiseaux terrestres figuraient en tête des rapports d'oiseaux échoués en Nouvelle-Écosse. Les plateformes en mer de Terre-Neuve-et-Labrador étaient plus lumineuses que les sites terrestres et étaient plus lumineuses que les plateformes situées en Nouvelle-Écosse, surtout pendant la saison de reproduction de l'Océanite cul-blanc, en partie à cause de l'activité de brûlage à la torche. L'échouement d'oiseaux était plus probable pendant les nuits avec peu ou pas de clair de lune, mais des recherches systématiques d'oiseaux échoués, documentant l'effort de recherche par du personnel qualifié, sont nécessaires pour mieux comprendre comment les caractéristiques de la lumière, les conditions météorologiques et l'emplacement des sites influent sur l'échouement, et pour surveiller l'efficacité des mesures d'atténuation de la lumière. La réduction de la menace de l'attraction lumineuse pour les populations d'Océanites cul-blanc en diminution dans le Canada atlantique est particulièrement importante étant donné le statut de conservation actuel de l'espèce.

Key Words: *Atlantic Canada; groundings; Leach's Storm-Petrel; light attraction; marine birds; radiance; stranded birds*

INTRODUCTION

The use of artificial light at night is a significant source of anthropogenic pollution with ecological impacts (Rich and Longcore 2006, Hölker et al. 2010, Davies et al. 2014, Manfrin et al. 2017). Marine birds often encounter artificial light from coastal sources, such as streetlights and lighthouses, which can attract and disorient birds during transits between colony and foraging sites (Montevecchi 2006, Troy et al. 2013, Rodríguez et al. 2017*b*). As a result, birds may die from collisions with human-made structures or the ground (Ainley et al. 2001), or succumb to predators, starvation, or dehydration when forced to land (Rodríguez et al. 2012, 2014).

In Atlantic Canada, significant light pollution is observed from large urban centers such as the coastal cities of Halifax, Nova Scotia (NS) and St. John's, Newfoundland and Labrador (NL), but also from less populated municipalities and coastal industrial sites (Falchi et al. 2016), some of which are adjacent to seabird

Address of Correspondent: Carina Gjerdrum, 45 Alderney Drive, 16th Floor, Dartmouth, NS , Canada, B2Y 2N6, carina.gjerdrum@canada.ca

colonies (Wilhelm et al. 2013). Beyond the shoreline, offshore oil and gas production platforms use artificial lights to illuminate working and living areas, and some installations regularly flare excess gas, which produces both light and heat, with the added mortality risk to birds that fly near or into the flare (Day et al. 2015, Ronconi et al. 2015). Fishing vessels, container ships, oil and gas industry support vessels, and cruise ships also contribute light to the offshore environment in areas where birds may encounter them (Merkel and Johansen 2011, Krüger et al. 2017).

Seabird fledglings are particularly vulnerable during their first flight from the nest to the ocean (Wilhelm et al. 2013, Rodríguez et al. 2017*b*, 2017*c*), perhaps due to their inexperience and an undeveloped visual system from lack of exposure to light during their development in underground burrows (Atchoi et al. 2020). In addition, bird attraction to light increases when visibility is poor due to rain or fog (Russell 2005, Montevecchi 2006), and when lunar illumination is low (Rodríguez and Rodríguez 2009, Miles et al. 2010). Seabirds can also aggregate around offshore oil drilling and production platforms due to olfactory and visual cues (Hope-Jones 1980, Wiese et al. 2001). In Atlantic Canada, nocturnal migratory landbirds, petrel species (Procellariiformes), and alcids (Alcidae) appear to be taxa most at risk to light attraction (Wiese et al. 2001, Ellis et al. 2013, Ronconi et al. 2015), but the relative impacts are largely unknown due to a lack of systematic monitoring and incomplete documentation of dead and stranded (i.e., grounded) birds. As a result, population-level impacts remain unknown, and effective mitigation methods are untested. This information is of particular importance for the Leach's Storm-Petrel (*Hydrobates leucorhoa*), the species most often found stranded on offshore platforms and vessels in the Atlantic (Baillie et al. 2005, Ellis et al. 2013, Ronconi et al. 2015, Davis et al. 2017) and a species that is in significant decline (Wilhelm et al. 2019).

We summarize existing data on stranded bird encounters submitted annually to the Canadian Wildlife Service, Environment and Climate Change Canada (CWS-ECCC) as a requirement of permits for the capture and handling of migratory birds. In addition, we compare light radiance values at a selection of coastal and offshore industrial sites in Atlantic Canada to those at natural foraging locations of the Leach's Storm-Petrel to better understand exposure, and hence risk, to artificial night lighting in this region.

METHODS

Bird stranding data

The Canadian Wildlife Service, Environment and Climate Change Canada in Atlantic Canada issues scientific permits for the capture and handling of migratory birds at coastal and offshore industrial sites where bird strandings may occur. The permit holder is authorized to collect dead migratory birds and capture, transfer, or release live migratory birds that are encountered on the site. Instructions for handling and documenting stranded birds are provided to the permit holder (Williams and Chardine 1999, Environment and Climate Change Canada 2017), and reporting of all stranded birds is required as part of the conditions of the permit. For this study, we obtained stranded bird data from 110 of the 226 permit reports submitted annually to CWS-ECCC between 1998 and 2018. The remaining reports (n = 116) indicated that no stranded birds were found. The data associated with each report included date, location, species, condition (live or dead), and fate of the bird (released, sent ashore, died in care, disposed of at sea). If oil was detected on the bird, this too was reported. During this period, scientific permits were also issued to a rescue organization authorized to capture and release Atlantic Puffins (*Fratercula arctica*), and more recently, Leach's Strom-Petrels, along the east coast of the Avalon Peninsula, NL. However, for this study, we did not include these data because they are published elsewhere (Wilhelm et al. 2013, 2021).

Study sites and sampling period for light radiance

We quantified artificial light emittance at 16 sites across Atlantic Canada (Table 1, Fig. 1): six in NL and 10 in NS. Sites included nine offshore oil or gas production facilities and three coastal onshore industrial sites where strandings had previously occurred (Baillie et al. 2005, Ellis et al. 2013); two coastal city sites to represent the brightest sites in the region; and the center of two core foraging areas of the Leach's Storm-Petrel as determined by telemetry studies from the nesting colonies on Gull Island, NL and Country Island, NS (Hedd et al. 2018). Offshore sites in NL included a gravity base structure (GBS) and two floating, production, storage, and offloading (FPSO) vessels used for oil extraction (all with flare systems for excess gas); in NS, offshore sites included two gas production platforms with flare systems, three satellite gas production platforms that were unstaffed with no flaring, and an exploratory drillship with a flare system (Table 1). The drillship was operating offshore NS for a portion of the study period, from June through September 2016. Although the NS gas production platforms were active during the study period, they have since been decommissioned and facilities were removed in 2020. The three onshore facilities used in the study all had flare systems (Table 1). The two foraging areas were included to represent dark sites against which industrial and city sites could be compared.

We standardized the area sampled for artificial light values at each site using a 15 km radius polygon, which was the size needed to encompass the area of the largest light radiance footprint measured at the offshore sites. We evaluated light radiance at each site monthly between April 2016 and March 2017. This period included one continuous Leach's Storm-Petrel breeding season (April 2016–October 2016) and one non-breeding season (November 2016–March 2017).

Light radiance analyses

To evaluate light radiance at each study site, we used average radiance composite imagery using nighttime data from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) produced by the Earth Observation Group, NOAA National Geophysical Data Center (Elvidge et al. 2017). Prior to averaging, the DNB data were filtered to exclude data affected by lightning, lunar illumination, and cloud cover. Light from fires, northern lights (aurora borealis), boats, and other temporal lights were not filtered out. During the summer months, solar illumination near the poles made it difficult to filter stray light from artificial light sources. To account for this, radiance values

Table 1. Location and description of 16 study sites in Newfoundland and Labrador (NL) and Nova Scotia (NS) used to quantify light emittance and radiance values in Atlantic Canada. The general location of sites is shown in Fig. 1.

Site	Province	Location	Description
City			
St. John's	NL	47.56° N, 52.71° W	Capital of Newfoundland and Labrador; population = 108,160 (Statistics Canada 2017*a*)
Halifax	NS	44.65° N, 63.58° W	Capital of Nova Scotia; population = 403,390 (Statistics Canada 2017*b*)
Onshore			
Come By Chance refinery	NL	47.80° N, 53.99° W	Crude oil refinery (with flare system)
Point Tupper refinery	NS	45.58° N, 61.34° W	Natural gas refinery (with flare system) and marine terminal for storage and transshipment of crude oil and petroleum products
Goldboro LNG	NS	45.18° N, 61.62° W	Gas plant and liquefied natural gas (LNG) processing facility (with flare system)
Offshore			
Hibernia GBS	NL	46.75° N, 48.78° W	Gravity base structure (GBS) for oil production (with flare system[†]) operating since 1997 in the Hibernia oil field
Sea Rose FPSO	NL	46.79° N, 48.02° W	Floating production, storage, and offloading (FPSO) vessel (with flare system[†]) operating since 2005 in the White Rose oil and gas field
Terra Nova FPSO[‡]	NL	46.48° N, 48.48° W	Floating production, storage, and offloading (FPSO) vessel (with flare system[†]) operating since 2002 in the Terra Nova oil and gas field.
Thebaud[§]	NS	43.89° N, 60.20° W	Gas production platform (with flare system) operating since 1999 as part of the Sable Offshore Energy Project
Venture/South Venture[§]	NS	44.02° N, 59.60° W	Satellite gas production platform (unstaffed wellhead platform) operating since 2000 as part of the Sable Offshore Energy Project. Two platforms ~5.3 km apart, assessed as one site.
North Triumph[§]	NS	43.70° N, 59.85° W	Satellite gas production platform (unstaffed wellhead platform) operating since 2000 as part of the Sable Offshore Energy Project
Alma[§]	NS	43.60° N, 60.69° W	Satellite gas production platform (unstaffed wellhead platform) operating since 2003 as part of the Sable Offshore Energy Project
Deep Panuke[§]	NS	43.81° N, 60.69° W	Gas production platform (with flare system[†]) operating since 2013 as part of the Deep Panuke Offshore Gas Development Project
Stena IceMax	NS	42.44° N, 62.25° W	Exploratory drillship (with flare system) operating from June to September 2016 at this location as part of the Shelburne Basin Venture Exploration Drilling Project
Core Leach's Storm-Petrel foraging area[†]			
Gull Island population	NL	45.65° N, 47.13° W	Breeding population estimate 180,000 pairs (Hedd et al. 2018) at Gull Island, Witless Bay (47.24° N, 52.78° W)
Country Island population	NS	42.68° N, 56.06° W	Breeding population estimate 12,000 pairs (Hedd et al. 2018) at Country Island (45.10° N, 61.54° W)

[†]Monthly data on flare emissions are available.
[‡]Facility moved inshore for upgrade in 2020.
[§]Facilities decommissioned and removed in 2020.

