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

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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 Change Climate 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.

INTRODUCTION

The use of artificial light at night is a significant source of anthropogenic pollution with ecological impacts (Rich and Longcore 2006, Höcker 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, Rodriguez et al. 2017b). 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 (Rodriguez 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...
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, Rodriguez et al. 2017c), 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, Montvecchi 2006), and when lunar illumination is low (Rodriguez and Rodriguez 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 (Bailie 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 Storm-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 (Bailie 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
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 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.

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 (m³) 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 cerulea*) 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 (χ² = 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).

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 km²) of the offshore industrial sites, followed by Hibernia GBS (86 ± 92 km²) and Sea Rose FPSO (59 ± 42 km²) (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 km²) (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 km²) in July, but at Sea Rose FPSO, the peak was in January (178 km²) (Table 3). The combined light footprint for these three sites in the NL offshore in July was more than 981 km². The Terra Nova FPSO also had the highest radiance value averaged across months (22,172 ± 35,854 nW·cm⁻²·sr⁻¹); the maximum light radiance value at this site was recorded during May (121,053 nW·cm⁻²·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).

For light footprint, there was a significant difference among site types (onshore, offshore NL, offshore NS; F₁,₉ = 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 (F₁,₉ = 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).
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                        | 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                        | 424 (57)                         | 502                             | Feb.       | 71                                            | 37,791 (15,221)             | 62,917                 | Jan.       |
| St. John’s, NL              | 495 (47)                         | 584                             | Mar.       | 83                                            | 51,845 (15,115)             | 85,126                 | Feb.       |
| Halifax, NS                 | 82 (25)                          | 123                             | Mar.       | 17                                            | 4,803 (1,037)               | 6,312                  | Mar.       |
| Onshore                     | 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                    | 86 (92)                          | 304                             | July       | 43                                            | 14,481 (16,831)             | 55,001                 | July       |
| Hibernia GBS, NL            | 59 (42)                          | 178                             | Jan.       | 25                                            | 9,314 (4,987)               | 18,298                 | July       |
| Sea Rose FPSO, NL           | 123 (179)                        | 598                             | July       | 85                                            | 22,172 (35,854)             | 121,053                | May        |
| Terra Nova FPSO, NL         | 2 (1)                            | 4                               | Nov.       | 1                                             | 517 (793)                   | 2,235                  | Nov.       |
| Venture/South Venture, NS   | 14 (12)                          | 43                              | Nov.       | 6                                             | 2,846 (2,033)               | 7,143                  | July       |
| Thebaud, NS                 | 1 (0.3)                          | 2                               | Sept. & Nov. | <1                                            | 505 (569)                   | 1,066                  | Nov.       |
| Alma, NS                    | 5 (5)                            | 20                              | Nov.       | 3                                             | 1,457 (2,244)               | 8,311                  | Nov.       |
| Deep Panuke, NS             | 1 (0.8)                          | 3                               | Nov.       | 0                                             | 449 (737)                   | 1,979                  | Nov.       |
| North Triumph, NS           | 4 (3)                            | 8                               | June       | 1                                             | 532 (1,157)                 | 2,187                  | June       |
| Bird foraging               | 0.1 (0.2)                        | 0.7                             | July       | 0                                             | 538 (593)                   | 1,424                  | May        |
| Core foraging area, NL      | 0 (0)                            | 0                               | –          | 0                                             | 357 (737)                   | 1,563                  | Nov.       |
| Core foraging area, NS      | 0 (0)                            | 0                               | –          | 0                                             |                             |                       |            |

*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 km²), followed by the Come By Chance refinery in NL (82 ± 25 km²). For comparison, the cities of St. John’s, NL and Halifax, NS recorded an average light footprint of 424 ± 57 km² and 458 ± 25 km², 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 (F₁,30 = 236.66, P < 0.001), as well as within offshore NS sites (F₁,50 = 60.94, P < 0.001), and within offshore NL sites (F₁,20 = 32.90, P < 0.001). We also found a positive correlation between flare volume and radiance (F₁,30 = 8.99, P = 0.005) but not with light footprint (F₁,30 = 2.21, P = 0.145). At Deep Panuke, flaring was positively correlated with light footprint (F₁,9 = 15.07, P = 0.004) but not radiance (F₁,9 = 2.92, P = 0.121), but within the three offshore NL sites (i.e., excluding Deep Panuke), flaring had a positive correlation with radiance (F₁,30 = 6.17, P = 0.019) but not light footprint (F₁,20 = 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. 2017b), 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...
found dead; the high mortality rate was most often the result of 97.5% were stranded in the offshore, and almost all (95.5%) were accounting for 51.6% of all the stranded birds in that region. Most associated operations. In NS and NB, however, the highest reporting requirements) were issued to primarily marine-species (92.5%), due in part because the permits (and thus permits) were considered among the seabirds most at-risk to light attraction has been linked to long-term declines (Ainley et Krug et al. 2020). Globally, petrels (including shearwaters and storm-petrels) are considered among the seabirds most at-risk to light pollution (Rodriguez et al. 2017b), 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 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 (Rodriguez et al. 2014). Although the data were not included in our study, fledging 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 (Rodriguez et al. 2017c) 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, Rodriguez 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 Rodriguez et al. 2017c, 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 foraging 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 (Rodriguez 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 as 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 (Rodriguez 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, Rodriguez et al. 2014) and shielded to reduce skyward illumination (Reed et al. 1985), and the use of high pressure sodium lights should be considered (Rodriguez et al. 2017a), 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

Acknowledgments:
A huge thanks to Julie Mallette, Dave Fishman, Paul Chamberland, and Jacinthe Cormier for the development of the stranded bird database and compilation of the strandings data related to CWS-ECCC permits. We also thank all personnel who have collected, released, and reported stranded birds in the region, including Marielle Thillet and Megan Tuttle, and the CNLOPB for flaring data. We also thank Becky Whittam for her comments on earlier drafts of the manuscript, Isabeau Pratt for analytical support, and Sabina Wilhelm for her insights related to birds and light attraction.

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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 fuscilllis* | 1               |
|                        | Semipalmented 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 platyrhynchos*      | 1               |
| Group            | Common Name                  | Latin                  | Number stranded |
|------------------|------------------------------|------------------------|-----------------|
| Waterfowl        | American Black Duck          | *Anas 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 rusticilla   | 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 |                     |                         | 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.