

Nesting habitat selection and distribution of an avian top predator in the Canadian Arctic

Kristen Peck, Alastair Franke, Nicolas Lecomte, and Joël Bêty

Abstract: Detecting and planning for ecosystem changes from climate and land-use alteration is limited by uncertainty about the current distribution of many species. This is exacerbated in remote areas like the Arctic, where the impacts of climate change are the strongest and where industrial exploration and development are expanding. Using remotely-sensed environmental information and known nest sites, we estimated the breeding distribution and habitat selection of the peregrine falcon (*Falco peregrinus*) throughout most of Nunavut, a massive northern Canadian territory (>1.8 M km²) encompassing ~15% of the world's tundra biome. Our results show that peregrine falcons selected features of prior known importance such as rugged topography, but also sites with higher than average summer temperatures, more productive land classes, lower mean elevations, and lower mean summer precipitation. Our model identifies several areas of high relative probability of peregrine occurrence, some of which were unrecognized to date. Some of these areas may be targets for future industrial developments and are located in an area where some of the fastest climate changes are expected. Our model will allow managers to identify the areas that could be the most critical for monitoring in the context of future development and climate change.

Key words: peregrine falcon, habitat selection, resource selection function, species distribution model, *Falco peregrinus tundrius/anatum*.

Résumé : La détection des changements écosystémiques en raison des modifications du climat et de l'utilisation des terres et la planification en fonction de ces changements sont limitées par l'incertitude entourant la répartition actuelle de beaucoup d'espèces. Ceci est aggravé dans les régions éloignées comme l'Arctique, où les impacts du changement climatique se font le plus ressentir et où l'exploration et le développement industriels sont en croissance. En utilisant les données sur l'environnement recueillies par télédétection et les sites de nidification connus, nous avons estimé la répartition de la reproduction et la sélection de l'habitat du faucon pèlerin (*Falco peregrinus*) partout dans la majeure partie du Nunavut, un vaste territoire dans le nord du Canada (>1.8 M km²) représentant ~15 % du biome de la toundra du monde. Nos résultats montrent que les

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faucons pèlerins ont choisi des endroits à caractéristiques dont l'importance est préalablement connue telles qu'une topographie irrégulière, mais aussi des sites avec des températures moyennes plus élevées en été, des classes de terrain plus productif, des élévations moyennes plus basses et des précipitations moyennes inférieures en été. Notre modèle identifie plusieurs régions où il y a une forte probabilité relative de présence de pèlerins, dont certaines étaient méconnues jusqu'à présent. Certaines de ces régions peuvent être des cibles pour des développements industriels futurs et sont situées où certains des changements climatiques les plus rapides sont prévus. Notre modèle permettra aux directeurs d'identifier les régions qui pourraient être les plus critiques au niveau de la surveillance dans un contexte de développement et de changement climatique à l'avenir. [Traduit par la Rédaction]

Mots-clés : faucon pèlerin, sélection de l'habitat, fonction de sélection de ressource, modèle de répartition des espèces, *Falco peregrinus tundrius/anatum*.

Introduction

The Arctic is among the biomes that have been, and will continue to be, the most affected by climate change (Stocker et al. 2013). Northern industrial development and exploration are also expected to expand to new Arctic areas as environmental changes allow greater access and a longer seasonal exploration window (Pearce et al. 2011). Yet detecting and planning for the impact on northern terrestrial ecosystems from multiple pressures may be limited by a lack of baseline information for many Arctic species. Charismatic or economically important species dominate existing broad-scale studies of species diversity and distribution [e.g., caribou (*Rangifer tarandus*) and muskoxen (*Ovibos moschatus*; Campbell et al. 2012; Yannic et al. 2014), wolves (*Canis lupus*; Heard and Williams 1992), wolverines (*Gulo gulo*; Copeland et al. 2010), and polar bears (*Ursus maritimus*; Wilson et al. 2014)]. Given the scale of changes predicted to affect northern ecosystems, an understanding of current species' distributions and habitat selection are needed to adequately detect and respond to global change.