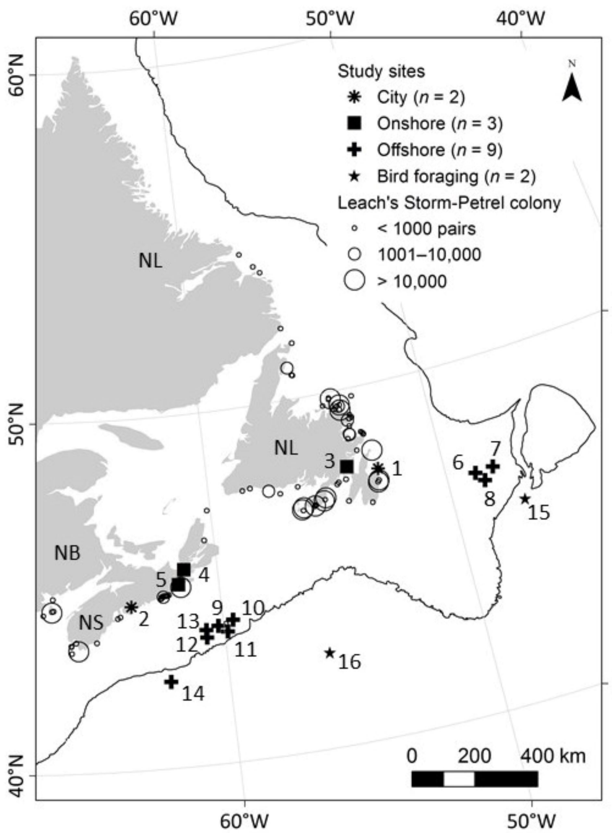
underwent a stray light correction procedure (Mills et al. 2013), although residual background noise may remain (radiance values < 1 nW·cm^{-2}·sr^{-1}).

Average radiance composite imagery was produced for each site for each month of the study period. Each pixel (317 x 317 m) in the monthly imagery represents the average radiance value of all measurements made during the month and is reported as nW·cm^{-2}·sr^{-1}. Monthly average radiance composite imagery was imported into ArcGIS for analysis (version 10.7.1; ESRI Inc. 2019). The project area was more than 1300 km wide and spanned four UTM grid zones. To minimize pixel distortion and calculate accurate light radiance areas, monthly imagery was first projected into one of the four UTM grid zones, as appropriate. Using the Spatial Analyst Zonal Statistics tool, the average radiance value of each pixel within the 15 km radius study site was summed to produce the total monthly average radiance for each site (herein referred to as light radiance).

To determine the area (km^2) of light emittance around each study site and to reduce the stray light background noise, we first defined dark pixels using radiance values from Leach's Storm-Petrel foraging areas, which were far from any light sources (minimum distance between the center of the foraging location and the industrial site = 139.6 km) (Fig. 1). These foraging areas had a maximum radiance range of 0.04–0.71 nW·cm^{-2}·sr^{-1} over the year. Therefore, a light radiance cutoff value of 0.75 nW·cm^{-2}·sr^{-1} was selected. Values less than 0.75 nW·cm^{-2}·sr^{-1} were therefore considered dark or areas with no light. In ArcGIS, the Con tool was used to define light and dark pixels within each site, and the Spatial Analyst Tabulate Area tool was used to quantify the light emittance area reported as square kilometers (i.e., light footprint). Across sites, we quantified the percentage of the total sampling area covered by pixels with a value greater than 0.75 nW·cm^{-2}·sr^{-1} by month (i.e., percentage of light emittance area) and reported in which month the greatest value was recorded (i.e., peak month of light emittance).

To compare light footprint and radiance values across sites, we first tested for normality within sites using Shapiro-Wilk's tests. Approximately half the sites showed non-normal distributions. We used boxplots to identify months with outliers (values above or below the whiskers of the boxplots) and removed those values from subsequent analyses (Terra Nova FPSO months 5 and 7;

Fig. 1. Location of Leach's Storm-Petrel colonies (black circles) and study sites: (1) St. John's, (2) Halifax, (3) Come By Chance refinery, (4) Point Tupper refinery, (5) Goldboro LNG, (6) Hibernia GBS, (7) Sea Rose FPSO, (8) Terra Nova FPSO, (9) Thebaud, (10) Venture/South Venture, (11) North Triumph, (12) Alma, (13) Deep Panuke, (14) Stena IceMax, (15) Core Leach's Storm-Petrel foraging area from Gull Island population, and (16) Core Leach's Storm-Petrel foraging area from Country Island population (see Table 1 for full site descriptions). NL = Newfoundland and Labrador; NS = Nova Scotia; NB = New Brunswick. The black line depicts the location of the 1000-m contour, which is the approximate location of the shelf break.



Deep Panuke month 11; Hibernia GBS month 7). Subsequent Shapiro-Wilk's tests showed remaining data to be normally distributed (or with just minor deviations from normality), with the exception of city sites, which showed strong deviations from normality. Further, we tested for homogeneity of variances across sites using Lavene's test, which showed strong differences owing to large variances around city and offshore NL sites, compared to small variances around foraging areas and offshore NS sites; we found no significant differences among sites within industrial sites types, which was one of the primary analyses (see *Results: Light radiance*). City sites were omitted from subsequent analysis owing to their strong deviation from normality and large variances. Foraging sites were included only as a control for analyses of radiance values (i.e., natural light radiance levels) but were omitted from analyses of light footprint (light footprint was nearly zero at foraging sites).

Analyses were conducted in R version 4.0.4 (R Core Team 2018). We tested for differences in light footprint and radiance values among the three industrial site types (onshore, offshore NL, offshore NS) using generalized linear mixed models (GLMM) (R package "nlme" and "multcomp" for post-hoc comparisons) (Hothorn et al. 2008, Pinheiro et al. 2020), with site as a random effect to account for multiple measures (months) at each site. Finally, we tested for differences within site types, again using GLMM, but included foraging areas as a control for radiance values, which resulted in six models (two light metrics x three industrial site types).

Independent from the satellite-derived light data, we also obtained the average monthly flare volumes (m^3) at specific platforms from operators or regulating agencies for the 12-month study period. Flaring data were obtained for just four of the nine sites with flaring systems (see Table 1). Monthly flare volume was compared to monthly light radiance and footprint values using GLMM with site as a random effect when pooling data across sites (R package "nlme"), and linear models (R function "glm") for correlation tests within individual sites (i.e., Deep Panuke, the only site in NS with flaring data). Throughout this paper we report mean ± standard deviation.

We were not able to relate stranded bird numbers directly to light radiance values because the bird stranding data were collected opportunistically over 20 years, whereas the radiance data were quantified over a single year, and because radiance data were not quantified at many of the sites where birds were reported to strand. In addition, we could not assess the effect of environmental conditions, such as rain, fog, and wind, on stranded bird numbers because these data were not collected in association with bird stranding events during the study period, and archival weather data are largely non-existent for the offshore (platforms collect these data as part of their daily operations, but they are not archived in a readily available database). Moreover, because stranded birds are discovered opportunistically, the date of detection and reporting of events may not match the date of the stranding event, thus making it difficult to link events with actual weather (e.g., precipitation). However, we examined the relationship between the observed frequency of large stranding events (≥ 10 birds reported stranded in a single day at a particular site; $n = 151$) and moon phase (very bright = ≥ 80% illumination; bright = 60–79%; medium = 40–59%; low = 20–39%; and very low = < 20%; [https://www.moongiant.com]) using the Chi-square test, and predicted that light attraction would diminish on nights when the moon was relatively bright (Miles et al. 2010).

RESULTS

Bird stranding data

Between 1998 and 2018, a total of 7922 stranded birds were reported to CWS-ECCC from permitted sites in Atlantic Canada (Table 2). Most of the reported strandings (91.2%) came from NL, where the rate of strandings (46.8 stranded birds reported per permit issued) was higher than the rate reported from NS and New Brunswick (NB) (15.4 stranded birds reported per permit). Offshore production platforms and support vessels reported most

Table 2. Numbers of birds, by species group, reported as stranded to Canadian Wildlife Service, Environment and Climate Change Canada in Atlantic Canada between 1998 and 2018

Species group	Family	Reported stranded	Found dead	Found alive	Died in care	Reported oiled
Storm-Petrels	Hydrobatidae	6920	1595	5042	55	134
Landbirds	19 families†	436	395	32	11	5
Gulls and terns	Laridae	173	148	21	1	5
Unidentified	Unidentified	148	99	43	2	17
Alcids	Alcidae	122	23	92	20	28
Shearwaters and fulmars	Procellariidae	45	4	40	1	1
Waterfowl	Anatidae	32	30	2	0	0
Shorebirds and waders	Ardeidae, Rallidae, Scolopacidae, Charadriidae	29	12	16	2	2
Birds of prey	Accipitridae, Falconidae, Strigidae	11	1	10	0	1
Phalaropes	Scolopacidae	5	5	0	0	0
Gannets and boobies	Sulidae	1	1	0	0	0
Totals		7922	2313	5298	92	193

†See Appendix 1.

of the strandings (46.1%), followed by onshore refinery and construction facilities (28.3%), and offshore seismic vessels (25.5%). However, the rate of bird strandings was highest at onshore facilities (66.0 stranded birds per permit) compared to both offshore production platforms and support vessels (44.0 stranded birds per permit) and seismic vessels (24.6 stranded birds per permit). Of the 27 permits issued to wildlife emergency response incidents (e.g., oil spill events), just one incident encountered stranded birds (six Leach's Storm-Petrels reported alive and released).

