GIS ASSESSMENT OF THE RISKS POSED BY COASTAL LIGHT POLLUTION FOR SEABIRDS NESTING IN ATLANTIC CANADA

BY

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Abstract

Light trespass occurs when more area is illuminated than intended, and the accumulation of this trespass is light pollution, which has become widely recognized an ecological risk to various seabird species around the globe. This investigation seeks to identify the relative sensitivity (degree of response) and vulnerability (the likelihood of exposure) to light pollution for 12 nesting seabird species in Atlantic Canada. Sensitivity and importance weightings for species were determined by using the methodology of the Analytical Hierarchy Process (AHP) and relative populations respectively. Leach's Storm Petrels were deemed the most sensitive to the risk, followed by Atlantic Puffins (49.6% relative to Petrels). Light pollution time-series data from the National Oceanic Aeronautics Administration (NOAA) with nesting seabird colony data from the Canadian Wildlife Service (CWS) were overlaid in GIS to determine light pollution vulnerability hotspots. Prominent vulnerable areas were identified near Grand Colombier, St-Pierre et Miquelon, and around the Witless Bay Ecological Reserve in Newfoundland.

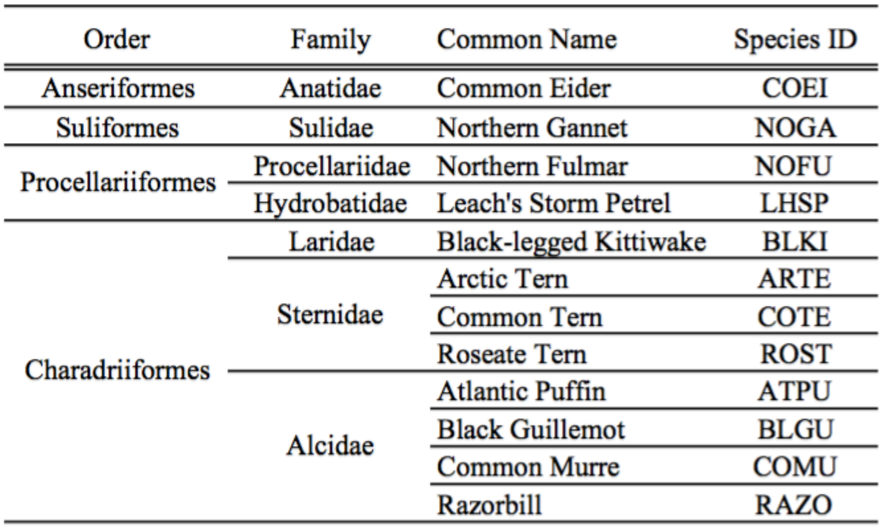
Introduction

Urban development and expansion has lead to an increase of artificial night-time lighting in many areas, with an average increase of six percent per year (Hölker et al., 2010). While night-time lighting offers safety to individuals requiring security and navigation in the dark, it can be ecologically disruptive to various species, such as insects (Perkin et al., 2013), amphibians (Wise, 2007), reptiles (Verutes et al., 2014), mammals (Longcore & Rich, 2004), and birds (Reed et al., 1985; Rodriguez et al., 2012), with a variety of species that thrive in natural night-time lighting and use the moon and stars for navigation. Light of higher intensities in a range of wavelengths can have negative effects on the biological rhythms of a variety of animals, potentially disrupting foraging and predator prey interactions (Grigione & Mrykalo, 2004) and breeding habits (Dominoni & Partecke, 2015). Research suggests that birds are at-risk to the effects of artificial light, causing disorientation and a disruption to biological and social rhythms (Kempenaers et al., 2010), notably for younger fledging individuals (Rodríguez et al., 2014, Troy et al., 2011). As many people tend to reside near coastlines (Creel, 2003), seabirds may encounter additional artificial lighting, especially compared to when they are at-sea. Atlantic Canada offers a rich ecosystem with extensive coastlines, and is home to numerous breeding seabird species relying on the region to forage and raise young.

This study seeks to answer several key questions pertaining to seabirds and light pollution in Atlantic Canada: (1) Where are the seabird colonies and what are their relative populations? (2) What is the intensity and variability of light pollution in areas with seabird breeding colonies? (3) What is the relative sensitivity of the 12 seabird species in Table 1 to light pollution? (4) What is the vulnerability of any seabird species, given their sensitivity, at a particular location? To answer these questions, a combination of GIS-based assessment, expert opinion surveys using the Analytical Hierarchy Process (AHP), and inferential statistics will be employed. This is a broad-scale preliminary assessment of the perceived risk that light pollution has on breeding seabirds in Atlantic

Canada, and seeks to identify vulnerability hotspots and potential areas for mitigation. It is expected that light pollution risk sensitivity will vary between seabird species, or groups of species, and seabird species should respond differently to the stressor(s) caused by the risk. Overlaying seabird data with light pollution data will provide a spatial vulnerability assessment of risk hotspots in Atlantic Canada (Zacharias and Gregr, 2005; Lieske et al., 2014). Twelve species of seabirds were chosen based on a preliminary assessment of seabird vulnerability to various anthropogenic risks, and this study is a part of a larger scale Atlantic Ecosystems Initiative (AEI) project investigating numerous anthropogenic risks and several additional species.

Table 1. Summarization of the seabird species in this study including taxonomic ordering and species code.



Order	Family	Common Name	Species ID
Anseriformes	Anatidae	Common Eider	COEI
Suliformes	Sulidae	Northern Gannet	NOGA
Procellariiformes	Procellariidae	Northern Fulmar	NOFU
	Hydrobatidae	Leach's Storm Petrel	LHSP
Charadriiformes	Laridae	Black-legged Kittiwake	BLKI
	Sternidae	Arctic Tern	ARTE
		Common Tern	COTE
		Roseate Tern	ROST
	Alcidae	Atlantic Puffin	ATPU
		Black Guillemot	BLGU
		Common Murre	COMU
		Razorbill	RAZO

1.1 Definitions

It is important to identify the meaning of several key terms in this study. Terminology will be similar to that of a study by Zacharias and Gregr (2005) marine hotspot risk-assessment for whales and oil discharge.

Risk: a stressor, or a deviation from standard conditions that results in a response by a seabird species.

Sensitivity: the degree to which seabirds respond to stress. The measurement is not a judgement of fragility or intolerance; rather, it is the probable intensity of the response a seabird has to the exposure of light pollution.

Vulnerability: likelihood of exposure, or the probability that a species will be exposed to a stressor to which it is sensitive. This measurement is based on the sensitivity and intensity of the light pollution at a particular location.

1.2 Light Pollution

Light pollution, or light trespass occurs when artificial light illuminates more area than is intended or necessary (Longcore & Rich, 2004). With a higher density of light sources, such as in urban centers or near industrial facilities, the accumulation of light trespass can reflect off of the atmosphere causing ‘sky glow’, further obstructing the view of the night sky (Gaston et al. 2012). While lighting has increased our abilities to travel and conduct business at night, light pollution has been recently recognized as having negative ecological effects on several species of seabirds. Known effects of light pollution on seabirds include disrupting navigation, causing disorientation, affecting predator prey interactions, and causing fatalities from collisions or stranding (Longcore & Rich, 2004; Rodriguez et al., 2012; Troy et al., 2011; Troy et al., 2013; Rodrigues et al., 2014). On Réunion Island, (Indian Ocean) at least 20-40% of fledgling petrels are attracted to artificial lights, resulting in fatalities (Le Corre et al., 2002). It is unknown if light pollution poses more or less disturbances to nocturnal seabird species, however one can speculate that the additional night-time activity could increase the likelihood of their exposure to the risk.

Light trespass originating from terrestrial sources can extend further distances over water, as there are no obstructions other than the atmosphere and the curvature of the Earth. In many cases, to illuminate vast areas and roadways, high intensity discharge (HID) lights are used, which provide a substantial amount of illumination. These include mercury vapour, and metal halide low and the more common high-pressure sodium (Rea et al., 2009). In 2009, Annapolis Royal was the first town in Canada to completely retrofit their streetlights to light emitting diodes (LEDs) for roadways as an alternative to HID lighting as it consumes less energy (Town of Annapolis Royal, 2015); however, there is some research that LEDs may disrupt the human biological clock (Falchi et al. 2011), and some citizens claim poor light quality (CBC 2015a). Even when municipalities install less intense light fixtures, private landowners are still often free to install floodlights.

The design of light fixtures also affects the amount of light trespass. Some fixtures allow for light to be directed downwards and illuminate an area in a more controlled manner. Other fixtures are designed more aesthetically and may allow for illumination in multiple directions, substantially increasing the amount of light trespass and resulting sky-glow. In some situations, such as for aerial and marine navigation, lights must be directed outwards and at an intensity that allows for optimal sighting in most weather conditions. Restricting the directional outputs of these artificial light sources can mitigate these effects; however, even if lighting is directed properly with focused fixtures, it can still be reflected and scattered from the ground and other surfaces, and the accumulation of both fixed and variable light sources contributes to ecological light pollution. Similar to fixtures, is the blocking of lights from the home using curtains or blinds, especially for homes situated on the coast or near breeding colonies. The combination of less intense lights with proper fixtures would reduce light pollution in an area.While variable sources of light pollution, such as from vehicles or marine traffic, can cause disruptions and avian fatalities (Gehring et al. 2009), this study will focus on the fixed sources of light pollution.

1.3 Study Area

Atlantic Canada (Figure 1) is considered one of the largest and most diverse of the six regions administered by the Department of Fisheries and Oceans (DFO, 2015). The region offers long coastlines that are home to many intertidal organisms both endemic and migrant. The Scotian and Laurentian continental shelves contribute further to biodiversity and species richness, as they are both biologically active pelagic regions with gyres, currents, and nutrient rich upwelling (MacLean et al., 2013). According to a recent technical report for the Canadian Wildlife Service (CWS, Allard et al., 2014), there is a large industry for fisheries as the region offers many fish species, and birds recognize this as well, congregating in high numbers. These regions offer important foraging areas for pelagic seabirds, and have high year-round concentrations, which are mostly terns and large gulls (Allard et al., 2014). While the region is ecologically important to migrating seabirds and shorebirds, this study will be limited to seabird species that form breeding colonies or nest in the area. Labrador and Quebec are not included in this study due to limited colony data.

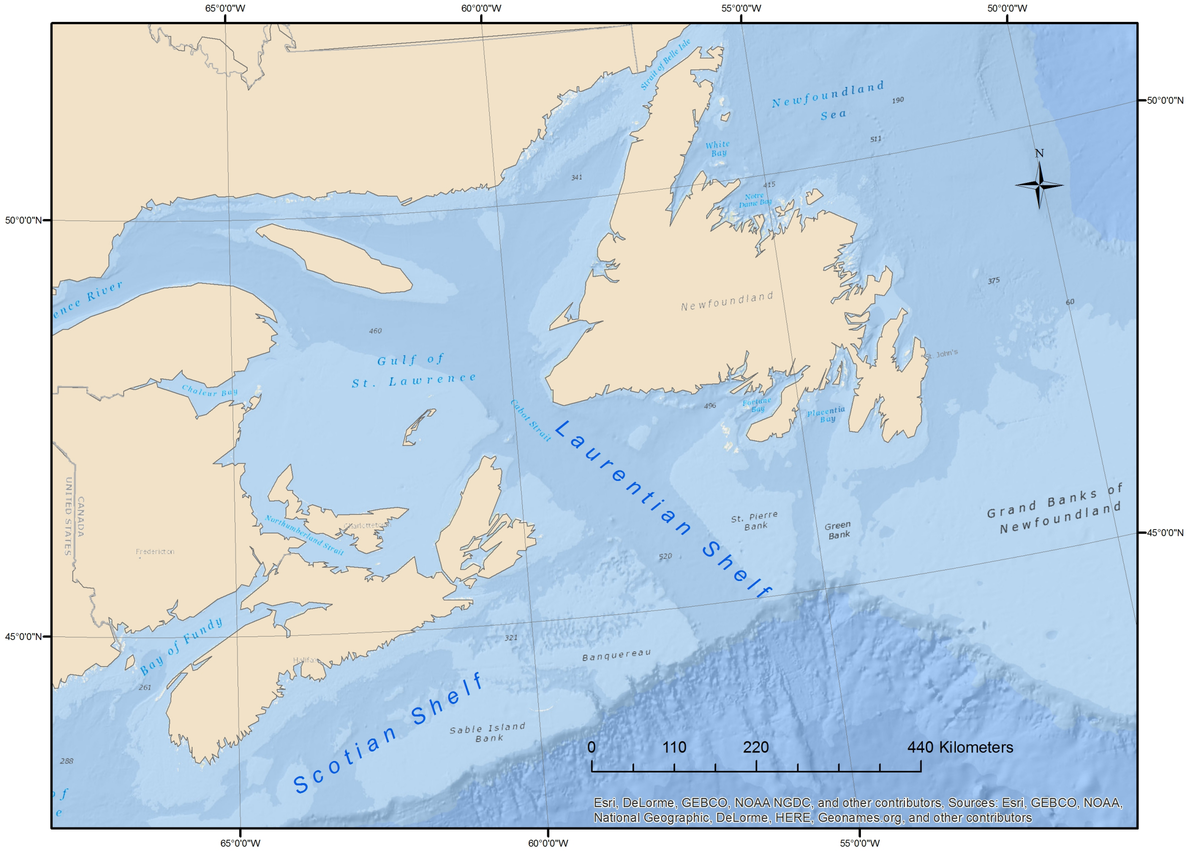


Figure 1. Area of Interest (AOI), Atlantic Canada. Only the regions of NS, NB, PEI, and Newfoundland are included. No colony data are available or present in Quebec including

the island of Anticosti or the Magdalen Islands. Extent of AOI in NAD1983 decimal degrees: North 51.56, East -40.09, South 36.115, and West -67.85.