Species distribution models are commonly used in conservation biogeography (Guisan and Thuiller 2005; Franklin 2013) to relate the occurrence, abundance, or physiological response of a species, or groups of species, to environmental features (Guisan and Zimmermann 2000; Guisan and Thuiller 2005; Franklin 2013). They are often used at regional scales, are ideal for producing baseline species distribution maps, and yet are powerful enough to delineate how species interact with their environment (Rushton et al. 2004). These models are often based on imperfect datasets with incomplete coverage such as in the Arctic, where human settlements are widely dispersed and high costs limit field-work (Foy et al. 2014).

Here we employ a species distribution model to study the peregrine falcon (*Falco peregrinus tundrius/anatum*): an avian top predator with an extensive northern breeding distribution that uses both terrestrial and marine resources (Ratcliffe 1980; White et al. 2002). We limited our study area to areas north of the tree line, which was traditionally considered the breeding area of the Arctic peregrine falcon (*F. peregrinus tundrius*) but genetic evidence shows that the study area likely also includes *F. peregrinus anatum* (Johnson et al. 2010; Talbot et al. 2017). Conducting surveys to address distribution gaps would be prohibitively expensive and labour intensive, thus we used an existing database of nesting raptors (Poole 2011; Peck et al. 2012) to estimate the current distribution of peregrines in the north-east Canadian Arctic.

The objectives of this study were to investigate the habitat selection of peregrines over a large area of tundra biome in the eastern Canadian Arctic, and then to estimate their breeding distribution throughout the study area. We expected that peregrine habitat selection

would be strongly influenced by topographical variability (Gainzarain et al. 2000; Wightman and Fuller 2005; Brambilla et al. 2006; Bruggeman et al. 2016). Because climatic variables are often key determinants of the distribution of species at regional- or landscape-scales (Pearson and Dawson 2003), and since our study area is at the northern limit of their distribution, we predicted that peregrines would prefer areas with relatively warmer temperatures. In contrast, heavy precipitation events have been shown to negatively influence the productivity of peregrines in the Low Arctic (Anctil et al. 2014). We thus expected that peregrines would avoid breeding in areas with relatively high summer precipitation. Jenkins and Hockey (2001) suggested that prey availability may determine peregrine falcon density at the regional scale. However, prey abundance estimates over large areas are logistically difficult to obtain in the Arctic, and there is often a huge annual variation in bird and small mammal abundance (e.g., Gauthier et al. 2013; Robinson et al. 2014). Therefore, we assumed greater prey availability in Arctic land classes of relatively high productivity (e.g., graminoid tundra, shrubby tundra, and wetlands; Callaghan et al. 2004). Other features likely important to peregrine nest site selection or productivity included the proximity to the coast (L'Hérault et al. 2013) and the mean elevation (Sergio et al. 2004). Our final step was to estimate relative probability of occurrence throughout the study area, including areas where surveys were absent.