The 7922 stranded birds represented 108 species and 32 families (Table 2, Table A1.1). The majority (87.4%) were storm-petrels (Table 2), most of which (83.9%) stranded in September and October (Fig. 2). A total of 1746 of the 6920 (25.2%) stranded storm-petrels were not identified to species; 5116 (73.9%) were identified as Leach's Storm-Petrels, and just 58 (0.8%) were reported as Wilson's Storm-Petrels (*Oceanites oceanicus*). Storm-petrels were the most common species to be stranded in NL (92.9%) (Fig. 3), but made up just 29.8% of reported species in NS and NB combined, where landbirds dominated the reports (51.6%) (Fig. 3). Gulls and terns, alcids, shearwaters and fulmars, waterfowl, shorebirds and waders, birds of prey, phalaropes, and gannets and boobies made up the remainder of the stranded birds reported during the study period (Table 2). Stranded bird reports also included a number of federally listed species at risk, including the endangered Ivory Gull (*Pagophila eburnea*) and Cerulean Warbler (*Setophaga cerulean*) and threatened Barn Swallow (*Hirundo rustica*) and Canada Warbler (*Cardellina canadensis*), as well as species of special concern (Red-necked Phalarope [*Phalaropus lobatus*], Peregrine Falcon [*Falco peregrinus*], Common Nighthawk [*Chordeiles minor*], and Eastern Wood-Pewee [*Contopus virens*)] (Table A1.1).

Fig. 2. Total number of stranded Storm-Petrels (Leach's, Wilson's, and unidentified species combined) reported by month to the Canadian Wildlife Service, Environment and Climate Change Canada in Atlantic Canada between 1998 and 2018.

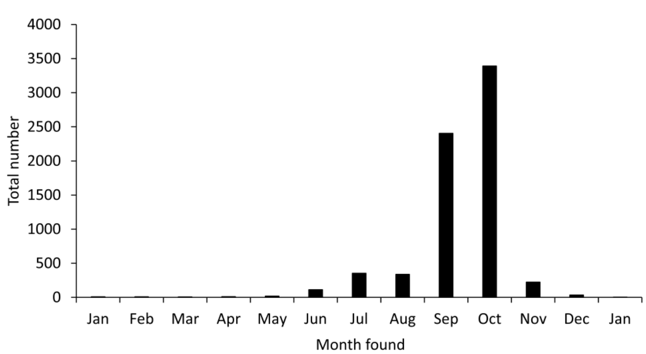
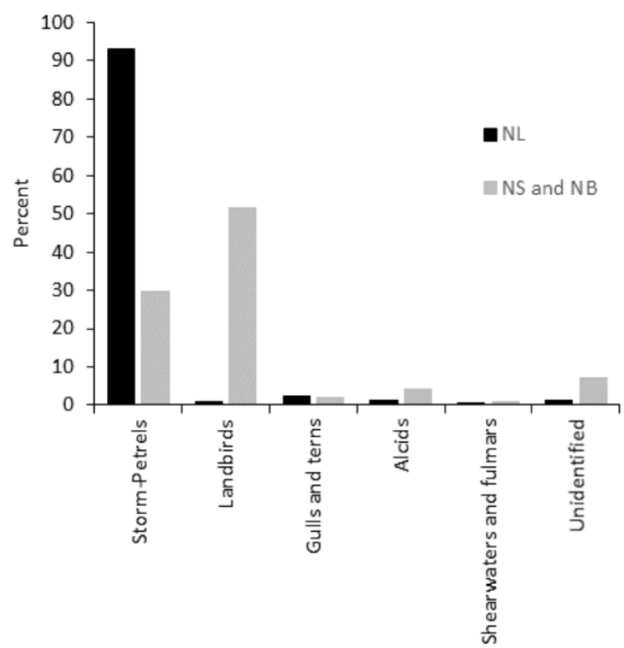


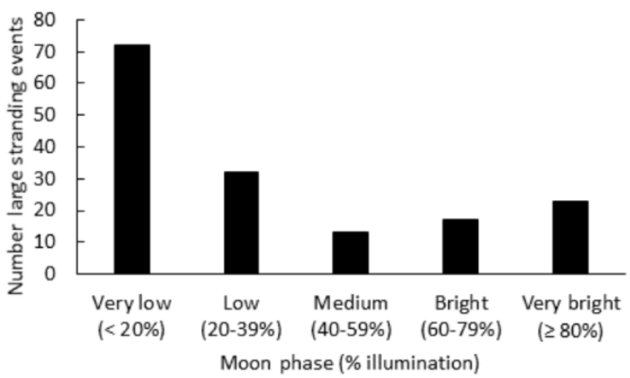
Fig. 3. Relative composition of the top six (99.4%) species groups found stranded in Newfoundland and Labrador (NL; black bars) and in Nova Scotia (NS) and New Brunswick (NB) combined (grey bars) based on reports submitted to the Canadian Wildlife Service, Environment and Climate Change Canada in Atlantic Canada between 1998 and 2018.



The condition of the stranded bird (dead or alive) was reported for all but 311 of the strandings (Table 2). Most stranded birds (69.6% with reported condition) were found alive, and just 92 of those subsequently died in care. For storm-petrels, in particular, 76.0% of the birds found were alive (5042 of 6637 with reported condition), and 98.2% of those were released. In contrast, 92.5% of the landbirds with known fate (i.e., 395/427), 87.6% of the gulls and terns (148/169), 93.8% of the waterfowl (30/32), and all of the phalaropes were found dead (Table 2). A total of 193 (2.4%) of the stranded birds were reported to have oil on their plumage, although the source of the oil (e.g., contaminated surfaces at industrial sites, sheens on the surface of the water) was not determined. Alcids were the group with the highest proportion of stranded birds reported with oil (23.0%), followed by birds of prey (10.0%), and shorebirds and waders (6.9%) (Table 2). Only 1.9% of storm-petrels were reported as oiled (134/6920)

The frequency of large stranding events (≥ 10 birds reported stranded in a single day at a particular site) was significantly related to moon phase (χ^2 = 78.14, P < 0.001). Consistent with our prediction, nine of the largest 10 stranding events (which reported between 75 and 369 birds) and 45.9% of all large stranding events (68 of 157 events where ≥ 10 birds were reported) occurred when the moon was less than 20% illuminated (Fig. 4).

Fig. 4. Frequency of large stranding events (≥ 10 birds reported stranded in a single day at a particular site; n = 151) by moon phase (% illumination) based on reports submitted to the Canadian Wildlife Service, Environment and Climate Change Canada in Atlantic Canada between 1998 and 2018.



Light radiance

For light footprint, there was a significant difference among site types (onshore, offshore NL, offshore NS; $F_{2,9}$ = 13.74, P = 0.002), whereby post-hoc tests showed offshore NL platforms had a larger light footprint than platforms offshore NS (P < 0.001; mean light footprint for offshore NL sites was 19x larger than offshore NS) (Table 3) but were not different from onshore sites (P = 0.93). Mean light footprint from offshore NS platforms was 14x smaller than that of onshore sites (P < 0.001) (Table 3). For radiance values, there was also a significant difference among site types ($F_{2,9}$ = 43.86, P < 0.001): offshore NL platforms were 14x brighter on average than offshore NS platforms (P < 0.001), and were 4x brighter on average than onshore sites (P < 0.001) (Table 3). However, mean radiance for onshore sites was 3x higher than mean radiance for offshore NS platforms (P = 0.003) (Table 3).

For within-site type comparisons, we included Leach's Storm-Petrel foraging areas as a control for radiance values (the light footprint for foraging areas was essentially zero) (Table 3). Within the three offshore NL sites, light footprint and radiance did not differ among platforms (P > 0.80), but platforms had significantly higher radiance values than foraging areas (all pairwise comparisons P < 0.05). Averaged across all months, Terra Nova FPSO recorded the largest light footprint (123 ± 179 km^2) of the offshore industrial sites, followed by Hibernia GBS (86 ± 92 $km^{2.}$) and Sea Rose FPSO (59 ± 42 km^2) (Table 3); all three sites are located in the NL offshore (Fig. 1). The maximum light footprint across all sites was recorded at Terra Nova FPSO in July (598 km^2) (Table 3) during the breeding season of Leach's Storm-Petrels: the light covered 85% of the sampled area (Fig. 5h). Hibernia GBS also recorded its largest light footprint (304 km^2) in July, but at Sea Rose FPSO, the peak was in January (178 km^2) (Table 3). The combined light footprint for these three sites in the NL offshore in July was more than 981 km^2. The Terra Nova FPSO also had the highest radiance value averaged across months (22,172 ± 35,854 $nW \cdot cm^{-2} \cdot sr^{-1}$); the maximum light radiance value at this site was recorded during May (121,053 $nW \cdot cm^{-2} \cdot sr^{-1}$), the Leach's Storm-Petrel incubation period, and was 2x higher than the maximum radiance value recorded from the city of St. John's, NL (Table 3). All three sites in the NL offshore recorded maximum light radiance values during the Leach's Storm-Petrel breeding season (Table 3).

Fig. 5. Average radiance values recorded during the peak month (Table 3) between April 2016 and March 2017 at (A) St. John's, NL; (B) Halifax, NS; (C) Come By Chance refinery, NL; (D) Point Tupper refinery, NS; (E) Goldboro LNG, NS; (F) Hibernia GBS, NL; (G) Sea Rose FPSO, NL; (H) Terra Nova FPSO, NL; (I) Venture/South Venture, NS; (J) Thebaud, NS; (K) Alma, NS; (L) Deep Panuke, NS; (M) North Triumph, NS; and (N) Stena IceMax, NS. NL = Newfoundland and Labrador; NS = Nova Scotia; NB = New Brunswick. The white circle depicts the study area with a radius of 15 km, with the study site located at the centre of the circle. Pixel size is 317 x 317 m.