1.4 Seabird Species

Not all seabird species within Atlantic Canada could be represented in this assessment, and 12 were chosen based on literature review, available knowledge, and expert opinion. Of these species, some are grouped taxonomically for simplicity, but analyzed separately to identify any trends or differences. They include Terns (Arctic, Common, and Roseate), Auks (Atlantic Puffin, Black Guillemot, Murres, Razorbill), Petrels (Leach's Storm-petrel and Northern Fulmar), Black-legged Kittiwake, Common Eider, and Northern Gannet. Unless otherwise noted, information for all species is retrieved from Birdlife international or Cornell Lab of Ornithology (Birdlife International, 2015; Cornell Lab of Ornithology, 2015).

1.41 Terns

Members of the family Sternidae include Arctic Terns (*Sterna paradisaea*), Common Terns (*Sterna hirundo*), and Roseate Terns (*Sterna dougallii*), and are mostly found throughout Nova Scotia, New Brunswick, and Prince Edward Island, with colonies in Newfoundland (See results section 3.1, Figures 2a,g,l). They are ubiquitous seabirds found near the coast, rivers, lakes, streams, and wetlands. Terns are medium sized slender birds with angular wings and forked tails, and plunge dive for food such as fish. They typically breed in dense colonies laying their eggs directly on the ground and attempt to sometimes viciously ward off any predators. Most terns commonly live over ten years, and travel great distances within their lifetimes, but may be declining in numbers due to anthropogenic activities and habitat loss. The Roseate tern is considered threatened, and there have been no known assessments on the effect of light pollution on Terns.

1.4.2 Auks

The birds comprising the family Alcidae include Atlantic Puffins (*Fratercula arctica*), Black Guillemots (*Cepphus grylle*), Common Murres (*Uria aalge*), and Razorbills (*Alca torda*). These species are often small to medium sized diving birds that do not tend to be strong flyers, as they must flap their wings rapidly to stay aloft. Because they are adept swimmers, most Auk species spend much of their time at sea, and typically remain near coasts during breeding season, where they nest on rocky cliffs. Light pollution is known to affect Atlantic Puffin fledglings, as they leave the nest at night to avoid predators. The volunteer network of Puffin Patrol has been rescuing stranded roadside Puffins around Witless Bay Newfoundland for a decade, (CPAWS, 2016; CBC 2015b). While there are studies on how the Black-Guillemot responds to direct disturbances, such as ship traffic (Ronconi and St. Clair, 2002), little is known about the direct or indirect response to light pollution.

1.4.3 Petrels

Northern Fulmars (*Fulmarus glacialis*) in the family Procellariidae, and Leach's Storm Petrel (*Oceanodroma leucorhoa*) in the family Hydrobatidae, are both Procellariiformes, formerly referred to as tubenose birds due to the presence of a prominent nasal gland (. Petrels are cosmopolitan in their pelagic distribution, and only come to shore to breed. They are often active nocturnally, specifically when attending nests in their colonies, and there have been some studies on the negative effects that light pollution has on it (Rodriguez et al., 2009) and a similar species, the shearwater (Raine et al., 2011; Troy et al., 2013), sometimes resulting in fatal attractions to light sources. While not included in this study, the effects of light pollution on shearwaters is likely similar to petrels, both being nocturnal around nesting sites. Petrels are known to have trouble navigating even on cloud-covered nights and prefer being active during moonless nights (Lockley 1967), suggesting that a clear, unobstructed view of the night sky is necessary, and that light pollution may have negative effects on Petrels.

1.4.4 Black-legged Kittiwakes

Black-legged Kittiwakes (*Rissa tridactyla*) are members of the Laridae family and closely related to Terns, but are often medium sized. Like Terns, Kittiwakes are also very colonial, and they give birth to precocial young that quickly become resourceful and intelligent. Similar to other gulls, Kittiwakes are very generalist in their feeding, and are well adapted to life in the air, water, and on land. Kittiwakes (Figure 4d) are somewhat more specialized than gulls, as they tend to nest on cliffs, and winter at sea. There is no known information about the positive or negative effects of light pollution on any of these species.

1.4.5 Northern Gannets

The only bird in this study of the family Sulidae, is the Northern Gannet (*Morus bassanus*), a large plunge diving seabird, reaching high vertical speeds in order to eat fish shoaling near the surface. Gannets often forage for food very far from their colonies, where they usually nest on cliffs. There are several main colonies of Northern Gannets worldwide, with only several known surveyed locations within Atlantic Canada in the past century. They are known to migrate vast distances, and may encounter various urban areas and structures. Observations have been made where Gannets would not pass under or over the Confederation Bridge soon after construction (Interview of Gay Hansen), and this could indicate sensitivity to habitat loss. There have been no formal studies on the effects of light pollution on Northern Gannets.

1.4.6 Common Eiders

Representing the family Anatidae, the Common Eider (*Somateria mollissima*) is the largest duck in the Northern Hemisphere. They winter offshore near marine shoals, and breed in coastal areas with their nests on the ground, in colonies up to several thousand individuals. Eiders are diving birds and forage the sea floor for food, like urchins and molluscs, and do not tend to forage vast distances offshore. Hunting Eiders for their down is still common, but the conservation status of the species is not of least concern. Considering Eiders spend much of their time near the coast, it’s possible that they may encounter light pollution more often than pelagic species; however, little is known regarding the impact that light pollution has on this species.

Methods

This is a GIS-based assessment that requires several components to measure the spatial patterns of a species' vulnerability to light pollution and to generate the hotspot locations where certain colonies are most vulnerable to the risk. For the purpose of this study, the most vulnerable species will be those that are in the top tenth percentile for vulnerability values. Hotspots will be created spatially based upon the vulnerability of a seabird species at any location in the study area. Seabird species will be analyzed separately, but sometimes discussed as a group.

2.1 Quantifying Vulnerability

The degree to which seabird colonies are vulnerable is a function of two factors, and can be summarized in the following equation for each colony point:

$$V_{i,j} = S_i * R_j$$

Where vulnerability, *V*, for species *i* any location (colony), *j*, is a function of the intensity, *R* of the light pollution experienced by colony *j*, multiplied by a species' sensitivity, S_i, which is determined by the equation:

$$S_i = w_i * I_{i,j}$$

Sensitivity depends on both the relative importance, *I*, of for the species, *i*, at colony, *j*, multiplied by the weighting of the sensitivity, *w*, for each species, *i*.

Values for *w* were established using expert opinions and the methodology of the Analytical Hierarchy Process (AHP, section 2.2). Importance, *I*, is based on the population of a colony divided by the entire population of all seabirds in this study, and is, thereby normalized and scaled from 0 to 1. For this study, the breeding seabird population data are not always certain or available, and caution should be taken during interpretation. This importance value does not consider ecological significance, and for the purposes of this hotspot analysis, all seabird individuals are considered equal.

2.2 Sensitivity Weightings Using AHP

Computing the sensitivity weighting of a species for a GIS-based analysis required the creation of sensitivity index values for each species, which hinged on preexisting ecological knowledge. The Analytic Hierarchy Process (AHP) was introduced by Saaty in the late 1970s and is used as a decision making tool for comparing the priorities of various alternatives and resource allocation (Sipahi & Timor 2010). The process has recently been employed in ecological assessments, such as determining which coastal regions to prioritize for conservation (Pourebrahim et al. 2014). The process relies on pairwise comparisons made by a group of experts to obtain relative priority values for each species ranging from zero to one. The decision making process of AHP described by Saaty (2008) was employed in this analysis to determine the sensitivity weighting index, w, for each of the 12 seabird species, and should be consulted for additional information regarding the AHP methodology.

Within this model, experts compared two species and ranked the relative importance of light pollution on a scale from one, indicating equal importance, to nine, indicating strong evidence of importance for one species (Figure 2). This was repeated until all comparisons were made. In this case the relative importance is the degree to which a seabird is sensitive to light pollution. Each species is compared to each other in every possible combination, and for 12 species, this totals 66 possible comparisons. Survey values were put into a matrix, and redundant comparisons were given the reciprocal of the survey value. A total of ten experts participated in the survey.

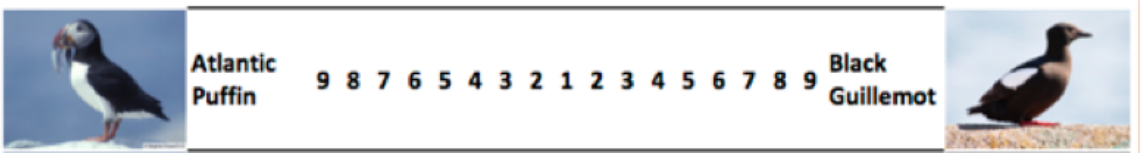


Figure 2. Sample of a pairwise comparison provided to experts for AHP sensitivity surveys. Selecting ‘one’ indicates equal sensitivity to light pollution. Selecting ‘two’ to ‘nine’ on the left favours Atlantic Puffin as more sensitive, while selecting ‘two’ to ‘nine’ on the right favours Black Guillemot. Seventeen possible selections exist within the ranking range.

Experts were asked to scale their perceived knowledge of light pollution as a risk and the 12 seabird species from 1 to 5, with 1 being little knowledge, and 5 being advanced knowledge. These responses were then put into a composite matrix as a weighted average of all experts, where the weighting was defined as each expert’s self-assessed knowledge score. The matrix was then powered to a high power (1000), and each cell was divided by the total sum of the powered matrix. The sum of the cells across each row provided the priority value for a given species, and are then normalized for inter-specific comparisons, scaled from 0 to 1. These relative values are used as the weighted sensitivity values, w_i in the vulnerability equation.

2.3 Modeling Light Pollution with GIS

A novel GIS process using the model builder tool in ArcGIS 10.2 and iterative Python scripting allowed for the synthesis of the light pollution raster and the colony data points. Within the model, each colony point was isolated and a 20km Euclidean distance buffer was applied. The 20km distance is an indiscriminate, conservative average intended to capture impacts on the core area and immediate neighborhood of the colony (Birdlife International, 2015; Cornell Lab of Ornithology, 2015) and capture some of the effects from cumulative sky glow. A viewshed using a digital elevation model (DEM) layer obtained from the Government of Canada (http://geogratis.gc.ca) kept only grid cells that were not topographically obstructing light trespass, which was also a conservative approach, as topography would be less limiting for any seabirds in flight. DN values of each remaining grid cell within the 20km buffer were then attenuated based on the inverse square law by multiplying the intensity value of each cell by $\frac{1}{d^2}$, where d is equal the cell's distance from the colony center. This attenuation simulates how light waves are diminished and scattered through the atmosphere before reaching the colony point. The sum of all attenuated DN's provided a Light Pollution Index (LPI) value for each colony point. This process was iterated in ArcGIS for each colony point, and for each year. The LPI values for each colony point are often small (1×10^{-8}), so each value was transformed by multiplying it by $1\text{x}10^6$ for statistical analysis. For the vulnerability analysis, LPI values of each colony were normalized by dividing it by the maximum LPI value for all seabird colonies in this study. The normalized scaled values from 0 to 1were used as the value *R,* for a colony location *j,* within the vulnerability equation (section 2.1), allowing for a composite vulnerability hotspot map relative to all 12 species. For vulnerability analysis, LPI values were averaged across 1993 to 2013 for each colony point and, similar to population, were scaled relative to the maximum LPI experienced by all seabird colonies for all species ($\mathrm{LPI}_{i,j}/\mathrm{LPI}_{\max}$). The estimates for R_j may be conservative, as they do not fully account for sky glow, or more variable light pollution, such as lighthouses and short-term lighting.

2.4 Data Collection

2.4.1 Light Pollution Data

Light pollution raster data were obtained from the website of the National Oceanic and Atmospheric Administration (NOAA). The files were in TIFF format and included yearly surveys from 1993 through 2013 as a part of the Defense Meteorological Satellite Program (DMSP) using Operational Linescan System (OLS) satellites. The products consist of 30 arc second grids, or about 650m at 45º latitude, and considered to be calibrated with an error of +/- 3km (Bennie et al. 2014). Each file is comprised of monochromatic pixel values, or digital numbers (DN) ranging from 0, for no light measured, to 63 for fully saturated areas. These light pollution data are from an advanced survey program and are used in several light pollution studies and modelling techniques (Imoff et al., 1997; Tan, 2015). There are more calibrated options for later years using Visible Infrared Imaging Radiometer Suite (VIIRS) satellites, which would be ideal for time-series analysis, however these data are large and timely to process given the current techniques and computation limitations, and are only available for the last several years. Fine scale calibration was not used given that the 20km buffer around colony points is somewhat indiscriminate to allow for a small variation of several kilometres, and the use of the DMSP-OLS data was deemed appropriate.

2.4.2 Colony Data

Seabird colony data are maintained by CWS, and are comprised of surveys species-specific seabird survey information pertaining to population, nesting, and geographic coordinates. Colony surveys spanned back into the 19th century, and all colony location points could be considered possible nesting habitats; however, there are more uncertainties and missing data for older surveys, and some may no longer exist as breeding locations. When possible, only census years from 1993 onwards were used for the light pollution time-series variability analysis if more than five records were available. If less than five records existed for a species, then the five most recent years were used up to a decade prior to the first light pollution map, 1983; this is assuming the nesting locations could still be used by seabirds, however, the population information was not always available for multiple years to be used in any population dynamics analyses. For in-depth hotspot analysis or each species, all locations were considered, and when possible, literature and other sources were used to verify active colonies for discussion purposes.