Methods

Study area

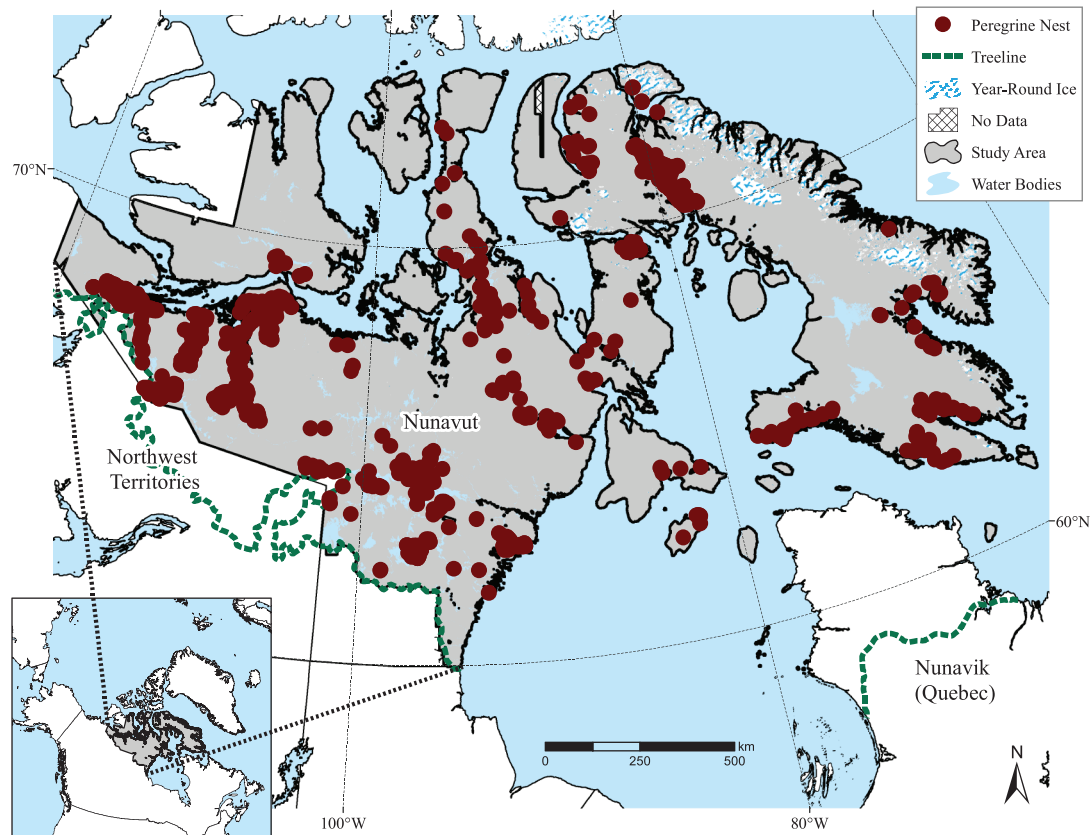
Our study area covered about 15% of the Arctic biome, encompassing ca. 1 689 000 km² (~80%) of Nunavut, the largest of Canada's provinces and territories. The study was situated in the Arctic ecozone (Rankin et al. 2010) and covered all Arctic bioclimatic subzones except the coldest (i.e., Arctic desert, Walker et al. 2005). We included areas north of the tree line to derive a model relevant to the tundra. We defined the tree line according to Olthof et al. (2008), and excluded some islands north of the Parry Channel where survey effort was limited or absent (Fig. 1). Some islands in the southern Hudson's Bay (e.g., the Belcher Islands) were excluded due to inadequate environmental information, as were locations where remote sensing data were absent (e.g., a small strip of the Brodeur Peninsula on Baffin Island, see Fig. 1). Due to differing sources and accuracy of the environmental variables, we buffered the coastline within the study area by 1 km to ensure all land areas were included.

Throughout our study area, the average summer temperature (May to August) is 1.5 °C (range from -16.2 °C May minimum to a 17.2 °C July maximum) and the average summer precipitation was 26.9 mm [range: 8.3–60.5 mm; calculated from Worldclim climate data (averaged from 1950 to 2000); Hijmans et al. 2005]. A large proportion of the study area was coastal but was continental to the southwest where it borders the Northwest Territories (Fig. 1). The highest elevation, 2133 m, was on Baffin Island (Natural Resources Canada 2000). The dominant vegetation land classes were sparsely vegetated bedrock, prostrate dwarf shrub, and barren ground (25.4%, 11.9%, and 10.0% of land area, respectively; Olthof et al. 2008). Overall, the study area covered most of the tundra habitats and management areas within Nunavut, and was an appropriate scale to study a widely-distributed and highly mobile species like the peregrine falcon.

Nest sites and occurrence cells

We used data from the Nunavut and Northwest Territories Raptor Database, which contained raptor nest site records from the 1950s to the present across Nunavut (Shank 1997; Poole 2011; Peck et al. 2012). Nest records were collected from a variety of sources, including

Fig. 1. Locations of 1168 known peregrine falcon (*Falco peregrinus*) nest sites (red dots), occupied at least once from 1959 to 2013, throughout the majority of Nunavut, Canada. Nest locations are from the Nunavut and Northwest Territories Raptor Database (Poole 2011; Peck et al. 2012). The study area (light green) used in the analysis and subsequent predictions is bounded to the south by the tree line (broken green line) or by administrative borders (straight black lines for territories; thin straight lines for provinces), water bodies (in blue), and to the north by the Parry Channel (ca. 74°N). Areas lacking environmental data, water bodies or with year-round ice were excluded from the analysis (see “Methods”).