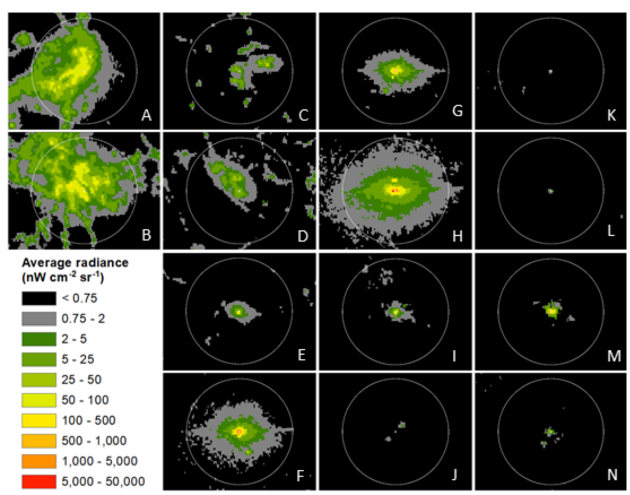


Table 3. Light footprint and light radiance values at offshore and onshore sites in Newfoundland and Labrador (NL) and Nova Scotia (NS) between April 2016 and March 2017

Site	Light footprint (km^2)				Light radiance (nanoWatts·cm^{-2}·sr^{-1})		
	Mean area of light emittance (SD)	Maximum area of light emittance	Peak month	Percentage of area with light during peak month	Average light radiance (SD)	Maximum light radiance	Peak month
City							
St. John's, NL	424 (57)	502	Feb.	71	37,791 (15,221)	62,917	Jan.
Halifax, NS	495 (47)	584	Mar.	83	51,845 (15,115)	85,126	Feb.
Onshore							
Come By Chance refinery, NL	82 (25)	123	Mar.	17	4,803 (1,037)	6,312	Mar.
Point Tupper refinery, NS	88 (40)	172	Mar.	24	4,425 (1,667)	7,633	Mar.
Goldboro LNG, NS	21 (14)	49	Jan.	7	2,304 (1,249)	3,996	Mar.
Offshore							
Hibernia GBS, NL	86 (92)	304	July	43	14,481 (16,831)	55,001	July
Sea Rose FPSO, NL	59 (42)	178	Jan.	25	9,314 (4,897)	18,298	July
Terra Nova FPSO, NL	123 (179)	598	July	85	22,172 (35,854)	121,053	May
Venture/South Venture, NS	2 (1)	4	Nov.	1	517 (793)	2,325	Nov.
Thebaud, NS	14 (12)	43	Nov.	6	2,846 (2,033)	7,143	July
Alma, NS	1 (0.3)	2	Sept. & Nov.	<1	505 (569)	1,606	Nov.
Deep Panuke, NS	5 (5)	20	Nov.	3	1,457 (2,244)	8,311	Nov.
North Triumph, NS	1 (0.8)	3	Nov.	0	449 (737)	1,979	Nov.
Stena IceMax, NS†	4 (3)	8	June	1	532 (1,157)	2,187	June
Bird foraging							
Core foraging area, NL	0.1 (0.2)	0.7	July	0	538 (593)	1,424	May
Core foraging area, NS	0 (0)	0	–	0	357 (737)	1,563	Nov.

†Light footprint and radiance values restricted to June–Sept 2016, when the Stena IceMax drillship was on-site.

Within the six offshore NS sites, light footprint and radiance values were significantly larger for Thebaud than all other platforms ($P < 0.01$), but other platforms were not statistically different from one another. Moreover, Thebaud platform had higher radiance values than foraging areas ($P < 0.001$). The maximum light radiance at Thebaud was highest in July during the Leach's Storm-Petrel breeding season (7143 nW·cm^{-2}·sr^{-1}). The maximum radiance value recorded at Deep Panuke (8311 nW·cm^{-2}·sr^{-1}) exceeded that at Thebaud but occurred in November after most Leach's Storm-Petrels have departed the breeding grounds. Average radiance at the Stena IceMax drillship (532 ± 1157 nW·cm^{-2}·sr^{-1}) was not statistically different from the other NS platforms, with the exception of Thebaud, and was the only other site to record maximum radiance values during the breeding season (June).

Onshore, the Point Tupper refinery in NS recorded the largest light footprint (88 ± 40 km^2), followed by the Come By Chance refinery in NL (82 ± 25 km^2). For comparison, the cities of St. John's, NL and Halifax, NS recorded an average light footprint of 424 ± 57 km^2 and 458 ± 25 km^2, respectively, although the actual light footprints of the city sites were larger because they extended beyond the area (15 km radius) measured in this study (Fig. 5).

We also examined the variance in light footprint and radiance values with respect to each other, and in relation to monthly flaring levels, for sites with available data (Table 1). There was a positive correlation between radiance and light footprint pooled across all offshore sites ($F_{1,86} = 236.66$, $P < 0.001$), as well as within offshore NS sites ($F_{1,56} = 60.94$, $P < 0.001$), and within offshore NL sites ($F_{1,29} = 32.90$, $P < 0.001$). We also found a positive correlation between flare volume and radiance ($F_{1,39} = 8.99$, $P = 0.005$) but not with light footprint ($F_{1,39} = 2.21$, $P = 0.145$). At Deep Panuke, flaring was positively correlated with light footprint ($F_{1,9} = 15.07$, $P = 0.004$) but not radiance ($F_{1,9} = 2.92$, $P = 0.121$), but within the three offshore NL sites (i.e., excluding Deep Panuke), flaring had a positive correlation with radiance ($F_{1,29} = 6.17$, $P = 0.019$) but not light footprint ($F_{1,29} = 1.41$, $P = 0.245$). None of these relationships were different when outlier values were included in the models.

DISCUSSION

While searches for stranded birds at some industrial sites have occurred in Atlantic Canada since 1998, they have been largely opportunistic and have lacked any documentation of search effort (Fraser and Carter 2018). As such, numbers reported here should be viewed as a minimum, and the relative impact of different site types on stranding rates needs to consider potential biases, including variation in the length of time certain industrial activities operate (i.e., permits are issued annually, but some industrial sites do not operate year-round), single permits that cover multiple facilities, and variation in search effort and personnel experience across sites. Despite these limitations with the data reported, our study adds to a growing body of literature that demonstrates that artificial lights from terrestrial and marine sources ground seabirds (reviewed by Rodríguez et al. 2017*b*), one of the most endangered groups of birds globally (Croxall et al. 2012, Dias et al. 2019).

Storm-petrels (primarily Leach's Storm-Petrels) were the most common species reported as stranded in both NS and NL, similar to previous reports from eastern Canada (Baillie et al. 2005, Ellis et al. 2013, Davis et al. 2017). Leach's Storm-Petrel foraging areas from two of the largest colonies in the world, both of which are in decline (Wilhelm et al. 2019), overlap with current oil and gas production and exploration areas in NL (Hedd et al. 2018) where most of the strandings occurred. Fledglings are particularly vulnerable when they leave the colonies on their first flights to sea (Rodríguez et al. 2017*b*, 2017*c*), and although we do not know the age of the stranded birds reported in this study, the high proportion of strandings that occurred in fall suggests that this is also the case for fledgling storm-petrels in Atlantic Canada, which leave their nest at night from August through October (Pollet et al. 2020). Storm-petrels found stranded at coastal facilities (94% were found in September and October) were a minimum of 30 km from the nearest colony (Fig. 1), perhaps because they were attracted to the lights after they had successfully reached the ocean (Troy et al. 2013), or they were blown from their colony in the direction of the light source (Syposz et al. 2018, Krug et al. 2020). Globally, petrels (including shearwaters and storm-petrels) are considered among the seabirds most at-risk to light pollution (Rodríguez et al. 2017*b*), and for some populations, light attraction has been linked to long-term declines (Ainley et al. 2001, Fontaine et al. 2011, Gineste et al. 2017, Raine et al. 2017).

The birds reported as stranded were primarily coastal or marine species (92.5%), due in part because the permits (and thus reporting requirements) were issued to primarily marine-associated operations. In NS and NB, however, the highest proportion of stranded birds were migratory landbirds, accounting for 51.6% of all the stranded birds in that region. Most (97.5%) were stranded in the offshore, and almost all (95.5%) were found dead; the high mortality rate was most often the result of collisions with the infrastructure (CWS-ECCC, *unpublished data*). The Gulf of Maine region, which extends between NS and Cape Cod, Massachusetts, is part of the Atlantic Flyway, and is a major migration corridor for many migratory landbird species (Holberton et al. 2015). During migration, the stranded birds may have confused the vessels or platforms as resting or refueling sites, or may have been disoriented by the lights during poor weather conditions or fog (Russell 2005, Montevecchi 2006). In contrast, industrial sites offshore NL are located outside the Atlantic Flyway, beyond the reach of most landbird and coastal species but within the foraging or wintering range of several seabird species (Mallory et al. 2008, McFarlane Tranquilla et al. 2015, Gjerdrum and Bolduc 2016, Hedd et al. 2018).

Reports of stranded birds also included federally listed species at risk in Canada (i.e., SARA-listed species) as well as provincially listed species from NL and NS, which highlights light attraction as a potential threat to a large suite of species whose conservation status is a concern. It should be noted, however, that the data submitted to CWS-ECCC is provided largely by industry personnel who lack training or experience in bird identification. While all the SARA-listed species were verified through photo-documentation, the identification of some species was uncertain given what we know of their typical ranges (Table A1.1).