Population data include visual and photographic estimates of breeding pairs and total individuals, while nesting data includes number of nests or burrows and eggs per breeding pair, although this was not always available. There were very few colony points that appeared to have the same or nearly identical geographic coordinates in successive yearly surveys (n = 14), so population changes were not assessed. Not all species had active colonies that were surveyed every year between 1993 and 2013, and accurate time series changes could not be completed for these species. Northern Gannet only had one colony survey between 1983 and the present, and 4 total, and was not be analysed in the time-series. All colony points were overlaid with light pollution data as they are still deemed potential breeding locations, and provide historical data that can be discussed. When available, population data were used to infer relative importance of a particular colony location; however, the error around these population estimates is not always known.

Results

3.1 Composite Light Pollution

The Atlantic Canada region is not particularly saturated with light pollution relative to some North American coastal regions and larger urban areas, (e.g. Long Island, New York, USA), so the region offers some refuges that are relatively dark or void of any lighting and relatively low habitat disturbances. The region is mostly illuminated around large urban areas like Halifax, Saint John, Moncton, and St. John's (Figure 3). Even without full light saturation, Atlantic Canada clearly has many coastal areas with persistent light pollution that could potentially overlap with sensitive seabird breeding sites.

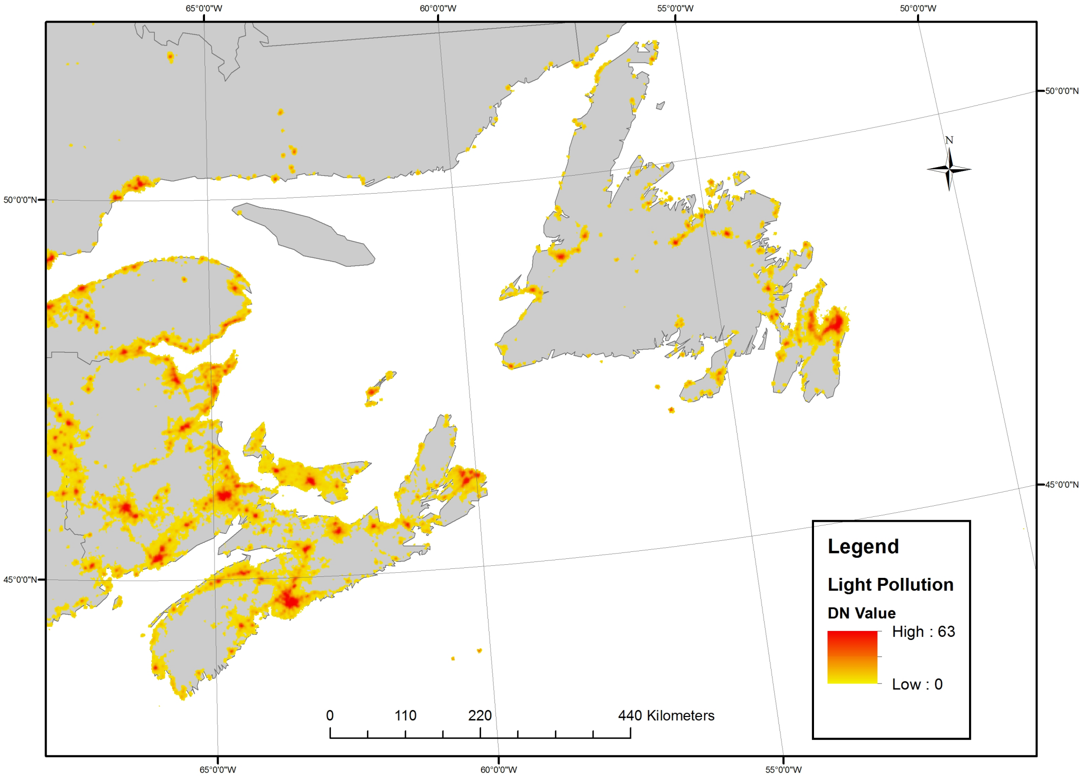


Figure 3. Light pollution map of the area of interest (AOI) using the latest DMSP-OLS night-time light series map (2013) with DN pixel values representing light pollution intensity. Areas with no color (grey) indicate no measurable light pollution.

For the years 1993 through 2013, there actually appeared to be a slight overall negative correlation between year and light pollution DN values (slope = -0.328), but it was not significant across the entire study area (p = 0.167) and highly variable between years (Figure 4). When analyzing points within urban centers only (Bathurst, Charlottetown, Halifax, Moncton, Saint John, St. John's, and Sydney), there was also no statistical correlation between year and light pollution DN values (p = 0.092). The highest total DN values were found in years 1995 and 2001, while the lowest values were in 2003 and 2006. There appeared to be high variability of light pollution over the entire time-series analysis. When analyzing the total DN values for the study area over the course of the study period, there were similar variations, and no significant trends.

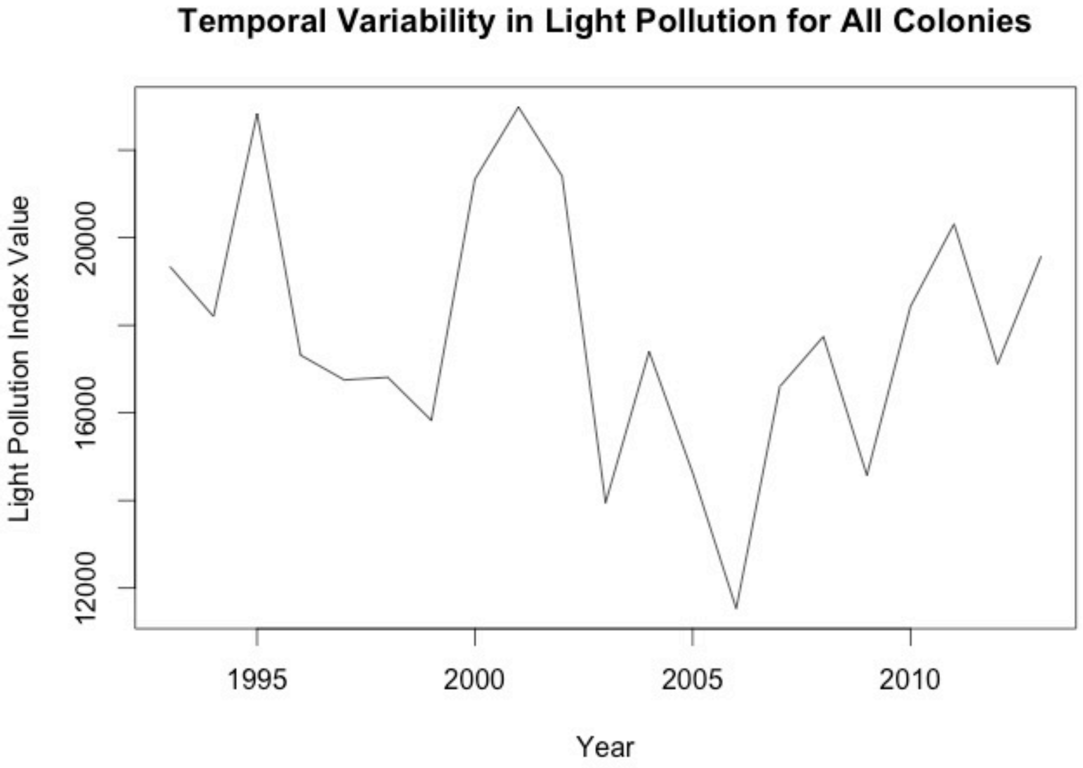
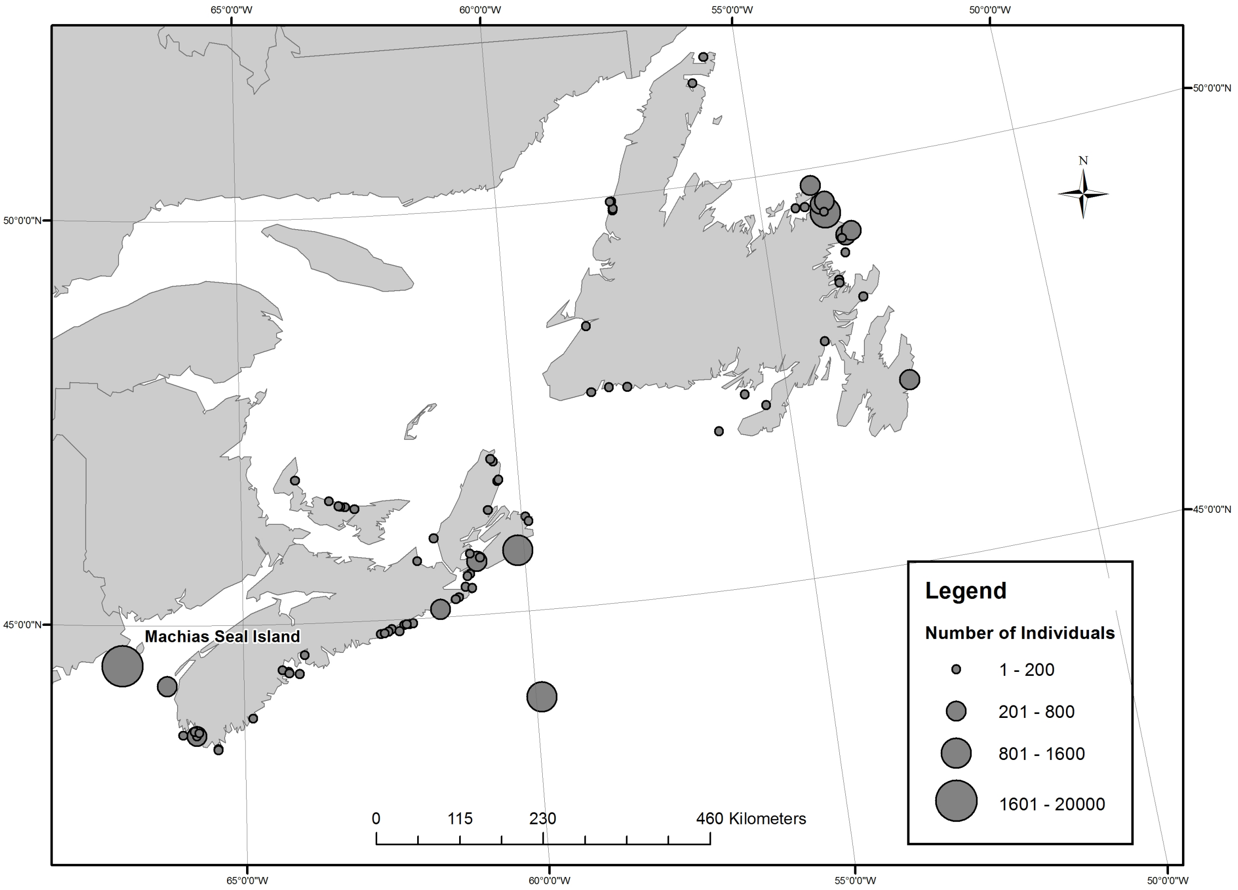


Figure 4. Temporal variability in perceived light pollution will all colony points pooled together, using transformed LPI values. Variability is sometimes high from year to year but 2013 has similar LPI values as 1993.

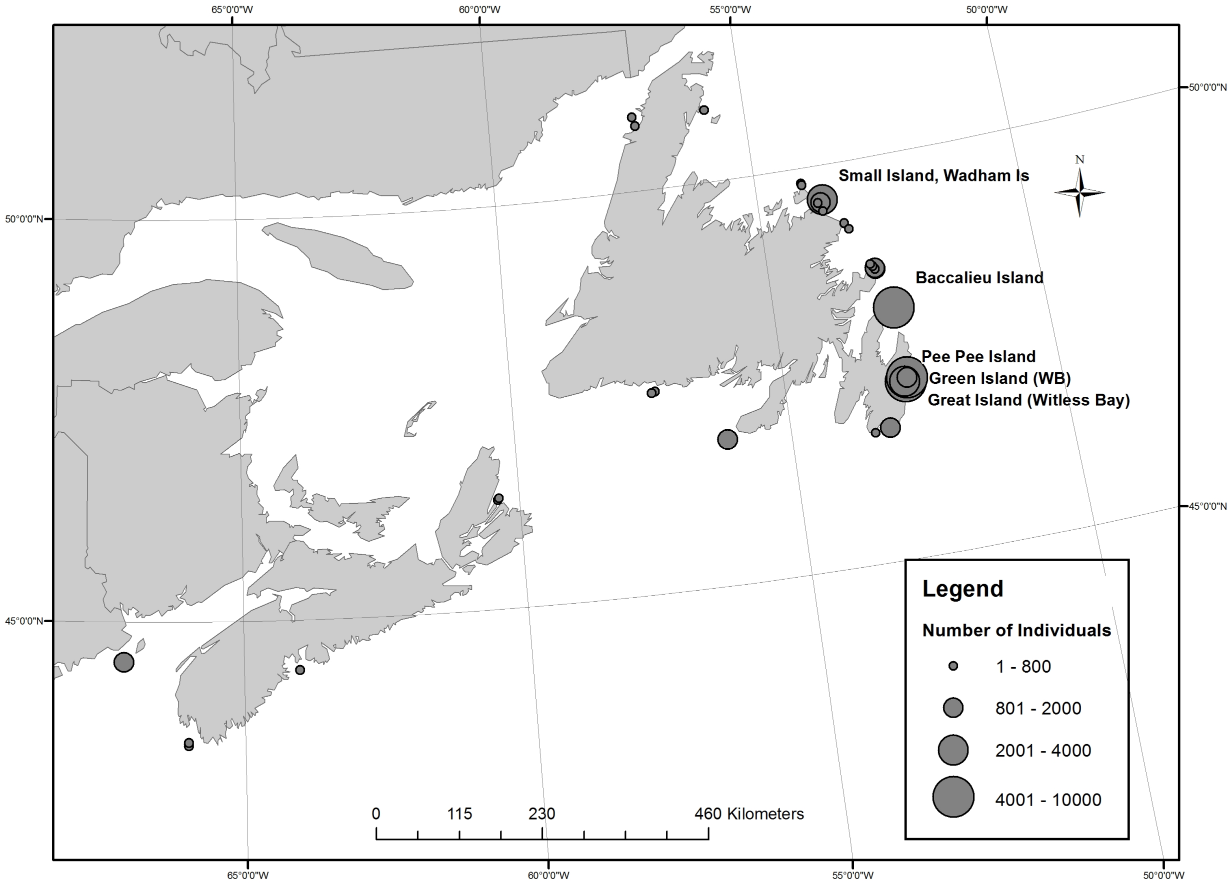
3.2 Colony Locations and Relative Light Pollution Intensity

Colonies for each species were mapped based on NAD83 geographic coordinates and population data were included to demonstrate relative importance of each colony location (Figures 5a – l, colony colonies). A total of N = 1122 colonies and n = 8,187,310 individuals are included in this study. For vulnerability analysis, the population of each colony was scaled from zero to one, by dividing it by the total population of all individual seabirds within this study (n_j/n_{max}). When possible, surveys deemed unreliable were removed from analysis or an attempt was made to verify the population by other means such as literature review (Robertson et al. 2006).