industry, universities, government, and records from eBird. The database contained nest records and visit histories for eight species of raptor in Nunavut, of which 1168 nests were occupied by peregrines at least once from 1959 to 2013 (Fig. 1). The majority (92%) of nest visits occurred between 1980 and 2013. For the records in which peregrines falcon nest visit methods were noted (5881 records), 81% were surveyed by helicopter, 11% by ground transport, 7% by boat, and <1% fixed wing airplane. The identification of peregrines was consistent across these various survey methods, irrespective of the possible variation in survey detectability (Peck et al. 2012).

Nesting data were gathered by different sources and search effort was not recorded in the database. Nest locations were therefore spatially clumped, with a disproportionately high density of nesting sites in some well-surveyed areas of Nunavut (e.g., the long-term monitoring program at Rankin Inlet, Nunavut; Jaffré et al. 2015). There are several ways to account for biased sampling effort including down-weighting records in areas that received more survey effort, adding more data by surveying areas that are under-represented, or sampling background or pseudo-absence data only from areas that were likely surveyed

(e.g., Phillips et al. 2009). In the case of peregrine nesting habitat selection in Nunavut, it would be logistically difficult to add data with targeted surveys due to the spatial and temporal spread of information included in this analysis ($>1 \text{ M km}^2$). For this reason, we simplified the nesting data (following Thuiller 2003) into “occurrence” cells on a $10 \text{ km} \times 10 \text{ km}$ grid to account for spatial sampling bias. If at least one nest fell inside a cell, it was considered an occurrence (see Supplementary Fig. S1¹ for an example). This 100 km^2 cell size was chosen to represent an approximate and conservative size of breeding peregrine home range in the Arctic (L'Hérault et al. 2013; Sokolov et al. 2014; A. Franke, unpublished data). This transformation to grid cells reduced the weight of nests found in areas that were monitored more intensively, thereby accounting for some of the spatial autocorrelation and sampling bias. It also masked spatial error in the nest position caused by variable search methods (e.g., helicopters versus ground surveys) and the variable accuracy of site recording technology (e.g., physical maps versus handheld GPS) over the years. After this reduction of data, 550 peregrine occurrence grid cells remained of the original 1168 nests sites (approximately 50% of total nest sites), which represents a very small proportion of the study area (prevalence: $550/41\,440 = 0.01$, or 1.3%, of total grid cells).

Pseudo-absences

Search effort and survey tracks were not available to determine areas in which peregrine nest sites were absent, we therefore generated pseudo-absences to compare with occurrence cells. Pseudo-absences were generated throughout the entire study area as we considered the entire study area to be available to breeding peregrine falcons. Such an approach is less robust than comparing occurrences and true absences, but the detection of animals or animal sign is rarely perfect and true absences can be difficult to determine (MacKenzie et al. 2003; Booms et al. 2010; Lobo et al. 2010). Pseudo-absences were sampled from nonoccurrence cells throughout the study area and resampled 10 times to cover a wider range of background environmental variation. Environmental information from an equal number of occurrences and pseudo-absences was compared in each habitat selection model ($n = 550$ each). This comparison was repeated with each of the 10 pseudo-absence resampled datasets.

Habitat variables

We chose environmental variables based on those identified in previous studies of peregrine habitat selection at local scales. Austin (2002) suggested that direct variables, or variables with a direct effect on a species' biology, should be used over indirect variables whenever possible. In the case of peregrines, direct variables might include availability of nest site substrate, prey availability, or weather extremes. However, at the regional scale, species distributions are often driven indirectly by climate, while at the local scale occurrences are driven more by direct, small-scale processes such as interspecific interactions and microtopography (Pearson and Dawson 2003). The large scale of our study required the selection of variables that were indirectly related to peregrine site occupancy. For example, we included overall terrain ruggedness instead of nest site availability, and primary productivity instead of prey availability. The biological effects of indirect variables can be more challenging to interpret than variables with a direct effect on a species (Austin 2002), but at this scale of study signals can be detected and interpreted cautiously.