In addition to accidental oil spills at oil and gas platforms, which can kill thousands of birds (Wilhelm et al. 2007), chronic oil pollution from routine operations creates sheens on the surface of the water (Fraser et al. 2006), which may also impact birds by compromising feather structure and thus thermoregulation (O'Hara and Morandin 2010). Contaminated surfaces and oily machinery at industrial sites can be another source of oiling when birds strand at these sites and attempt to hide, a risk that presumably increases the longer the bird is stranded. Our study found that a low percentage (2.4%) of the stranded birds were reported as oiled (i.e., oil was detected on the plumage), which suggests they were found relatively quickly after stranding. The relatively high oiling rates of alcids, birds of prey, shorebirds, and waders may reflect oil contamination prior to stranding, although samples of oiled feathers are needed to confirm the source of the oil. Regular searches for stranded birds would not only increase the likelihood of finding and releasing the birds alive, but would also diminish the risk of oil exposure.

Unlike the reported strandings of landbirds, gulls and terns, waterfowl, and phalaropes, most of which were found dead, almost three-quarters of the stranded storm-petrels were found alive and were released. Although the fate of released birds remains unknown, without regular searches at industrial sites, mortality rates of stranded storm-petrels would be far greater without this intervention. Grounded birds will seek refuge under vegetation, in crevices, or under equipment where they are easily overlooked, and without intervention, we assume most of these grounded birds subsequently die and become harder to find, and are therefore underrepresented in stranded bird data sets (Rodríguez et al. 2014). Although the data were not included in our study, fledgling Atlantic Puffins are grounded every year in August along community roadsides in NL due to light attraction (Wilhelm et al. 2013, 2021). The predictability of this fallout in both space and time means a high proportion of the stranded birds are returned to the wild by organized volunteer rescue efforts. Similar rescue and rehabilitation efforts for grounded birds in locations around the world (Rodríguez et al. 2017*c*) mitigate against light-associated mortality by reducing predation, starvation, or dehydration after grounding. Systematic searches for birds conducted by trained and experienced personnel with standardized documentation can increase the proportion of birds found (Podolsky et al. 1998, Ainley et al. 2001, Rodríguez et al. 2014), as well as improve our ability to quantify the impacts of light attraction across sites. However, search and release programs alone are not adequate for mitigating the threat of light attraction because not all birds will be found, especially those that encounter the flare and fall in the water, and the survival of birds after release is still unknown (but see Rodríguez et al. 2017*c*, Raine et al. 2020).

Given that the search effort for stranded birds has to-date been largely opportunistic, we were not able to relate stranding numbers directly to the light characteristics at the sites in which the birds were found. However, our quantification of light footprint and radiance at a subset of sites both onshore and offshore in Atlantic Canada provides new information on the relative contribution of various sites to the lightscape experienced by birds in this region. Offshore NL platforms produced light that was brighter and had a larger footprint than offshore NS platforms, likely owing to the overall size of the structures, the number of onboard personnel, and the specific aspects of production (i.e., flaring). Moreover, NL platforms were brighter than onshore processing sites but had a similar light footprint. This suggests that NL platforms created a formidable amount of offshore light, with one platform lighting up an area of almost

600 km^2, and with radiance values at times exceeding those at major cities in Atlantic Canada. Together, the three offshore production platforms in NL produced a lighted area of almost 1000 km^2 during the month of July, when the largest colony of Leach's Storm-Petrels in the world is foraging in the same area (Hedd et al. 2018), and where this study reported the most storm-petrel strandings relative to the other site types.

Monthly and site-specific variance in radiance, but not light footprint, can at least partially be explained by monthly average flaring. Light emission was based on monthly averaged satellite data from only a few nights per month; thus, direct relationships between flaring activity and light emission could not be quantified precisely, and further examination of this phenomenon, with concurrent and systematically collected data on bird strandings, is warranted to understand flaring levels that might be problematic to birds.

In the Nova Scotia offshore, platforms had much smaller footprints than those in offshore NL, particularly where platforms were unstaffed and were without flares (Alma, North Triumph, and Venture) (Table 1). In addition, radiance values, which were averaged over the study site (15 km radius), were not different from background light levels measured at dark foraging sites. This does not mean that light at the source of the platform was not changing the lightscape, but rather that the light itself did not extend far from the source. The exception to this was the Thebaud platform, which had active flaring and produced a larger footprint and radiance values than other platforms in the same region. Conversely, the more modern facility of Deep Panuke, which also had a flare, had a significantly smaller footprint and radiance values compared to Thebaud. Of note, the Stena IceMax drillship produced light values (footprint and radiance) similar to those of several NS production platforms. Stranded birds were also reported from this site, indicating that even temporary industrial activities such as those conducted by exploratory drillships produce lights that pose a threat to birds. Currently, there are no active production platforms offshore NS because facilities were removed in 2020.

It is not known exactly how birds respond to light, whether there is some threshold of light intensity for attraction to occur, at what distance lights may elicit a behavioral change, and how these responses vary by species and age class. Experimental approaches based on migratory landbirds over terrestrial sites demonstrated the importance of wavelength, although results may be contradictory (Evans et al. 2007, Poot et al. 2008). For marine birds, shielding lights to prevent upward radiation reduced attraction of fledgling Hawaiian seabirds by almost 40% (Reed et al. 1985), and turning lights off completely reduced the number of petrels grounded on St. Kilda (Miles et al. 2010). Brighter sites attracted more Cory's Shearwaters (*Calonectris borealis*) on Sao Miguel Island and attracted birds from further distances compared to less bright sites (Rodríguez et al. 2014). The height of the light source, distance to the colony or foraging grounds, ambient light conditions, weather conditions, and lunar phase have all been found to influence bird attraction and thus mortality (Montevecchi 2006), and the nocturnal behavior of many migratory bird species makes even low-intensity light sources possible threats (Troy et al. 2011). We too observed more stranding events on nights of darker moon phases, but this effect is likely to be confounded by weather conditions (Ronconi et al. 2015), which were not tested in this study. Predicting responses to lighting based on environmental conditions as well as behavioral or visual characteristics of the birds, combined with minimizing the intensity, direction, and duration of the lighting, will help reduce the adverse effects from existing light sources (Longcore et al. 2018). For declining populations of Leach's Storm-Petrels, a long-lived species with high adult survival and low fecundity (Pollet et al. 2020), the minimization of light attraction will be a critical component of population recovery.

Satellite-derived light radiance values used in this study could not be obtained to quantify light emittance from moving, temporary sources of lights, such as those produced by fishing, cargo, and cruise ships moving through the region. However, we know from verbal reports (anecdotal) that these types of ships also attract and strand birds (C.G. and R.A.R.). Light-induced bird strikes occur on a regular basis on vessels that operate in southwest Greenland during winter, particularly in coastal areas and when visibility is poor (Merkel and Johansen 2011). An estimated 3000 vessels reach the shores of Atlantic Canada every year through the ports of Halifax (https://www.portofhalifax.ca/) and St. John's (https://sjpa.com/), and many more transit through the area (Lieske et al. 2020); exposure to all vessel-based lights will need to be considered when assessing the cumulative threat posed by artificial light sources in the marine environment. For the Leach's Storm-Petrel, the threat of light-induced mortality also extends beyond Atlantic Canada into the species' wintering grounds, which overlaps fishing and oil and gas activities off northeastern Brazil and West Africa (Pollet et al. 2014, 2019).

CONCLUSION

Both offshore and onshore light sources, such at those emitted at oil and gas platforms, support vessels, drillships, seismic vessels, refineries, construction sites, and municipalities attract birds in Atlantic Canada. The Leach's Storm-Petrel is the species most often found stranded, and fledglings appear particularly vulnerable. Regularly scheduled, systematic searches are needed to increase the probability of finding live birds and releasing them back to the wild (Rodríguez et al. 2015). Standardized documentation of stranded birds, with detailed spatial information, including data on search effort, will improve our ability to understand site-specific factors that impact stranding rates and better direct mitigation strategies. The use of satellite-derived light information will help identify additional areas where bird strandings are not monitored but mitigation may be warranted (Rodrigues et al. 2012). Lights should be turned off when not needed (Miles et al. 2010, Rodríguez et al. 2014) and shielded to reduce skyward illumination (Reed et al. 1985), and the use of high pressure sodium lights should be considered (Rodríguez et al. 2017*a*), particularly when weather conditions or the lunar phase increase the likelihood of disorientation (Montevecchi 2006), and during the fall when strandings are most common. Other studies have suggested that lights of different spectra should be used to reduce their attraction of migratory landbirds (Poot et al. 2008, Rebke et al. 2019), but the effectiveness of this for marine birds remains untested. Importantly, the monthly variation we observed in both light footprint and radiance values (Fig. A2.1) suggests that the amount of light generated at particular sites may be moderated, in part, by flaring activity, but perhaps also in living or operational activities. Recommendations for reducing the amount of light used at any site should begin with increasing the awareness of the workforce. For the Leach's Storm-Petrel, reducing light-induced mortality by minimizing the attractiveness of the lights is of paramount importance given the declines observed in Atlantic populations (Wilhelm et al. 2019) and their current conservation status (BirdLife International 2018).

Responses to this article can be read online at:
https://www.ace-eco.org/issues/responses.php/1860

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LITERATURE CITED

Ainley, D. G., R. Podolsky, L. Deforest, G. Spencer, and N. Nur. 2001. The status and population trends of the Newell's Shearwater on Kaua'i: insights from modeling. *Studies in Avian Biology* 22:108-123.

Atchoi, E., M. Mitkus, and A. Rodríguez. 2020. Is seabird light-induced mortality explained by the visual system development? *Conservation Science and Practice* 2:e195. https://doi.org/10.1111/csp2.195

Baillie, S. M., G. J. Robertson, F. K. Wiese, and U. P. Williams. 2005. *Seabird data collected by the Grand Banks offshore hydrocarbon industry 1999–2002: results, limitations and suggestions for improvement*. Environment Canada, Canada.

BirdLife International. 2018. *Hydrobates leucorhous*. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T132438298A132438484.en

Croxall, J. P., S. H. M. Butchart, B. Lascelles, A. J. Stattersfield, B. Sullivan, A. Symes, and P. Taylor. 2012. Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International* 22:1-34. https://doi.org/10.1017/S0959270912000020

Davies, T. W., J. P. Duffy, J. Bennie, and K. J. Gaston. 2014. The nature, extent, and ecological implications of marine light pollution. *Frontiers in Ecology and the Environment* 12:347-355. https://doi.org/10.1890/130281

Davis, R. A., A. L. Lang, and B. Mactavish. 2017. Study of seabird attraction to the Hebron production platform: a proposed study approach. LGL Limited. St. John's, Newfoundland and Labrador, Canada.