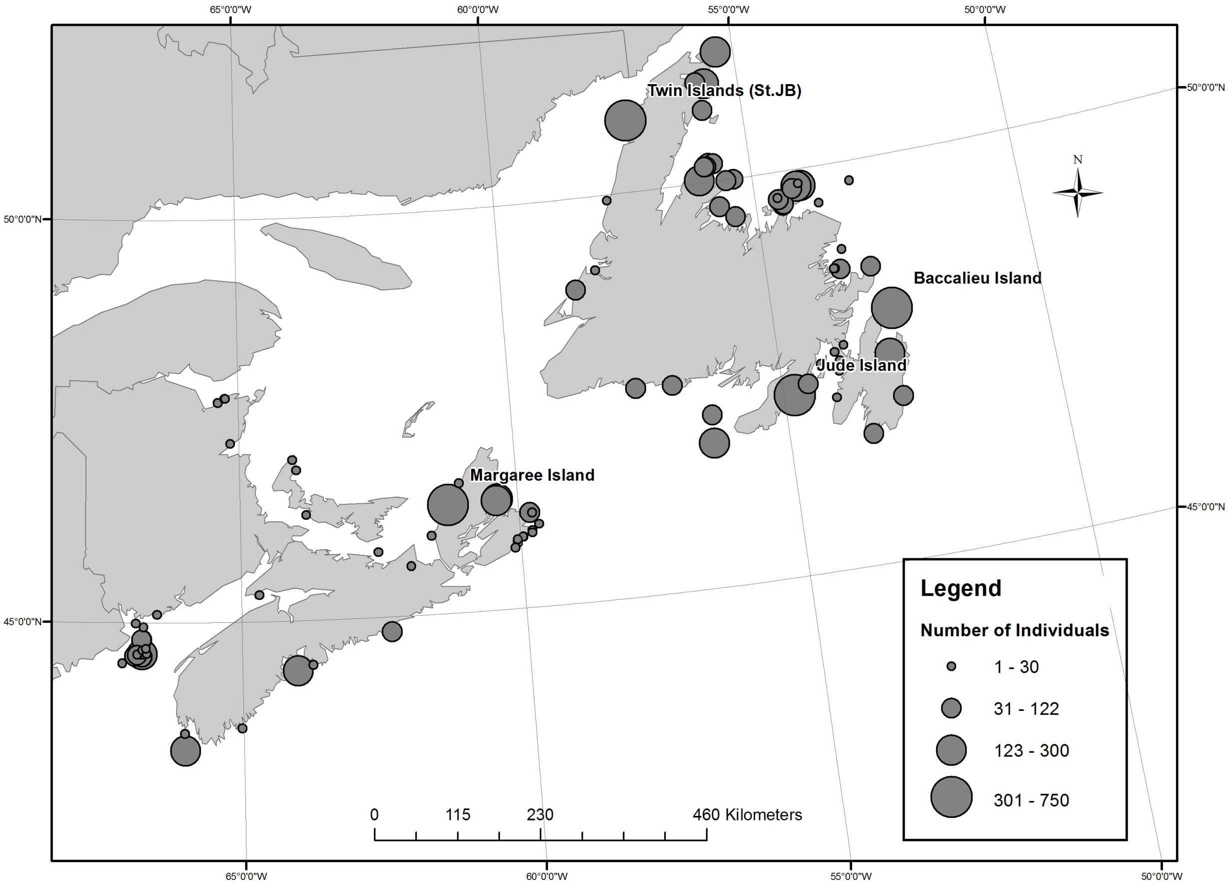
(a) Arctic Tern (n = 98)



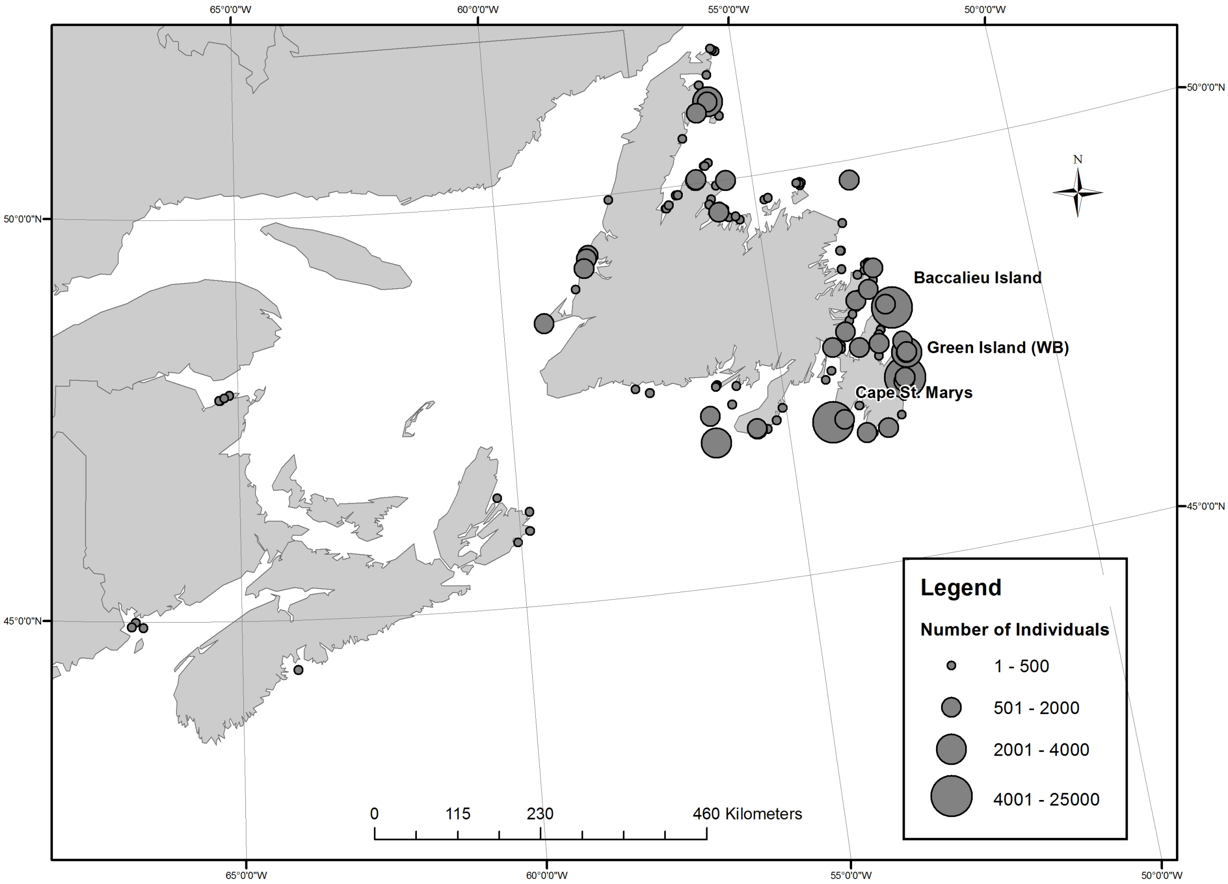
(b) Atlantic Puffin (n = 38)



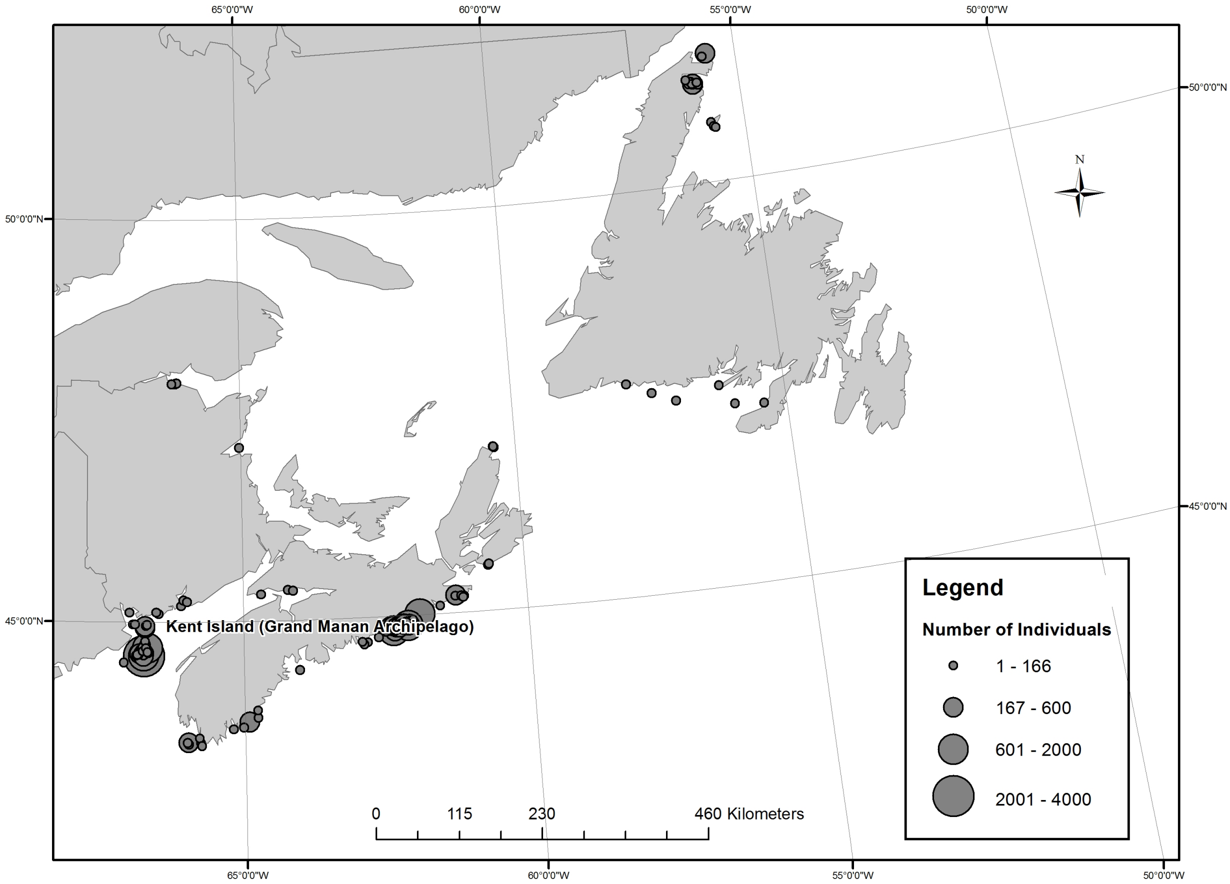
(c) Black Guillemot (n = 157)



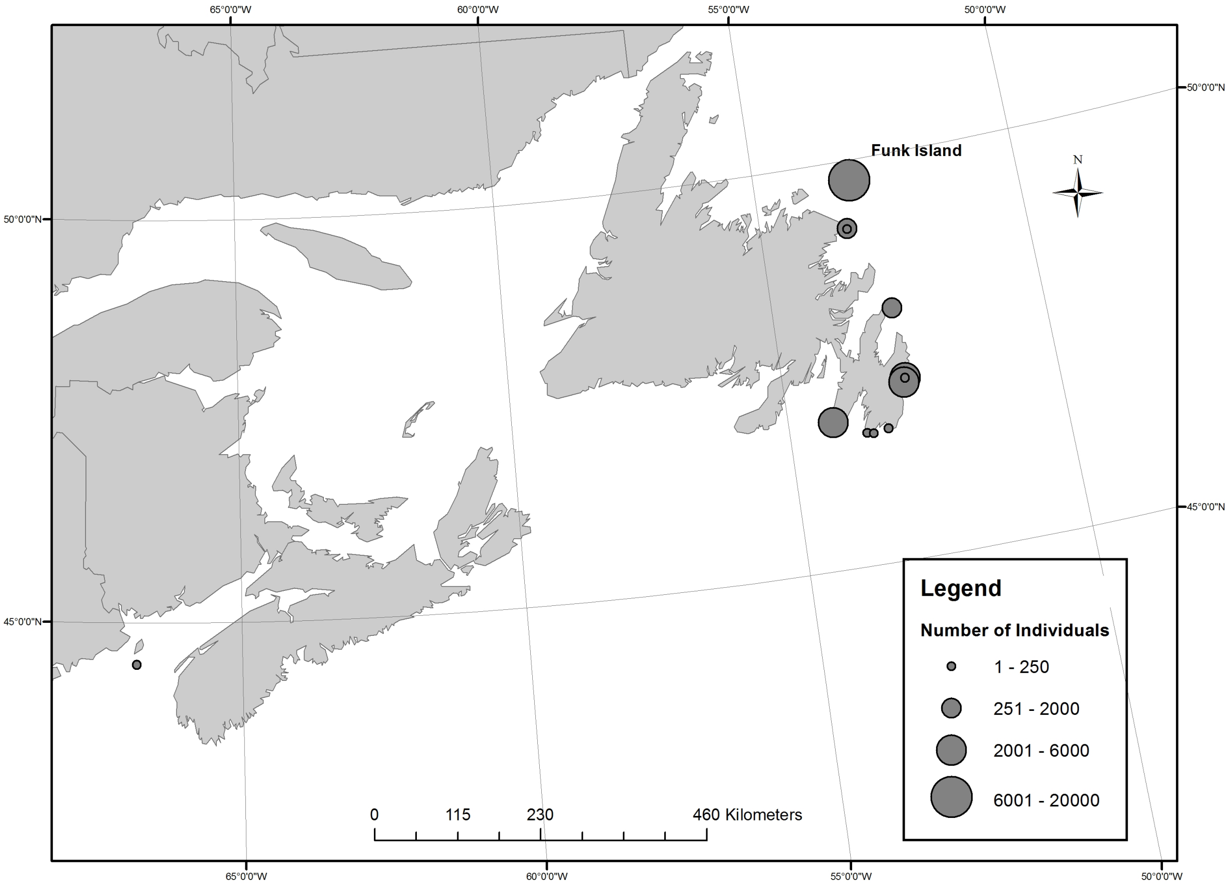
(d) Black Legged Kittiwake (n = 180)