We converted all environmental information to $10 \text{ km} \times 10 \text{ km}$ occurrences or pseudo-absences (Table 1). We derived the standard deviation of elevation (Ruggedness), squared

¹Supplementary data are available with the article through the journal Web site at <http://nrcresearchpress.com/doi/suppl/10.1139/as-2017-0048>.

Table 1. Source data (grey rows) and derived habitat variables (white rows) included in a peregrine falcon (*Falco peregrinus*) habitat selection analysis at the regional scale in Nunavut, Canada.

Variable	Data source	Resolution	Description	Occurrence	Pseudo-absence
Land cover	Circa-2000 Northern Land Cover (NRCan) ^a	30 m	15 land cover classes consolidated into five classes: graminoid tundra, shrub tundra, wetlands, bare and sparse ground, and water		
Cover (%)			The percentage of 30 m × 30 m pixels classed as graminoids, shrubs, and wetlands out of all classified pixels (including water and ice)	$\bar{x} = 54.23$ $s = 28.09$	$\bar{x} = 37.50$ $s = 28.05$
Coastline	CANVEC (NRCan)	N/A (vector)	Nunavut coastline		
Coastal (1 = inland; 0 = coastal)			If cell centre <15 km from the coast = coastal (0); if >15 km = inland (1)	50.81%	35.99%
Elevation	Canadian Digital Elevation Model (NRCan)	30 m horizontal 1 m vertical	Altitude above mean sea level (asl)		
Elevation (m)			The log10 of the mean elevation	$\bar{x} = 101.09^c$ $s = 3.40^c$	$\bar{x} = 133.60^c$ $s = 3.34^c$
Ruggedness (m)			The log10 of the standard deviation of elevation	$\bar{x} = 30.00^c$ $s = 2.19^c$	$\bar{x} = 22.63^c$ $s = 2.81^c$
Ruggedness ²			Square of the standardized log10 of the standard deviation of elevation	NA	NA
Climate	Worldclim ^b	30 arc-seconds, ca. 244 m × 944 m in Nunavut	Global interpolated climate data averaged from 1950 to 2000 (calculated with Environment Canada weather station data in Canada)		
Temperature (°C)			Average of monthly mean temperatures May to August	$\bar{x} = 2.49$ $s = 1.58$	$\bar{x} = 0.25$ $s = 0.16$
Precipitation (mm)			Average of monthly mean precipitation May to August	$\bar{x} = 25.97$ $s = 6.29$	$\bar{x} = 27.18$ $s = 8.39$

Note: All variables were calculated within a 10 km × 10 km cell using the source data resolution. When appropriate, sample mean (\bar{X}), and standard deviation (s) of variables in "occurrence" and an equal number of "pseudo-absence" cells were reported. For "Coastal", a binary variable, the percentage of cells classed as coastal was reported instead. For occurrences and pseudo-absences, $n = 550$.

^aOlthof et al. (2008).

^bHijmans et al. (2005).

^cValues have been back-transformed from the mean and standard deviation of the log base 10 to their original units.

standard deviation of elevation (Ruggedness²), and mean elevation (Elevation) from the Canadian Digital Elevation Model (Natural Resources Canada 2000). We calculated the percentage of productive land cover classes (Cover: graminoids, shrubs, and wetlands) out of all land classes, including water and ice, from the Northern Land Cover of Canada: Circa 2000 (Olthof et al. 2008). We calculated mean summer temperature (Temperature: May to August, which represents the entire breeding period) and precipitation (Precipitation: May to August) from Worldclim data (monthly averages from 1950 to 2000; Hijmans et al. 2005), and whether the cell was inland or coastal (Coastal: >15 km or ≤15 km from the centre of the cell to the nearest coast, respectively) by using CanVec political boundaries (Natural Resources Canada 2014). We used the cut-off of 15 km from the coast to ensure that the bounds of all inland cells were at least 10 km from the coast. We attempted to represent this variable as continuous, both as truncated after 15 km and as a decay variable, but the distribution of the values of the cells was approximately bimodal, so we maintained this