Day, R. H., J. R. Rose, A. K. Prichard, and B. Streever. 2015. Effects of gas flaring on the behavior of night-migrating birds at an artificial oil-production island, Arctic Alaska. *Arctic* 68:367-379. https://doi.org/10.14430/arctic4507

Dias, M. P., R. Martin, E. J. Pearmain, I. J. Burfield, C. Small, R. A. Phillips, O. Yates, B. Lascelles, P. G. Borboroglu, and J. P. Croxall. 2019. Threats to seabirds: a global assessment. *Biological Conservation* 237:525-537. https://doi.org/10.1016/j.biocon.2019.06.033

Ellis, J. I., S. I. Wilhelm, A. Hedd, G. S. Fraser, G. J. Robertson, J.-F. Rail, M. Fowler, and K. H. Morgan. 2013. Mortality of migratory birds from marine commercial fisheries and offshore oil and gas production in Canada. *Avian Conservation and Ecology* 8:4. https://doi.org/10.5751/ACE-00589-080204

Elvidge, C. D., K. Baugh, M. Zhizhin, F. Chi Hsu, and T. Ghosh. 2017. VIIRS night-time lights. *International Journal of Remote Sensing* 38:5860-5879. https://doi.org/10.1080/01431161.2017.1342050

Environment and Climate Change Canada. 2017. *Procedures for handling and documenting stranded birds encountered on infrastructure offshore Atlantic Canada.* Canadian Wildlife Service, Dartmouth, Nova Scotia, Canada.

ESRI Inc. 2019. *ArcGIS Pro (version 10.7.1)*. Redlands, California, USA. [online] URL: https://www.esri.com/en-us/arcgis/products/arcgis-pro/

Evans, W. R., Y. Akashi, N. S. Altman, and A. M. Manville. 2007. Response of night-migrating songbirds in cloud to colored and flashing light. *North American Birds* 60:476-488.

Falchi, F., P. Cinzano, D. Duriscoe, C. C. M. Kyba, C. D. Elvidge, K. Baugh, B. Portnov, N. A. Rybnikova, and R. Furgoni. 2016. *Supplement to the new world atlas of artificial night sky brightness*. V. 1.1. GFZ Data Services. http://doi.org/10.5880/GFZ.1.4.2016.001

Fontaine, R., O. Gimenez, and J. Bried. 2011. The impact of introduced predators, light-induced mortality of fledglings and poaching on the dynamics of the Cory's shearwater (*Calonectris diomedea*) population from the Azores, northeastern subtropical Atlantic. *Biological Conservation* 144:1998-2011. https://doi.org/10.1016/j.biocon.2011.04.022

Fraser, G. S., and A. V. Carter. 2018. Seabird attraction to artificial light in Newfoundland and Labrador's offshore oil fields: documenting failed regulatory governance. *Ocean Yearbook* 32:265-282. https://doi.org/10.1163/22116001-03201011

Fraser, G. S., J. Russell, and W. M. Von Zharen. 2006. Produced water from offshore oil and gas installations on the Grand Banks, Newfoundland: are the potential effects to seabirds sufficiently known? *Marine Ornithology* 34:147-156.

Gineste, B., M. Souquet, F.-X. Couzi, Y. Giloux, J.-S. Philippe, C. Hoarau, J. Tourmetz, G. Potin, and M. Le Corre. 2017. Tropical Shearwater population stability at Reunion Island, despite light pollution. *Journal of Ornithology* 158:385-394. https://doi.org/10.1007/s10336-016-1396-5

Gjerdrum, C., and F. Bolduc. 2016. Non-breeding distribution of Herring Gull (*Larus argentatus*) and Great Black-backed Gull (*L.*

marinus) in eastern Canada from ship-based surveys. *Waterbirds* 39:202-219. https://doi.org/10.1675/063.039.sp119

Hedd, A., I. L. Pollet, R. A. Mauck, C. M. Burke, M. L. Mallory, L. A. McFarlane Tranquilla, W. A. Montevecchi, G. J. Robertson, R. A. Ronconi, D. Shutler, S. I. Wilhelm, and N. M. Burgess. 2018. Foraging areas, offshore habitat use, and colony overlap by incubating Leach's Storm-Petrels *Oceanodroma leucorhoa* in the Northwest Atlantic. *PLOS ONE* 13:1-18. https://doi.org/10.1371/journal.pone.0194389

Holberton, R. L., S. L. Van Wilgenburg, A. J. Leppold, and K. A. Hobson. 2015. Isotopic evidence of "loop migration" and use of the Gulf of Maine Flyway by both western and eastern breeding populations of Blackpoll Warblers. *Journal of Field Ornithology* 86:213-228. https://doi.org/10.1111/jofo.12112

Hölker, F., C. Wolter, E. K. Perkin, and K. Tockner. 2010. Light pollution as a biodiversity threat. *Trends in Ecology & Evolution* 25:681-682. https://doi.org/10.1016/j.tree.2010.09.007

Hope-Jones, P. 1980. The effect on birds of a North Sea gas flare. *British Birds* 73:547-555.

Hothorn, T., F. Bretz, and P. Westfall. 2008. Simultaneous inference in general parametric models. *Biometrical Journal* 50:346-363. https://doi.org/10.1002/bimj.200810425

Krug, D. M., R. Frith, S. N. P. Wong, R. A. Ronconi, S. I. Wilhelm, N. J. O'Driscoll, and M. L. Mallory. 2020. Marine pollution in fledged Leach's Storm-Petrels (*Hydrobates leucorhous*) from Baccalieu Island, Newfoundland and Labrador, Canada. *Marine Pollution Bulletin* 162:111842. https://doi.org/10.1016/j.marpolbul.2020.111842

Krüger, L., V. H. Paiva, M. V. Petry, and J. A. Ramos. 2017. Strange lights in the nights: using abnormal peaks of light in geolocator data to infer interaction of seabirds with nocturnal fishing vessels. *Polar Biology* 40:221-226. https://doi.org/10.1007/s00300-016-1933-y

Lieske, D. J., L. McFarlane Tranquilla, R. A. Ronconi, and S. Abbott. 2020. "Seas of risk": assessing the threats to colonial-nesting seabirds in Eastern Canada. *Marine Policy* 115:103863. https://doi.org/10.1016/j.marpol.2020.103863

Longcore, T., A. Rodrigues, B. Witherington, J. F. Penniman, L. Herf, and M. Herf. 2018. Rapid assessment of lamp spectrum to quantify ecological effects of light at night. *Journal of Experimental Zoology* 329:511-521. https://doi.org/10.1002/jez.2184

Mallory, M. L., J. A. Akearok, D. B. Edwards, K. O'Donovan, and C. D. Gilbert. 2008. Autumn migration and wintering of Northern Fulmars (*Fulmarus glacialis*) from the Canadian high Arctic. *Polar Biology* 31:745-750. https://doi.org/10.1007/s00300-008-0417-0

Manfrin, A., G. Singer, S. Larsen, N. Weib, R. H. A. van Grunsven, N.-S. Weib, S. Wohlfahrt, M. T. Monaghan, and F. Holker. 2017. Artificial light at night affects organism flux across ecosystem boundaries and drives community structure in the recipient ecosystem. *Frontiers in Environmental Science* 5:1-14. https://doi.org/10.3389/fenvs.2017.00061

McFarlane Tranquilla, L., W. A. Montevecchi, A. Hedd, P. M. Regular, G. J. Robertson, D. A. Fifield, and R. Devillers. 2015. Ecological segregation among Thick-billed Murres (*Uria lomvia*) and Common Murres (*Uria aalge*) in the Northwest Atlantic persists through the nonbreeding season. *Canadian Journal of Zoology* 93:447-460. https://doi.org/10.1139/cjz-2014-0315

Merkel, F. R., and K. L. Johansen. 2011. Light-induced bird strikes on vessels in Southwest Greenland. *Marine Pollution Bulletin* 62:2330-2336. https://doi.org/10.1016/j.marpolbul.2011.08.040

Miles, W., S. Money, R. Luxmoore, and R. W. Furness. 2010. Effects of artificial lights and moonlight on petrels at St. Kilda. *Bird Study* 57:244-251. https://doi.org/10.1080/00063651003605064

Mills, S., S. Weiss, and C. Liang. 2013. VIIRS day/night band (DNB) stray light characterization and correction. *Proceedings SOIE 8866, Earth Observing Systems* XVII. https://doi.org/10.1117/12.2023107

Montevecchi, W. A. 2006. Influences of artificial light on marine birds. Pages 94-113 *in* C. Rich and T. Longcore, editors. *Ecological consequences of artificial night lighting*. Island Press, Washington, D.C., USA.

O'Hara, P. D., and L. A. Morandin. 2010. Effects of sheens associated with offshore oil and gas development on the feather microstructure of pelagic seabirds. *Marine Pollution Bulletin* 60:672-678. https://doi.org/10.1016/j.marpolbul.2009.12.008

Pinheiro, J., D. Bates, S. DebRoy, and D. Sarkar. 2020. *nlme: linear and nonlinear mixed effects models*. R package version 3.1-149.