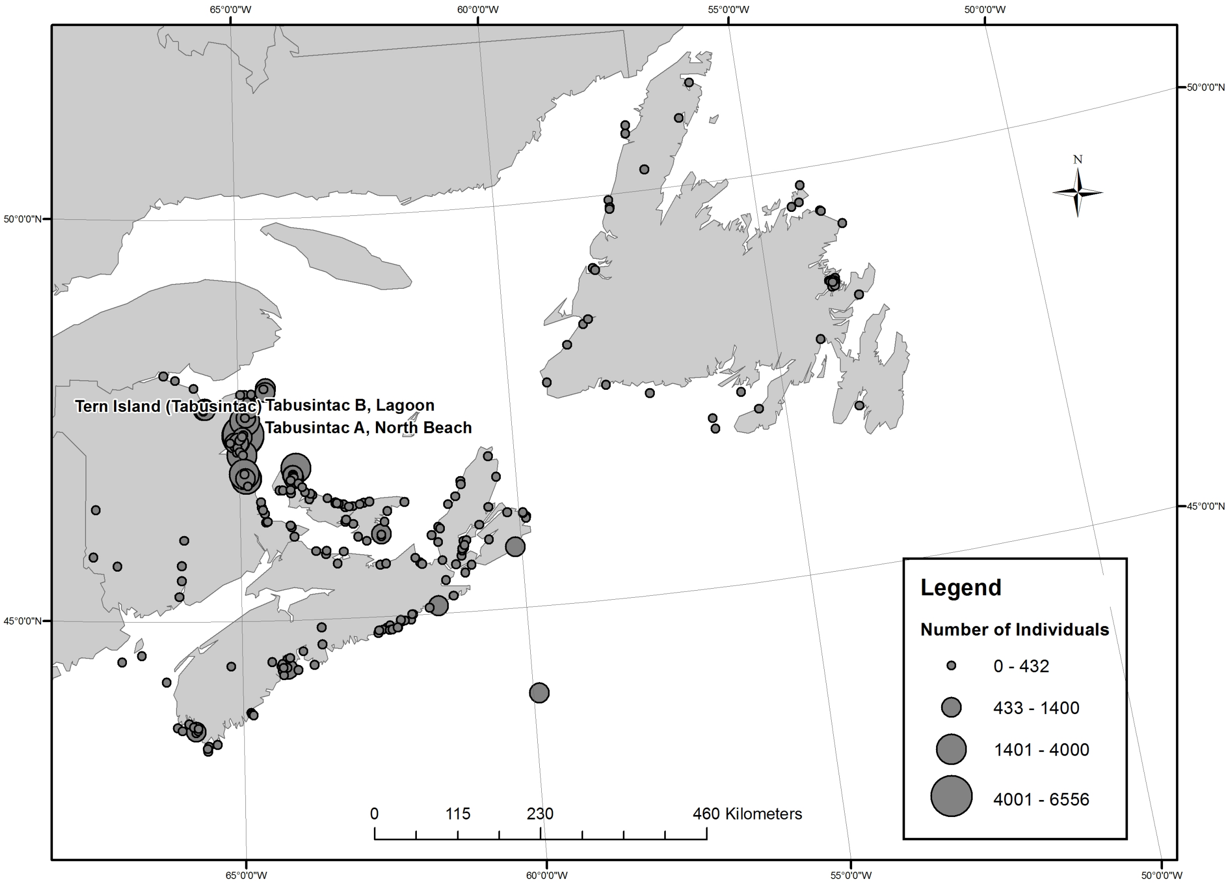
(e) Common Eider (n = 175)



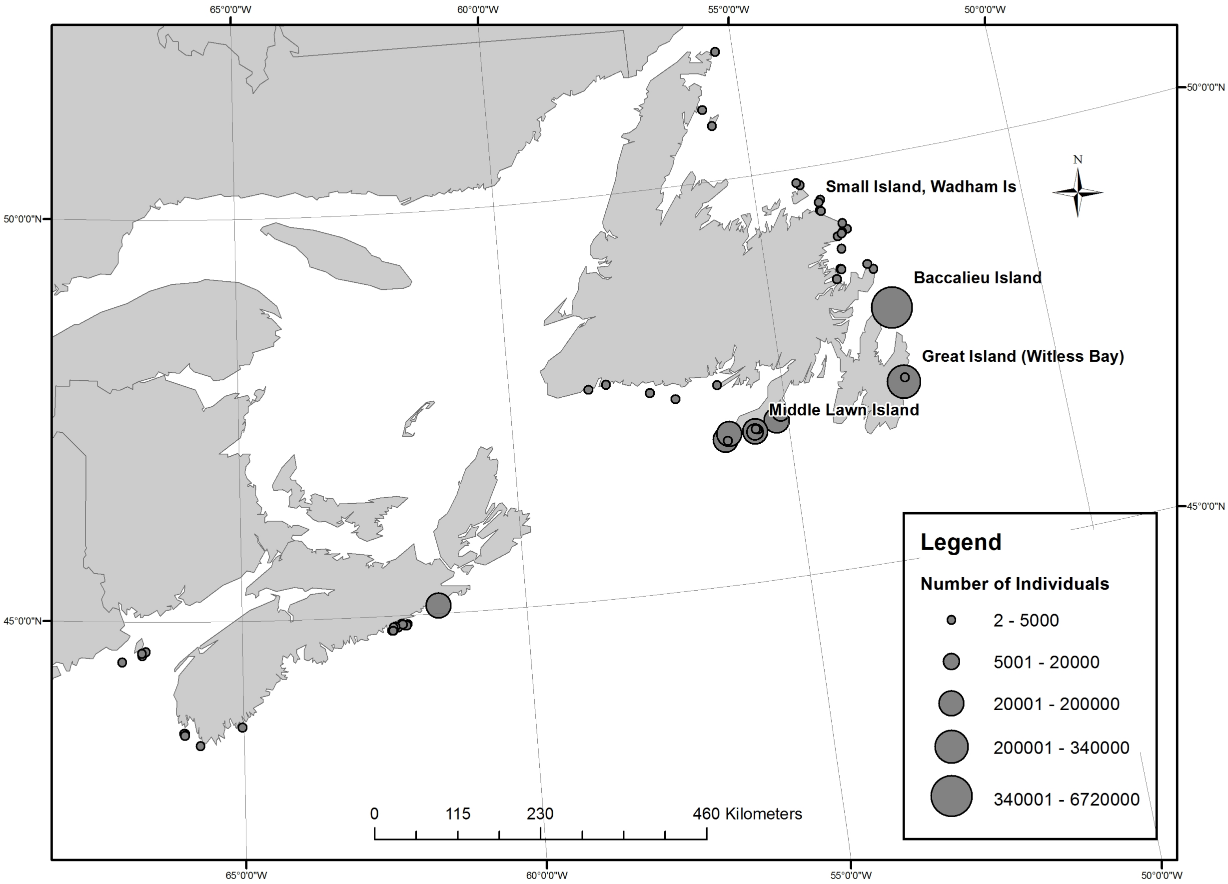
(f) Common Murre (n = 18)



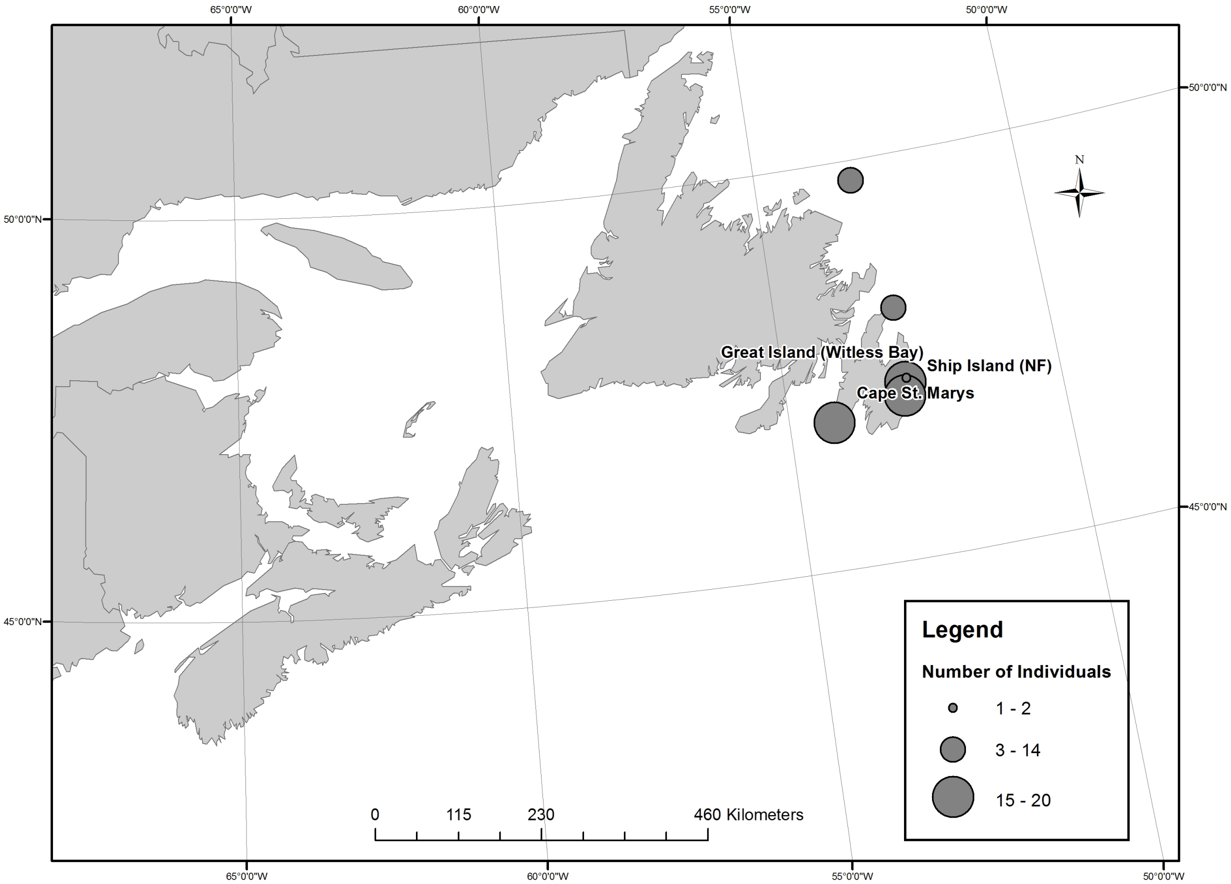
(g) Common Tern (n = 279)



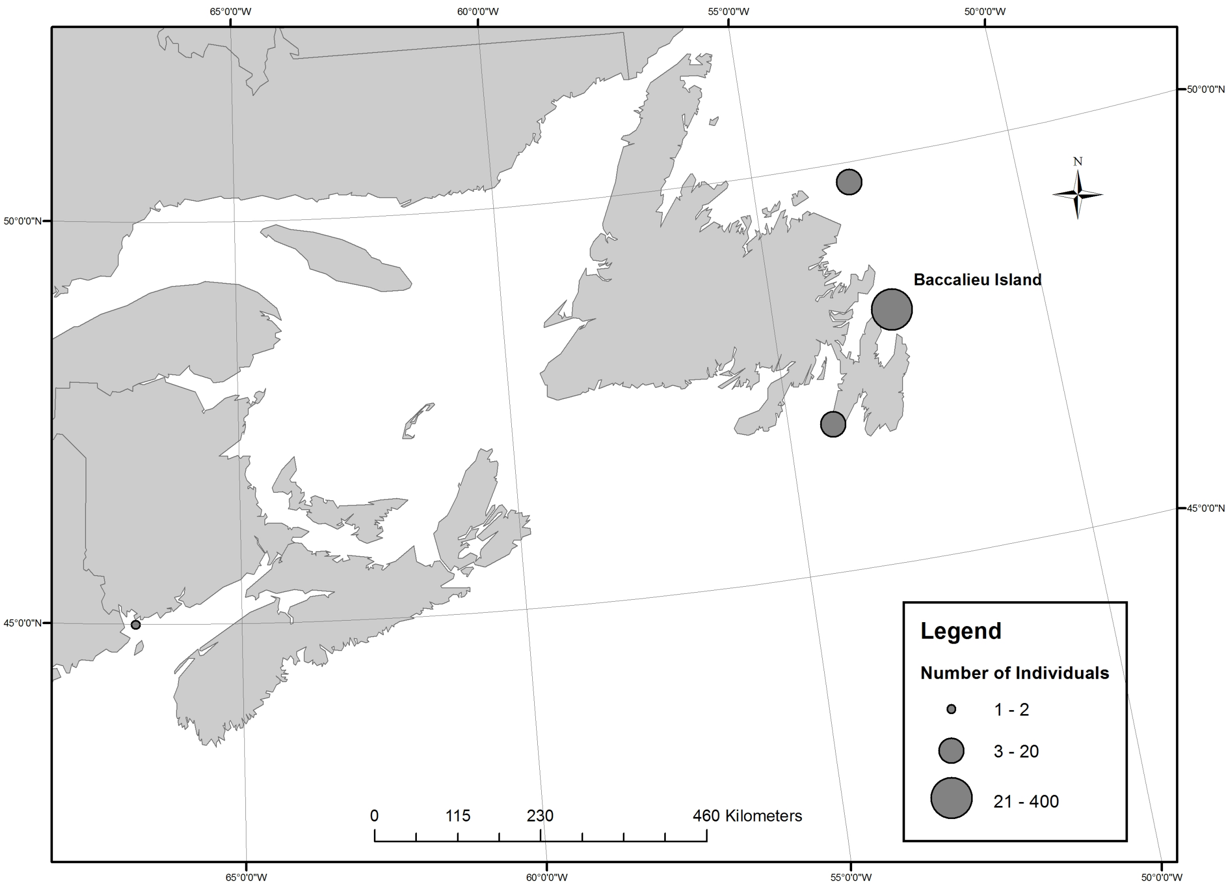
(h) Leach's Storm Petrel (n = 101)



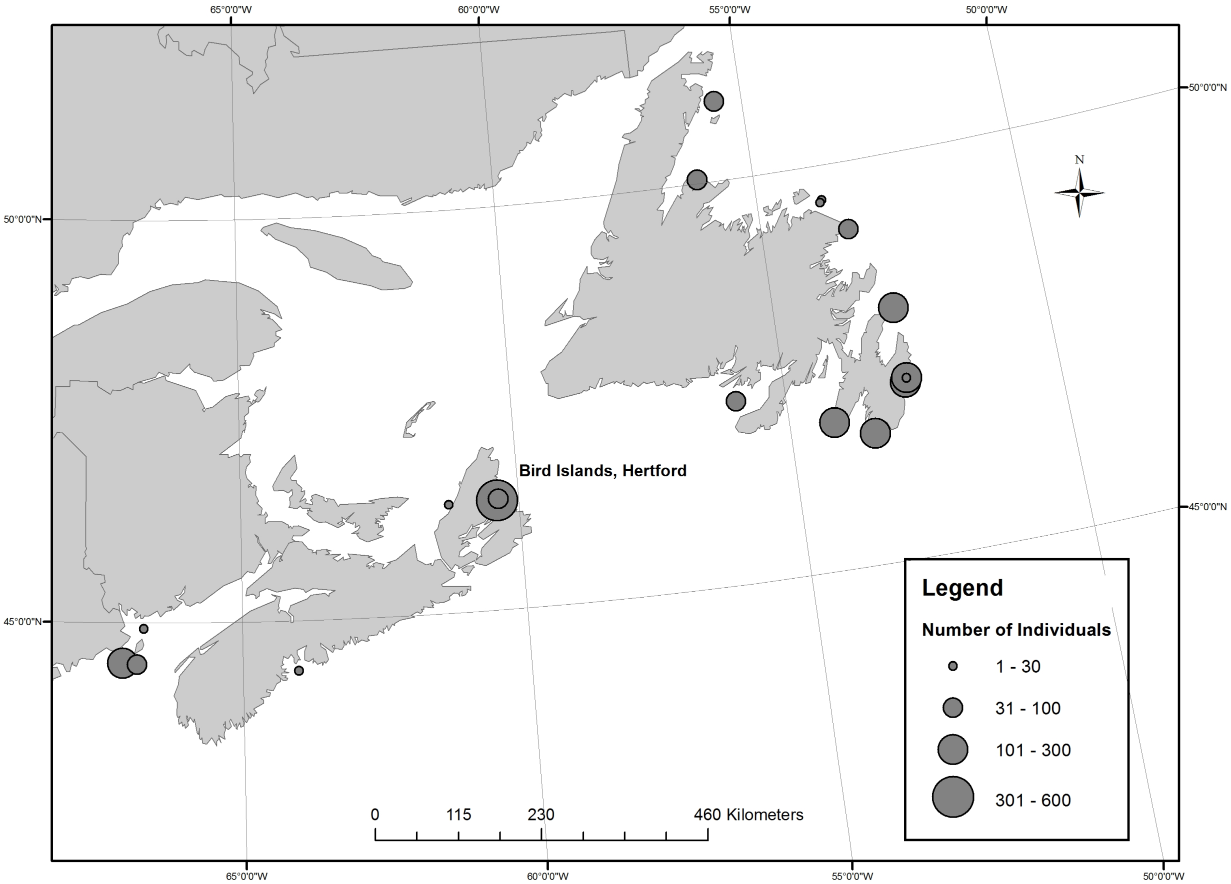
(i) Northern Fulmar (n = 7)



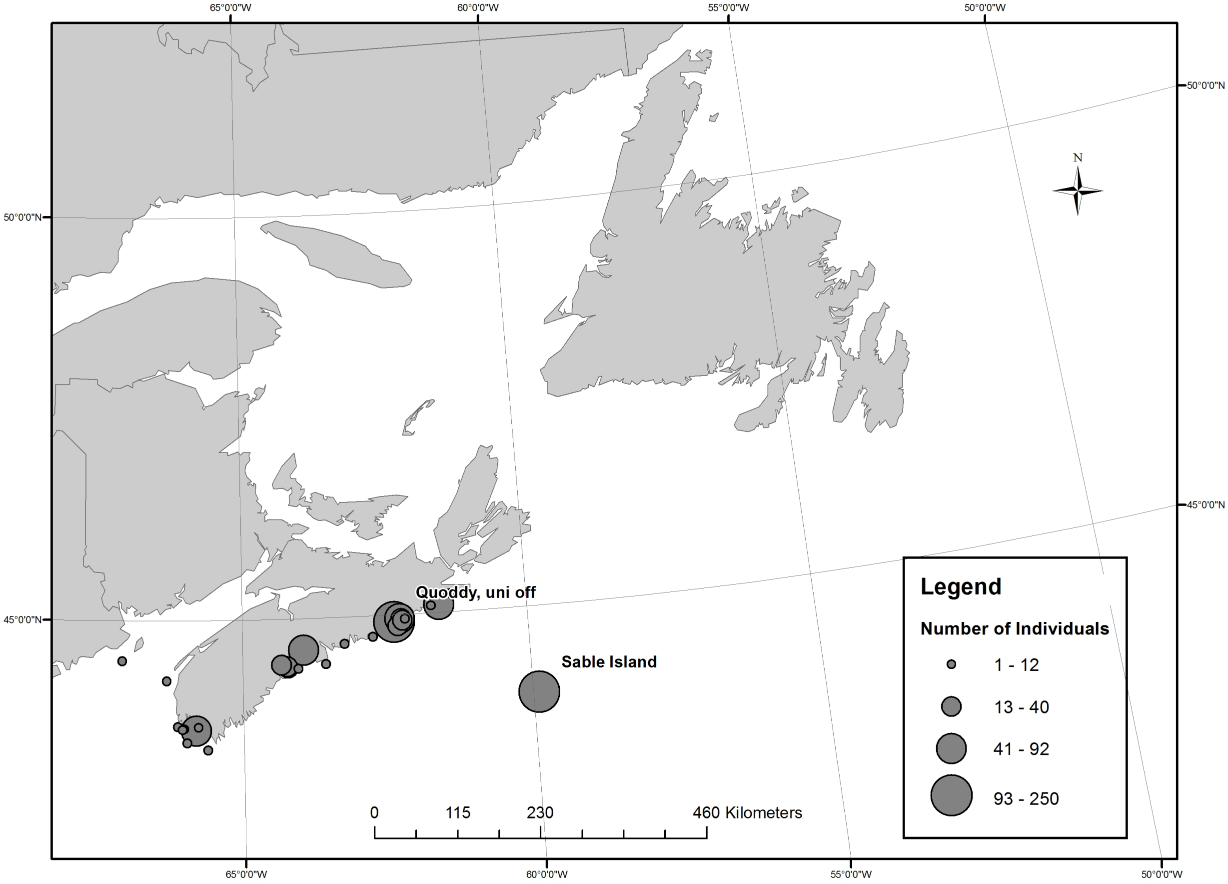
(j) Northern Gannet (n = 4)



(k) Razorbill (n = 29)



(l) Roseate Tern (n = 35)



Figures 5(a – l). Species-specific colony population centers used in light pollution hotspot analyses. Circle symbols indicate relative population size for each species, and the center of the circle represents the geographic center point of each colony based on coordinates provided in the Seabird Colony Database from CWS. Jenks natural breaks with 3 to 5 classes were used to classify population symbol size. Labels of prominent colony names based on population are included for each species.

All colony points were then processed and analyzed in ArcGIS, and each colony was assigned an LPI value for each year from 1993 through 2013. Separate LPI values for each year were then analyzed further to determine if there were any trends for light pollution experienced by each species over time, but no significant trends could be found.

3.3 Statistical Tests for Difference Between Year and Species

Each colony point is considered a sample, and only colonies experiencing some form of measureable light pollution (transformed LPI value > 0.009) were retained for time-series regression analysis. Many colonies experienced no measureable LPI values from 1993 through 2013, and thus experienced no variability in light pollution; these data points were removed from any linear regression or ANOVA model. More recent survey data were lacking for some species, such as Common Murres, Northern Fulmars, Leach's Storm Petrels, and Razorbills, so colony points from only the most recent five surveys until 1983 were used. Northern Gannets had only one colony experiencing any significant light pollution, and therefore the species was not included in the time-series analysis.

LPI values for each colony were processed into a linear regression model to analyze if there were any temporal trends. Including all LPI values, an ANOVA between the LPI values determined if any species experienced light pollution that was significantly different from zero. Razorbills, Black-legged Kittiwakes, and all species of Terns had colonies that had the highest relative LPI values. A summary of statistics is provided for all species (Table 2) including probabilities, regression slopes, maximum and average light pollution experienced for each species. There was no significant trend in yearly LPI values for any species, although there did appear to be higher variability in yearly LPI values for colonies with higher average LPI values (Figure 7, plot comparing colonies). The colony with the highest measured LPI was Goat Island (Saint John), New Brunswick for a Common Tern colony, but the population for this colony was <100 individuals. There was also significant variability in light pollution when considering all colonies, as some species are more cosmopolitan and their colonies tend to be more likely to overlap with urban areas.

Table 2. Time-series analysis of 11 seabird species (NOGA not included due to small sample size, n = 2) comparing LPI values experiences by all colonies in the regression

analysis. Average values and significance from zero p values are for the entire time period. The Regression analysis analyzes any temporal trends in LPI values experienced.

Species	Average	Sig. from	Regression Slope		Highest Average LPI Value	
	LPI	0 p-value	p-value	Coefficient	Colony Name	Territory
Arctic Tern	47.8	0.4882	0.763	-0.152	Bathurst Harbour Island 1	NB
Atlantic Puffin	0.51	0.9610	0.716	-0.003	Grand Colombier	PM
Black Guillemot	20.62	0.0723	0.461	-0.214	Little Bell Island	NL
Black-legged Kittiwake	47.20	**0.0000**	0.572	-0.158	Freshwater Bay	NL
Common Eider	15.34	0.1898	0.916	0.019	Saint John	NB
Common Murre	1.11	0.9672	0.715	0.007	Great Island (WB)	NL
Common Tern	117.30	**0.0000**	0.156	-0.864	Goat Island	NB
Northern Fulmar	18.51	0.9992	0.816	-0.092	Ship Island	NL
Northern Gannet	NA	NA	NA	NA	Whitehorse Island	NB
Leach's Storm Petrel	0.52	0.2467	0.800	0.003	Grand Colombier	PM
Razorbill	31.30	**0.0198**	0.246	1.328	Grand Colombier	PM
Roseate Tern	36.30	**0.0048**	0.443	-0.461	The Brothers Islands	NS
All Colonies	59.87	0.0000	0.167	-0.328	-	

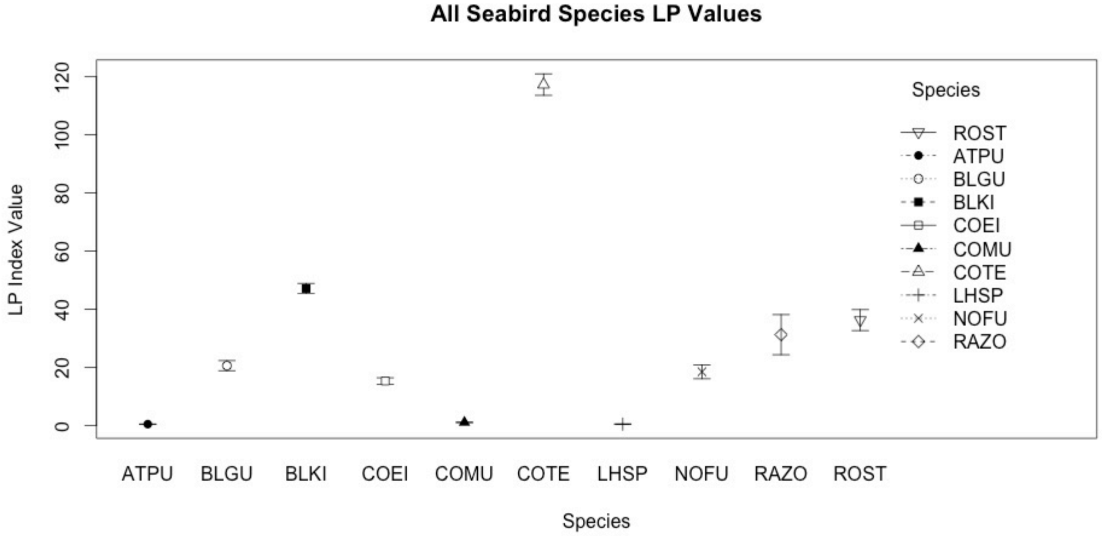
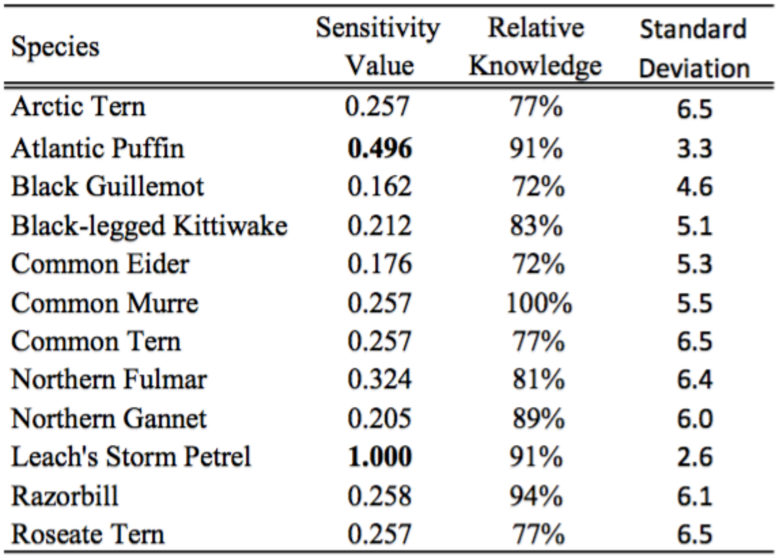


Figure 7. Species-specific transformed LPI values plotted with error bars showing variability between years and colony locations, and which species tend to experience higher than average light pollution.