Podolsky, R., D. G. Ainley, G. Spencer, L. Deforest, and N. Nur. 1998. Mortality of Newell's shearwaters caused by collisions with urban structures on Kauai. *Colonial Waterbirds* 21:20-34. https://doi.org/10.2307/1521727

Pollet, I. L., A. L. Bond, A. Hedd, C. E. Huntington, R. G. Butler, and R. A. Mauck. 2020. Leach's Storm-Petrel (*Oceanodroma leucorhoa*). Version 1.0 *in* S. M. Billerman, B. K. Keeney, P. G. Rodewald, and T. S. Schulenberg, editors. *Birds of the world*. Cornell Lab of Ornithology, Ithaca, New York, USA. https://doi.org/10.2173/bow.lcspet.01

Pollet, I. L., A. Hedd, P. D. Taylor, W. A. Montevecchi, and D. Shutler. 2014. Migratory movements and wintering areas of Leach's Storm-Petrels tracked using geolocators. *Journal of Field Ornithology* 85:321-328. https://doi.org/10.1111/jofo.12071

Pollet, I. L., R. A. Ronconi, M. L. Leonard, and D. Shutler. 2019. Migration routes and stopover areas of Leach's Storm-Petrels *Oceanodroma leucorhoa*. *Marine Ornithology* 47:55-65.

Poot, H., B. J. Ens, H. de Vries, M. A. H. Donners, M. R. Wernand, and J. M. Marquenie. 2008. Green light for nocturnally migrating birds. *Ecology and Society* 13:47. https://doi.org/10.5751/ES-02720-130247

R Core Team. 2018. R: a language and environment for statistical computing, v. 4.0.4.

Raine, A. F., S. Driskill, M. Vynne, D. Harvey, and K. Pias. 2020. Managing the effects of introduced predators on Hawaiian endangered seabirds. *Journal of Wildlife Management* 84:425-435. https://doi.org/10.1002/jwmg.21824

Raine, A. F., N. D. Holmes, M. Travers, B. A. Cooper, and R. H. Day. 2017. Declining population trends of Hawaiian Petrel and Newell's Shearwater on the island of Kaua'i, Hawaii, USA. *Condor* 119:405-415. https://doi.org/10.1650/CONDOR-16-223.1

Rebke, M., V. Dierschke, C. N. Weiner, R. Aumüller, K. Hill, and R. Hill. 2019. Attraction of nocturnally migrating birds to artificial light: the influence of colour, intensity and blinking mode under different cloud cover conditions. *Biological Conservation* 233:220-227. https://doi.org/10.1016/j.biocon.2019.02.029

Reed, J. R., J. L. Sincock, and J. P. Hailman. 1985. Light attraction in endangered procellariiform birds: reduction by shielding upward radiation. *Auk* 102:377-383. https://doi.org/10.2307/4086782

Rich, C., and T. Longcore. 2006. *Ecological consequences of artificial lighting*. Island Press, Washington, D.C., USA.

Rodrigues, P., C. Aubrecht, A. Gil, T. Longcore, and C. D. Elvidge. 2012. Remote sensing to map influence of light pollution on Cory's Shearwater in São Miguel Island, Azores Archipelago. *European Journal of Wildlife Research* 58:147-155. https://doi.org/10.1007/s10344-011-0555-5

Rodríguez, A., G. Burgan, P. Dann, R. Jessop, J. J. Negro, and A. Chiaradia. 2014. Fatal attraction of Short-tailed Shearwaters to artificial lights. *PLOS ONE* 9:e110114. https://doi.org/10.1371/journal.pone.0110114

Rodríguez, A., P. Dann, and A. Chiaradia. 2017*a*. Reducing light-induced mortality of seabirds: high pressure sodium lights decrease the fatal attraction of shearwaters. *Journal for Nature Conservation* 39:68-72. https://doi.org/10.1016/j.jnc.2017.07.001

Rodríguez, A., D. Garcia, B. Rodriguez, E. Cardona, L. Parpal, and P. Pons. 2015. Artificial lights and seabirds: Is light pollution a threat for the threatened Balearic Petrels? *Journal of Ornithology* 156:893-902. https://doi.org/10.1007/s10336-015-1232-3

Rodríguez, A., N. D. Holmes, P. G. Ryan, K. J. Wilson, L. Faulquier, Y. Murillo, A. F. Raine, J. F. Penniman, V. Neves, B. Rodríguez, J. J. Negro, A. Chiaradia, P. Dann, T. Anderson, B. Metzger, M. Shirai, L. Deppe, J. Wheeler, P. Hodum, C. Gouveia, V. Carmo, G. P. Carreira, L. Delgado-Alburqueque, C. Guerra-Correa, F. X. Couzi, M. Travers, and M. Le Corre. 2017*b*. Seabird mortality induced by land-based artificial lights. *Conservation Biology* 31:986-1001. https://doi.org/10.1111/cobi.12900

Rodríguez, A., J. Moffett, A. Revoltós, P. Wasiak, R. R. McIntosh, D. R. Sutherland, L. Renwick, P. Dann, and A. Chiaradia. 2017*c*. Light pollution and seabird fledglings: targeting efforts in rescue programs. *Journal of Wildlife Management* 81:734-741.

Rodríguez, A., and B. Rodríguez. 2009. Attraction of petrels to artificial lights in the Canary Islands: effects of the moon phase and age class. *Ibis* 151:299-310. https://doi.org/10.1111/j.1474-919X.2009.00925.x

Rodríguez, A., B. Rodríguez, A. J. Curbelo, A. Pérez, S. Marrero, and J. J. Negro. 2012. Factors affecting mortality of sheawaters stranded by light pollution. *Animal Conservation* 15:519-526. https://doi.org/10.1111/j.1469-1795.2012.00544.x

Ronconi, R. A., K. A. Allard, and P. D. Taylor. 2015. Bird interactions with offshore oil and gas platforms: review of impacts and monitoring techniques. *Journal of Environmental Management* 147:34-45. https://doi.org/10.1016/j.jenvman.2014.07.031

Russell, R. W., editor. 2005. Interactions between migrating birds and offshore oil and gas platforms in the northern Gulf of Mexico: final report. OCS Study MMS 2005-009. U.S. Department of the Interior, New Orleans, Louisiana, USA.

Statistics Canada 2017*a*. *St. John's, CY [Census subdivision], Newfoundland and Labrador, Canada*. Census profile. 2016 census. Statistics Canada Catalogue no. 98-316-X2016001. Statistics Canada, Ottawa, Ontario, Canada.

Statistics Canada 2017*b*. *Halifax [Census metropolitan area], Nova Scotia, Canada. Census profile. 2016 census*. Statistics Canada Catalogue no. 98-316-X2016001. Statistics Canada, Ottawa, Ontario, Canada.

Syposz, M., F. Gonçalves, M. Carty, W. Hoppitt, and F. Manco. 2018. Factors influencing Manx Shearwater grounding on the west coast of Scotland. *Ibis* 160:846-854. https://doi.org/10.1111/ibi.12594

Troy, J. R., N. D. Holmes, and M. C. Green. 2011. Modeling artificial light viewed by fledgling seabirds. *Ecosphere* 2:1-13. https://doi.org/10.1890/ES11-00094.1

Troy, J. R., N. D. Holmes, J. A. Veech, and M. C. Green. 2013. Using observed seabird fallout records to infer patterns of attraction to artificial light. *Endangered Species Research* 22:225-234. https://doi.org/10.3354/esr00547

Wiese, F. K., W. A. Montevecchi, G. K. Davoren, F. Huettmann, A. W. Diamond, and J. Linke. 2001. Seabirds at risk around offshore platforms in the North-west Atlantic. *Marine Pollution Bulletin* 42:1285-1290. https://doi.org/10.1016/S0025-326X(01)00096-0

Wilhelm, S. I., S. M. Dooley, E. P. Corbett, M. G. Fitzsimmons, P. C. Ryan, and G. J. Robertson. 2021. Effects of land-based light pollution on two species of burrow-nesting seabirds in Newfoundland and Labrador, Canada. *Avian Conservation and Ecology* 16(1):12. https://doi.org/10.5751/ACE-01809-160112

Wilhelm, S. I., A. Hedd, G. J. Robertson, J. Mailhiot, P. M. Regular, P. C. Ryan, and R. D. Elliot. 2019. The world's largest breeding colony of Leach's Storm-Petrel *Hydrobates leucorhous* has declined. *Bird Conservation International* 30:40-57. https://doi.org/10.1017/S0959270919000248

Wilhelm, S. I., G. J. Robertson, P. C. Ryan, and D. C. Schneider. 2007. Comparing an estimate of seabirds at risk to a mortality estimate from the November 2004 Terra Nova FPSO oil spill. *Marine Pollution Bulletin* 54:537-544. https://doi.org/10.1016/j.marpolbul.2006.12.019

Wilhelm, S. I., J. J. Schau, E. Schau, S. M. Dooley, D. L. Wiseman, and H. A. Hogan. 2013. Atlantic Puffins are attracted to coastal communities in eastern Newfoundland. *Northeastern Naturalist* 20:624-630. https://doi.org/10.1656/045.020.0409

Williams, U., and J. W. Chardine. 1999. The Leach's Storm-Petrel: general information and handling instructions. [online] URL: https://www.cnlopb.ca/wp-content/uploads/cggservices/stormpetrel.pdf

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Appendix 1.

Table A1.1. Number of individual bird species reported stranded to Canadian Wildlife Service, Environment and Climate Change Canada (CWS-ECCCC) in Atlantic Canada from 1998-2018.