3.4 AHP Sensitivity Weighting Analysis

The survey responses of all ten experts were compiled, weighted, averaged, and synthesized into one list of priority values. Due to biological similarities and preliminary AHP sensitivity analysis, all Tern species were grouped together for pairwise decisions, and received the same sensitivity values (Table 3). Two species, Leach's Storm Petrel and Atlantic Puffin, were clearly considered most sensitive to light pollution based on expert opinion. Leach's Storm Petrel represented 100% priority (w_i = 1.000) for sensitivity weighting, while Atlantic Puffin represented 49.6% (w_i = 0.496) relative to Petrels. By comparison, the next most sensitive species in this study, Northern Fulmar, represented 32.4% for sensitivity to light pollution, and most other species were less than 26% relative to Petrels.

Table 3. The sensitivity weighting values (*w*) were normalized for each species *i*, and applied to the vulnerability equation (section 2.1). This table is based on results from the AHP sensitivity survey. Leach's Storm Petrel received the highest sensitivity value. The relative knowledge field is based on combined expert knowledge self-assessments for each species. Common Murre received the highest self-assessed knowledge rank relative to all species and all other species are scaled relative to Murres, highlighting where some additional expertise may be required. Standard deviation demonstrates how much variation exists within the ranking range for a species (refer to Figure 2) and simply highlights that less variation exists between the ten experts for some comparisons, such as Leach's Storm Petrel and Atlantic Puffin. Areas in bold indicate the species with the highest sensitivity weights.



Species	Sensitivity Value	Relative Knowledge	Standard Deviation
Arctic Tern	0.257	77%	6.5
Atlantic Puffin	**0.496**	91%	3.3
Black Guillemot	0.162	72%	4.6
Black-legged Kittiwake	0.212	83%	5.1
Common Eider	0.176	72%	5.3
Common Murre	0.257	100%	5.5
Common Tern	0.257	77%	6.5
Northern Fulmar	0.324	81%	6.4
Northern Gannet	0.205	89%	6.0
Leach's Storm Petrel	**1.000**	91%	2.6
Razorbill	0.258	94%	6.1
Roseate Tern	0.257	77%	6.5

3.5 Hotspot Analysis

Vulnerability values were generated for each colony and quantified using risk intensity, R_i, AHP sensitivity weightings, w_i, and relative importance, $I_{i,j}$. Vulnerability values for colonies followed a negative exponential trend (Table 4) and a composite hotspot map was generated for colony points from all seabird species (Figure 8). The region around Grand Columbier, PM and Witless Bay, NL, which both contain millions of individuals from several seabird species, are notably where seabirds are most vulnerable to light pollution. Again, no ecological information is considered, and it is simply a spatial representation of which regions may require light pollution mitigation based on perceived, quantified seabird vulnerability.

Table 4. Twelve colonies (top 99th percentile) ranked with the highest measured vulnerability to light pollution, the first 5 of which are indicated in Figure 8. Relative values are scaled by dividing the value at one colony by the largest value. Relative vulnerability values were less than 0.01% for the lowest 90th percentile.

Rank	Species (code)	Colony Name	Province	Population (est.)	Risk Intensity (relative)	Sensitivity (relative)	Vulnerability (relative)
1	LHSP	Grand Colombier, St Pierre	NL	200000	25.1%	100%	100.00%
2	LHSP	Great Island (Witless Bay)	NL	340000	2.1%	100%	14.10%
3	LHSP	Iron Island [SW]	NL	20000	2.8%	100%	1.10%
4	ATPU	Grand Colombier, St Pierre	NL	2000	25.1%	50%	0.50%
5	COTE	Pointe-à-Bouleau	NB	2002	42.6%	26%	0.44%
6	COTE	Bathurst Harbour Island 1	NB	1400	47.1%	26%	0.34%
7	LHSP	Country Island	NS	121834	0.1%	100%	0.32%
8	ATPU	Pee Pee Island	NL	2600	12.3%	50%	0.32%
9	LHSP	Pound Island, South	NL	2000	6.4%	100%	0.26%
10	COTE	Bathurst Harbour Island 2	NB	674	63.9%	26%	0.22%
11	ATPU	Great Island (Witless Bay)	NL	10000	2.1%	50%	0.21%
12	BLKI	Deadmans Bay	NL	3500	12.0%	21%	0.18%

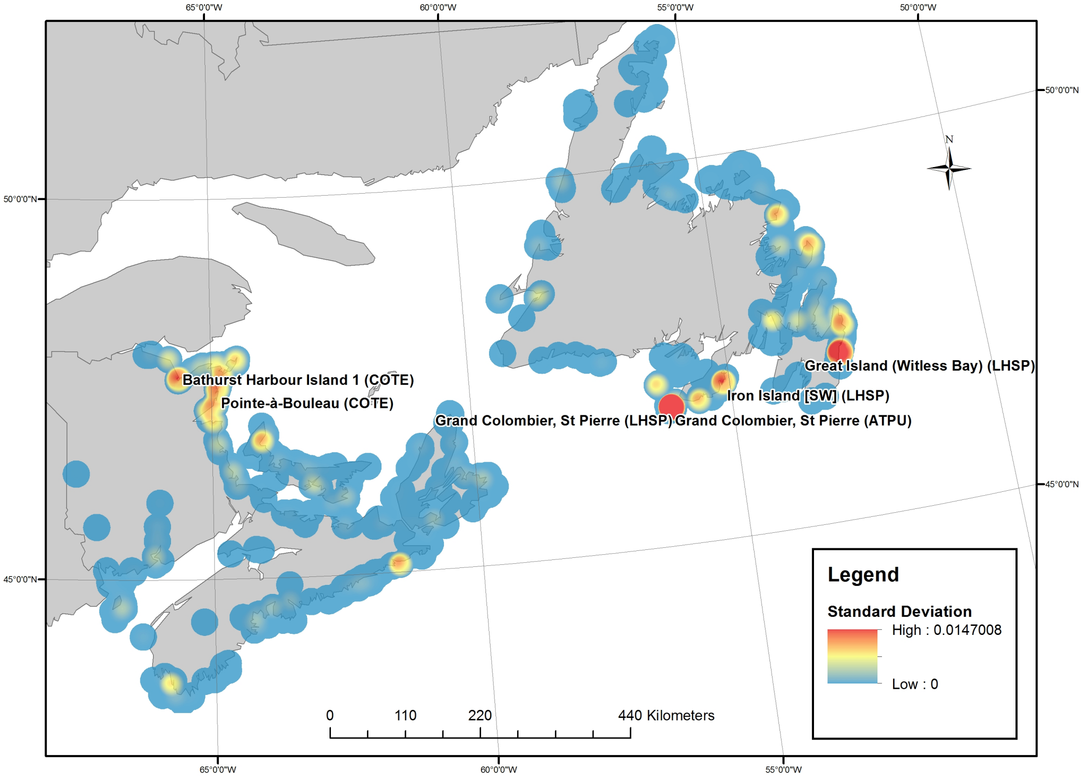


Figure 8. Composite light pollution heat map, or hotspot map displaying the colonies least and most vulnerable to light pollution (blue and red respectively) based on colony-specific vulnerability values, V_j, which is a product of sensitivity, importance, and LPI values, and is relative to all species. The most vulnerability hotspot locations with

species information are labelled in the map. Vulnerability values were classified by 4 standard deviations and gamma corrections were applied for visual contrast.

Several prominent colonies exist for Leach's Storm Petrels and Atlantic Puffins based on where the majority of the population (>20,000 individuals) nest. While larger populations of Leach's Storm Petrel appear to be stable, some smaller colonies (<20,000 individuals) on Small Island and Middle Lawn Island, NL have exhibited a significant population decline since the early 1980s (Robertson et. al, 2006), with the former Island having over 10,000 individuals in 1984 and only around 1,000 in 2006. Small Island also seems to experience relatively little light pollution compared to colonies such as Pearl Island that has around 100,000 breeding pairs, or Gull Island and Great Island in Witless Bay, which have over 620,000 breeding pairs combined (CPAWS, 2016; CWS seabird database). When plotting LPI values for several prominent Leach's Storm Petrel colonies, there appears to be no trend connecting light pollution with population levels (Figure 9), either in the level of intensity, or in year to year variability. The largest colony is found on Baccalieu Island, supporting over 3 million nesting pairs of Leach's Storm Petrel (Stenhouse and Montevecchi, 2000); however, LPI values for this area are zero for all years in the DMSP-OLS time-series. No recent population time-series data exist for Atlantic Puffin (Fig 10), and any comparisons of light pollution variability to population change could not be made; however, it is known that one of the largest nesting population exists in the Witless Bay Ecological Reserve (Great Island), with over 260,000 breeding pairs (CPAWS, 2016), and experiences moderately intense and somewhat variable light pollution levels from year to year.

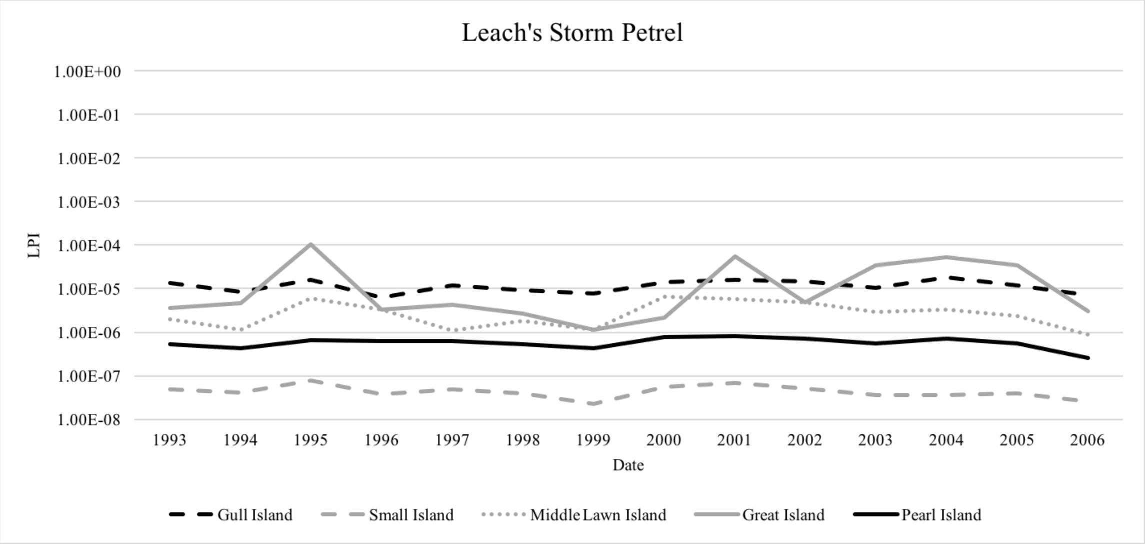


Figure 9. Time-series analysis of light pollution experienced by several colonies listed at the bottom of the figure. Analysis done from 1993 to 2006 to coincide with the population data from Robertson et al. (2006). LPI are untransformed, where 1 would mean equate to full 360-degree saturation within the colony point 20km buffer.