Group	Common Name	Latin	Number stranded
Shearwaters and fulmar	Northern Fulmar	*Fulmarus glacialis*	5
	Great Shearwater	*Ardenna gravis*	36
	Sooty Shearwater	*Ardenna griseus*	3
	Cory’s Shearwater	*Calonectris borealis*	1
Storm-Petrels	Wilson's Storm-Petrel	*Oceanites oceanicus*	58
	Leach's Storm-Petrel	*Oceanodroma leucorhoa*	5116
	Unidentified Storm-Petrel	Hydrobatidae	1746
Gannets and boobies	Brown Booby	*Sula leucogaster*	1
Shorebirds and waders	American Bittern	*Botaurus lentiginosus*	2
	Great Blue Heron	*Ardea herodias*	4
	Great Egret	*Ardea alba*	3
	Snowy Egret	*Egretta thula*	1
	Cattle Egret	*Bubulcus ibis*	1
	Yellow-crowned Night-Heron	*Nyctanassa violacea*	1
	Purple Gallinule	*Porphyrio martinicus*	2
	Sora	*Porzana Carolina*	4
	Virginia Rail	*Rallus limicola*	1
	American Golden Plover	*Pluvialis squatarola*	1
	Spotted Sandpiper	*Actitis macularius*	1
	Ruddy Turnstone	*Arenaria interpres*	2
	Sanderling	*Calidris alba*	1
	White-rumped Sandpiper	*Calidris fusciollis*	1
	Semipalmated Sandpiper	*Calidris pusilla*	1
	Least Sandpiper	*Calidris minutilla*	2
	Wilson's Snipe	*Gallinago delicata*	1
Phalaropes	Red Phalarope	*Phalaropus fulicaria*	2
	Red-necked Phalarope	*Phalaropus lobatus*	3
Waterfowl	Canada Goose	*Branta Canadensis*	2
	Mallard	*Anas platyrhynochos*	1

Group	Common Name	Latin	Number stranded
Waterfowl	American Black Duck	*Anus rubripes*	1
	Eider unidentified	*Somateria*	28
Birds of prey	Cooper's Hawk	*Accipiter cooperii*	1
	Merlin	*Falco columbarius*	2
	Peregrine Falcon	*Falco peregrinus*	5
	Snowy Owl	*Nyctea scandiaca*	2
	Boreal Owl	*Aegolius funereus*	1
Gulls and terns	Black-legged Kittiwake	*Rissa tridactyla*	6
	Ivory Gull	*Pagophila eburnea*	1
	Bonaparte's Gull	*Larus philadelphia*	1
	Herring Gull	*Larus argentatus*	130
	Glaucous Gull	*Larus hyperboreus*	3
	Great Black-backed Gull	*Larus marinus*	18
	Lesser Black-backed Gull	*Larus fuscus*	1
	Gull unidentified	Laridae	12
	Tern unidentified	*Sterna*	1
Alcids	Dovekie	*Alle alle*	64
	Black Guillemot	*Cepphus grylle*	1
	Common Murre	*Uria aalge*	34
	Thick-billed Murre	*Uria lomvia*	17
	Murre unidentified	*Uria*	2
	Atlantic Puffin	*Fratercula arctica*	4
Landbirds	Mourning Dove	*Zenaida macroura*	9
	Yellow-billed Cuckoo	*Coccyzus americanus*	1
	Black-billed Cuckoo	*Coccyzus erythropthalmus*	1
	Common Nighthawk	*Chordeiles minor*	1
	Belted Kingfisher	*Megaceryle alcyon*	1
	Eastern Wood-Pewee	*Contopus virens*	1
	Yellow-bellied Flycatcher	*Empidonax flaviventris*	1
	White-eyed Vireo	*Vireo griseus*	1
	Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	2
	Tree Swallow	*Tachycineta bicolor*	1
	Cliff Swallow	*Petrochelidon pyrrhonota*	2
	Barn Swallow	*Hirundo rustica*	3

Group	Common Name	Latin	Number stranded
Landbirds	Boreal Chickadee	*Poecile hudsonicus*	1
	Red-breasted Nuthatch	*Sitta canadensis*	3
	Golden-crowned Kinglet	*Regulus satrapa*	2
	Ruby-crowned Kinglet	*Regulus calendula*	1
	American Robin	*Turdus migratorius*	4
	Hermit Thrush	*Catharus guttatus*	1
	Gray Catbird	*Dumetella carolinensis*	2
	European Starling	*Sturnus vulgaris*	1
	White Wagtail	*Motacilla alba*	1
	Northern Parula	*Parula americana*	1
	Nashville Warbler	*Vermivora ruficapilla*	1
	Tennessee Warbler	*Oreothlypis peregrina*	2
	Yellow Warbler	*Dendroica petechia*	12
	Chestnut-sided Warbler	*Dendroica pensylvanica*	1
	Magnolia Warbler	*Dendroica magnolia*	3
	Black-throated Blue Warbler	*Dendroica caerulescens*	1
	Black-throated Green Warbler	*Dendroica virens*	4
	Palm Warbler	*Dendroica palmarum*	1
	Blackpoll Warbler	*Dendroica striata*	160
	Cerulean Warbler	*Setophaga cerulea*	1
	Yellow-rumped Warbler	*Setophaga coronata*	2
	American Redstart	*Setophaga ruticilla*	1
	Black-and-white Warbler	*Mniotilta varia*	4
	Ovenbird	*Seiurus aurocapilla*	8
	Northern Waterthrush	*Parkesia noveboracensis*	29
	Common Yellowthroat	*Geothlypis trichas*	3
	Wilson's Warbler	*Wilsonia pusilla*	2
	Canada Warbler	*Cardellina canadensis*	1
	Yellow-breasted Chat	*Icteria virens*	1
	Warbler unidentified	Parulidae	3
	Scarlet Tanager	*Piranga olivacea*	1
	Chipping Sparrow	*Spizella passerine*	3
	Seaside Sparrow	*Ammodramus maritimus*	2
	Savannah Sparrow	*Passerculus sandwichensis*	7
	White-throated Sparrow	*Zonotrichia albicollis*	26

Group	Common Name	Latin	Number stranded
Landbirds	Lincoln's Sparrow	*Melospiza lincolnii*	1
	Song Sparrow	*Melospiza melodia*	2
	House Sparrow	*Passer domesticus*	1
	Sparrow unidentified	Emberizidae	11
	Dark-eyed Junco	*Junco hyemalis*	3
	Lapland Longspur	*Calcarius lapponicus*	1
	Snow Bunting	*Plectrophenax nivalis*	13
	Baltimore Oriole	*Icterus galbula*	2
	Common Grackle	*Quiscalus quiscula*	1
	Pine Grosbeak	*Pinicola enucleator*	2
	Purple Finch	*Carpodacus purpureus*	2
	Common Redpoll	*Carduelis flammea*	1
	Pine Siskin	*Carduelis pinus*	3
	Lesser Goldfinch	*Spinus psaltria*	1
	American Goldfinch	*Carduelis tristis*	64
	Finch unidentified	Fringillidae	1
	Songbird unidentified	Passeriformes	7
Unidentified		Aves	148
Total			7922

Appendix 2.

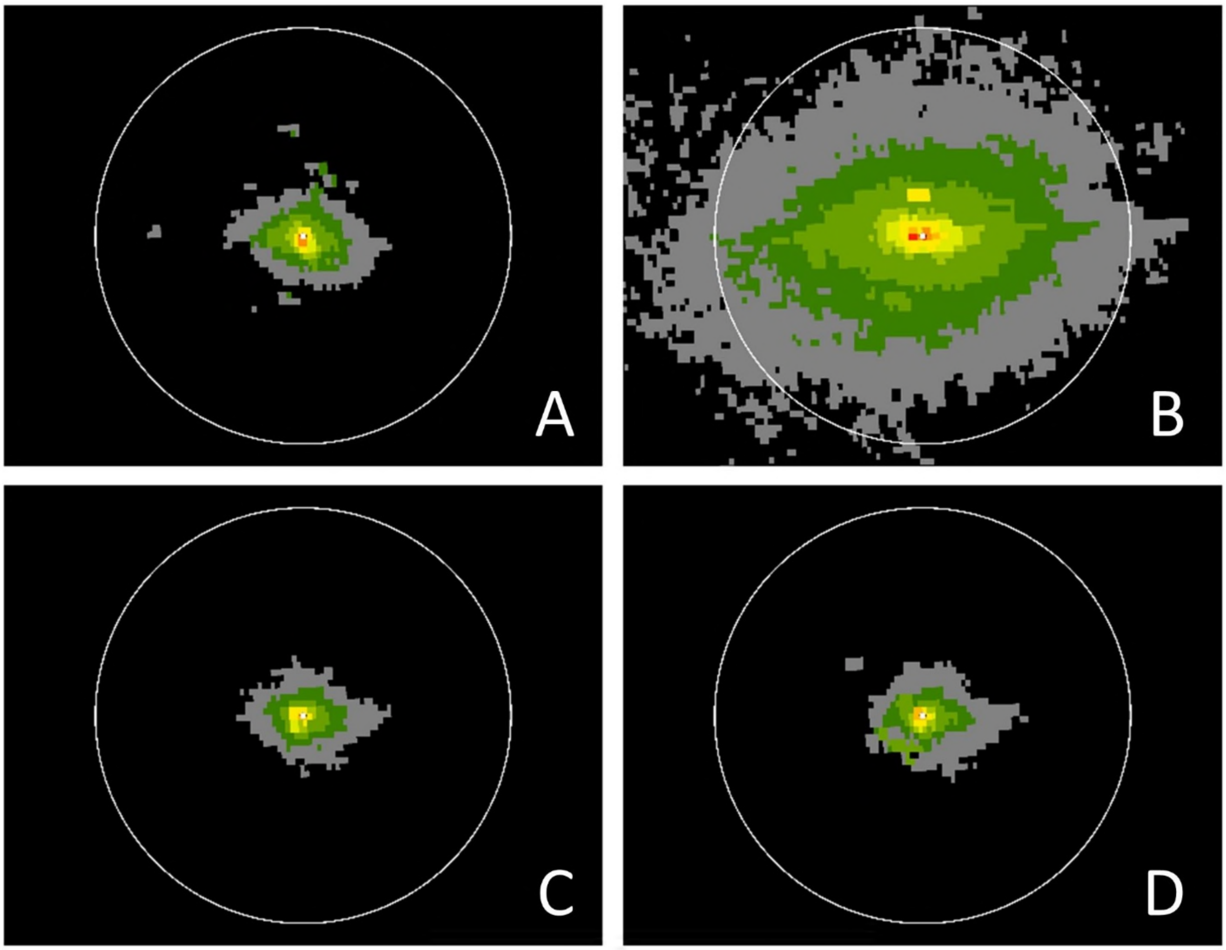

Figure A2.1 Average radiance values recorded at Terra Nova FPSO, NL in A) April 2016; B) July 2016; C) October 2016; and D) January 2017. Radiance values as per Figure 5. White circle depicts study area with radius of 15 km with Terra Nova FPSO located at the centre of the circle. Pixel size 317 x 317 m.