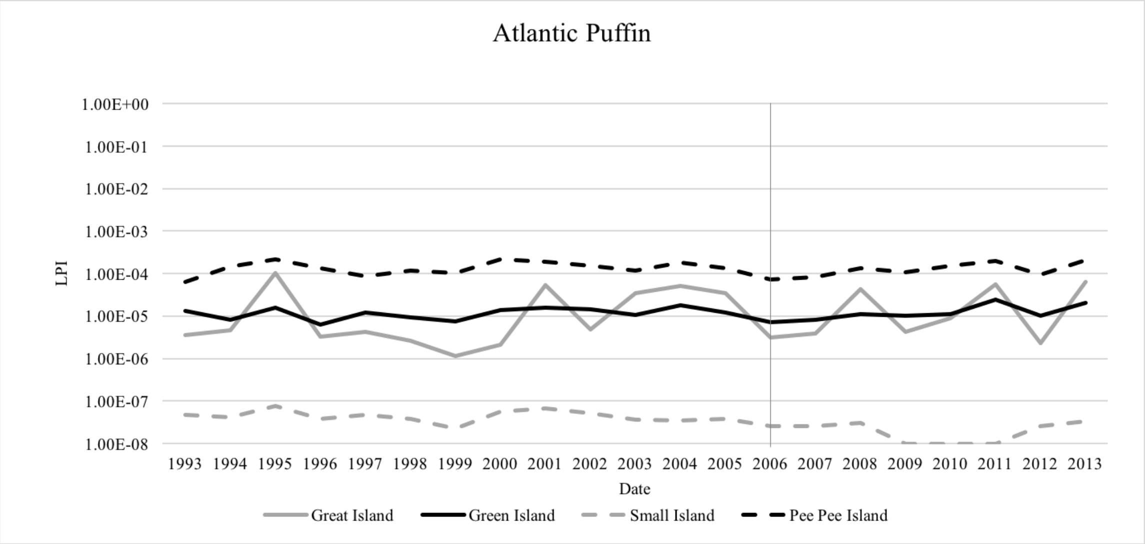


Figure 10. Time-series analysis of Atlantic Puffin LPIs for several prominent colonies, some located near Petrels (Great Island and Small Island). Vertical line at 2006 year for comparison with Figure 9. Great Island has over 520,000 individuals; Green Island has over 10,000; Small Island has 4,000; Pee Pee Island has 2,600 (1980s surveys). Baccalieu Island also is home to many individuals, but similar to Petrel colonies, the colony experiences no measurable light pollution throughout the time-series.

Discussion

4.1 Light Pollution trends and effects

Light pollution index (LPI) values were variable within and between species, however the colonies for some species, such as Terns, Razorbills, and Black-legged Kittiwakes, were more likely to experience higher average and maximum light pollution levels. Black Guillemot colonies also appeared to have higher than normal LPI values, although the slope of the linear trend did not vary significantly different from zero across all analyzed colonies. There did not appear to be any significant linear trend of LPI values for any species across the 21 years of light pollution maps. Some species had overall declines in LPI values, while others showed slight gains, although there was too much variability of LPI values between years, resulting in large residual values that made any correlations insignificant. Again, it was assumed that each colony for any species had a 20km, topographically limited buffer in which the colony would experience light pollution, however, this may not be consistent across all species. Variation in the visual acuity of seabirds may result in variable response (Blackwell et al., 2009), and development of species-specific methods for predicting how fledglings react to light pollution (Troy et al., 2011) is an important area of inquiry.

Despite having no overall trends relating LPI variability to year, analysis of each species provides details as to which colonies are receiving above average levels of light pollution, and potentially more at-risk to the disturbance. Maximum LPI values are recorded in Table 2 along side the colony ID, and the year of DMSP-OLS survey. These data provide the most extreme examples of light pollution and it would be expected that colonies around the largest urban centers would have the highest LPI values; however, not all species have prominent colonies near towns or cities, and instead colonies around less populated areas are subject to the most species-specific light pollution. Notably, St. Pierre et Miquelon (PM), a territory of France, seems to have the highest light pollution values in the region for Atlantic Puffins, Leach's Storm Petrels, and Razorbills, with relatively high values for Black Guillemots and Black-legged Kittiwakes. The area is not highly populated with only around 6300 people (United Nations, 2011), but evidently represents an important area for several species of seabirds. Some areas, like Halifax, Moncton, Saint John, St. John's, and Sydney have some breeding presence (Figures 4a – j); however, smaller cities have the most effect of light pollution on some colonies, such as around Pubnico, NS (Roseate Tern) and inland near Grand Lake, NB (Common Tern). As expected, hotspots for light pollution appear to be in proximity to urban areas, but prominent colonies do not appear near the largest urban centers, possibly explaining why there are no vulnerability hotspots in close proximity to major cities. Other important colonies are located in places that experience negligible light pollution, such as on Funk and Baccalieu Islands, both in Newfoundland, hosting millions of individuals from several species during breeding seasons, such Petrel and Puffin. These areas may not require light pollution mitigation presently; however, future nearby developments in these areas may pose a risk to sensitive species if the area is not conserved.

The AHP sensitivity analysis determined that Leach's Storm Petrels and Atlantic Puffins are the most sensitive to the effects of light pollution. The results of the sensitivity analysis appear to be in agreement with literature of previous studies (Le Corre et al., 2002; Raine et al., 2010; Rodriguez et al. 2012). These results are not surprising for several reasons: First, there are many studies regarding the effect of light pollution on Petrels, five of which appear in this paper. Second, some elements of the public are already aware of the issue and conducting efforts around large breeding colonies to rescue any individuals grounded by light pollution disorientation (Le Corre et al., 2002; CPAWS, 2016). Third, both species use the moon and stars for navigation at night (Lockley, 1967; Rodriguez and Rodriguez, 2009), and are therefore more susceptible to light pollution induced disorientation, especially when overcast skies produce reflected sky glow. Only young Atlantic Puffins fledge at night, while Leach's Storm Petrels are completely nocturnal, resulting in a large proportion of young Puffins being rescued and detained until daylight (825 in 2014 according to CPAWS, 2016), while some rescue operations only see a fraction <1% of adult petrels grounded (Rodriguez et al. 2012). Atlantic Puffin adults are not nocturnal, meaning the species is most vulnerable to light pollution during fledging season from August until October, while the nocturnal Leach's

Storm Petrel is vulnerable to the risk year-round, but tend to be found mostly during fall (CPAWS, 2016).

Vulnerability maps point to Grand Colombier, PM and Witless Bay, NL as risk-hotspots for light pollution. The Witless Bay Ecological Reserve has already identified this region as one of the most important breeding grounds for both the Leach's Storm Petrel and Atlantic Puffin in Atlantic Canada. Despite current efforts, such as the Puffin Patrol, and ecological protection, additional mitigation and support should be encouraged if nearby residential and commercial development continues. When considering the vulnerability of all species relative to Leach's Storm Petrel, some colonies in regions experiencing significant light pollution are down-weighted if the species was assessed to be relatively less sensitive. The composite hotspot analysis (Figure 8) combined with known population information, allowed for prioritization of the regions needing the largest mitigation efforts. Interestingly, The Northern Fulmar, which was deemed the third most sensitive to light pollution in this study, also nests predominantly around the same region, bolstering the importance of risk mitigation. Areas such as Witless Bay, NL, are known to experience seabird fatalities from light pollution, but that does not mean that other areas, such as Pubnico, NS, Bathurst, NB, and Grand Colombier, PM would also benefit ecologically from reduced light pollution.

An important consideration is how light pollution is often a direct result of urbanization and human development (Hölker et al. 2010), and how some seabird species may not be subject to the risk based on preferring habitats away from human populations on less disturbed landscapes. Another consideration is how some species, like Terns, may be individually susceptible to the risk on occasion, but its effect on the population could be offset by the colony actually benefiting from some light trespass, as it may offer additional illumination at night, providing a means of predator detection and vigilance in otherwise low-light conditions. Conversely, light trespass could also make seabirds more visible and vulnerable to predators. The population size of a species may also affect the impact of light pollution on a particular colony. In this study, importance, I, is greater with larger populations, but some colonies in this study with substantial populations have population increases despite relatively high LPI values. Again, the effects of how light pollution effects seabird ecologically is complex and not fully understood for some species. The risk may have various positive and negative effects, and its effects, positive or negative, are likely overshadowed by other ecological and environmental factors, especially for larger populations.

4.2 Limitations

Light pollution levels in Atlantic Canada do not seem to follow the similar trends observed globally by Hölker et al. (2010), but this could be due to the DMSP-OLS time-series chosen, or even a national trend, and may not be representative of a trend for longer periods or smaller regions. There does appear to be some variation of LPI values experienced by seabird colonies across Atlantic Canada between years, however, some of this variation could be attributable as errors in the DMSP-OLS satellite calibration, in which cities and surrounding areas are often fully saturated with the highest possible DN value (63) and contain no discernible details. Some calibration methods have been established to counter the sensitivity of the sensors (Hsu et al., 2015) and increase detail, however these methods were out of the scope of this preliminary study, which mainly sought to identify relative light pollution between species, and only required a coarse resolution to determine these hotspots. For future time-series analysis of light pollution variability and intensity corrections could be applied to the data, or local luminosity levels can be directly measured using a lux meter. Ideally, light pollution could also be measured on a monthly, or quarterly basis, as seabirds only nest in colonies at certain times of the year.

Population and nesting data were also not consistently available for all surveys in the Seabird Colony Database, especially for older surveys. Some data were confirmed through literature reviews, but may not be representative of current population sizes. Most colonies were also not resampled in subsequent years, so time-series changes in population compared with light pollution index values could not be properly analyzed. In future studies, direct and repeated sampling of selected seabird colonies would be ideal for a fine-scale analysis comparing light pollution variation with population, or even breeding and behavioural changes.

There is a strong need for continuing surveys and monitoring seabird breeding populations across Atlantic Canada and worldwide. Studying the effects of population dynamics could provide valuable information on how a seabird species responds to a particular anthropogenic risk. Successive yearly surveys would also allow for robust time-series analyses to be completed, and could also advise of any colonies that may be facing population changes, and the possible reason(s). Many of the surveys in the CWS seabird database are from the mid 20th century or older, and while recent efforts were made to verify and substantiate these older surveys, errors could exist that prevents these data from being fully effective in any modeling or statistical analyses, or making any concrete inferences.

Not all species could be included in this study, however some additional species could be included for future studies, and with sufficient survey data, this model can be expanded to include all migrants and not just breeding species. For this study, large gull species, such as Herring Gull and Great Black-backed Gull, were excluded based on preliminary AHP sensitivity analysis showing that they were not likely at risk to light pollution relative to other species, combined with their ubiquitous distribution of colonies ($N > 2000$) which could skew the results. Shear computational processing time also limited any analyses on these species. Other species, such as Cormorant, Dovekie, and Shearwaters, were considered only after computations and data were processed, which could provide information on additional risk-hotspots if they were to be included in future studies. In addition, traditional ecologic knowledge from locals and Aboriginal Peoples would benefit the AHP analysis greatly.

4.3 Mitigation

Reducing the risks posed by light pollution to seabirds is clearly not as simple as designating protected ecological areas. Many of the areas investigated, such as around

Witless Bay, NL, are already provincially protected, and most of the prominent colonies are already known and monitored to some degree. Much of the mitigation towards light pollution hinges on public and corporate awareness.

Reducing or eliminating light pollution while maintaining safety and security, can be accomplished simply by turning off unnecessary lights not in use, especially flood lights, or by using motion sensors for outdoor lighting. In coastal areas, especially for many of the breeding colonies near shore or on islands, windows facing seaward should have dark blinds or opaque window coverings to limit trespass. For outdoor lighting, the type of fixtures that limits trespass, especially skyward, is ideal and particularly important for brighter lights. The type of light may also have an effect, as some bulbs generate high intensities. Seabird sensitivities to various types of light is not fully understood and is contested (Poot et al., 2008; Evans 2010); however, the intensity of lights in an area is cumulative for sky glow and light pollution, and limiting overall light pollution is ideal for seabird conservation. Ideally all times of year could have some form of light pollution reduction, but it is much more important to take additional measures throughout breeding season, and particularly during bad weather when light pollution appears to have a stronger effect on nocturnal species (Le Corre et al., 2002).

Current rescue efforts, such as Puffin Patrol, are possibly the best forms of conservation to reduce light pollution fatalities. These programs and their participants rescue hundreds of grounded birds per year that would otherwise be at risk to predators, adverse weather, and automobile traffic when disoriented by light. Similar rescue efforts exist elsewhere for grounded seabirds, such as in Canaries, Hawaii, New Zealand, French Polynesia and Réunion (Le Corre et al., 2002), which allows the public to participate in the rescue efforts. This creates a lot of public awareness surrounding the issue through media and word-of-mouth, and even generates tourism in some areas for people interested in the rescue efforts (CPAWS, 2016).

4.4 Conclusion

This study is only a preliminary, albeit large-scale investigation into the risk hotspots of a large list of seabirds in Atlantic Canada. Additional species should be included in future assessments to provide a more accurate representation of vulnerable areas, and additional population factors could be included. Caution must be taken when interpreting hotspot results, as they hinge on populations that are scaled only to the number of seabirds within the study area. Sensitivity priority values, while proven to effective in decision making, are also dependent on expert opinion, for which some variation exists. Light pollution maps for time-series were chosen initially for time-series analysis, and while they provided much detail, they were lower in resolution and precision compared to years after 2013, and advanced calibration techniques were not within the scope of this study. Composite light pollution averages for an entire year may not represent the light levels experienced during breeding times, when large populations are put at-risk. Fine scale monthly, or quarterly analysis of light pollution in Atlantic Canada for additional studies, preferably using new VIIRS light pollution maps.

A robust model for identifying vulnerability hotspots given limited data has been applied in this study, and the methods in this study can be loosely applied to any spatial vulnerability assessment. The decision making tools of AHP appear to match reality when applied to perceived seabird sensitivity, and is strengthened by an expert self-assessment. The GIS-based model to assess light pollution experienced by a seabird colony also accurately identifies vulnerable areas based on CWS data. The effects that light pollution has on individual species of petrels are becoming well-known, however this study exposed the limited knowledge regarding how light pollution affects Atlantic Puffins, which are only nocturnal as fledglings. Relative to all species, Puffins have the highest number of grounded birds around Witless Bay, NL, and provide substantial weighting to the composite risk-hotspot map spatially depicting species-wide vulnerability. Additional studies are needed to understand the fine-scale ecological effects of light pollution on Atlantic Puffins, or how light pollution may affect one particular colony. With awareness, mitigation efforts, and additional research, the negative effects of light pollution can be understood and reduced.

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