variable in its categorical form. We also applied two logarithmic transformations to Elevation and Ruggedness to reduce the influence of extremely high values on the model results (Supplementary Fig. S2¹). Ruggedness² was also included because topography was consistently important to nesting peregrines in previous studies and we wanted to test if peregrines responded nonlinearly to extremes in ruggedness in the study area. On north-west Baffin Island, for example, peregrines can nest in highly mountainous areas with extreme ruggedness. To aid in the comparison of coefficients and the interpretation of first and second order polynomials within the same model, we centred all variables on the mean and standardized by the standard deviation (Schielzeth 2010). Variables were tested pair-wise for collinearity with a Pearson's correlation coefficient and for multicollinearity with variance inflation factor (VIF; Zuur et al. 2010) using the R package Car (Fox and Weisberg 2011) in R version 3.1.2 (R Core Team 2016). Following Dormann et al. (2007), we removed variables with Pearson's correlation coefficients >0.70 or a VIF >10. The largest pairwise Pearson's correlation coefficient remaining in the analysis was 0.60 (between Cover and Temperature, see Supplementary Fig. S3¹ for all pair-wise correlations) and the highest VIF score was 2.44 for Temperature. Dormann et al. (2013) indicated that collinearity of this magnitude should prevent type II errors from occurring.

Data analysis

We estimated peregrine habitat selection using resource selection functions (RSFs; generalized linear models with a binomial family and logit link). Several candidate models were chosen to test our hypotheses, in which we combined variables representing climate, topography, prey, and proximity to the coast. Candidate models were a suite of variables representing climate (Temperature and Precipitation), topography (Ruggedness, Ruggedness², and Elevation), and prey availability (Cover), as well as one model with a variable combining a number of environmental effects: the proximity to the coast (Coastal). Given the geography of the Canadian Arctic, we anticipated that Elevation and Coastal likely explained a similar effect (proximity to large water bodies) and thus did not include these variables in the same model, which resulted in two competing saturated models. We used Akaike's Information Criterion (AIC) to select the model that best explained the data variability (Burnham and Anderson 2002), using a cut-off of $\Delta\text{AIC} = 2$ to reject competing models and selecting the model with the lowest AIC value.

To allow pseudo-independent model validation, we divided the occurrences/pseudo-absences 70:30, with equal numbers of occurrences and pseudo-absences in each subset (Boyce et al. 2002; Buisson et al. 2010). Model selection and calculation of coefficients used 70% of the data, and validation of the predictive performance of the model used the remaining 30%. In total, we calibrated and validated 1000 runs (i.e., 10 pseudo-absence random selection \times 100 split-sample procedure), and averaged the coefficients among all iterations to provide input for the calculation of peregrine nesting distribution (Araújo and Guisan 2006). This number of runs should be sufficient to accurately estimate the coefficients of the RSF (Barbet-Massin et al. 2012). For the model validation, we used the area under the curve (AUC) of the receiver-operating characteristic (ROC) plot (Fielding and Bell 1997) to measure the predictive capability of the selected candidate model on the remaining 30% of the data. We calculated the ROC plot using the true positive rate (the rate at which the model correctly classified cells) versus the false positive rate (the rate at which the model falsely classified cells; Swets 1988). Models with AUC values ranging from 0.7 to 0.9 are considered to have useful applications (Manel et al. 2002).

We used the standardized and centred variable coefficients of the best model to calculate the predicted peregrine distribution map. We resampled all original habitat variable layers to a 10 km \times 10 km resolution within the limits of the study area using the tool "aggregate"

Table 2. Competing resource selection functions predicting the relative probability of occurrence of nesting peregrine falcons (*Falco peregrinus*) in Nunavut, Canada.

Model	Parameters	AIC	ΔAIC	AIC weight
Saturated-Elev	Temperature + Elevation + Ruggedness + Ruggedness² + Precipitation + %Cover	1131.48	0.00	1.00
Topo Bio	Elevation + Ruggedness + Ruggedness ² + %Cover	1153.57	22.09	<0.001
Clim Topo	Temperature + Elevation + Ruggedness + Ruggedness ² + Precipitation	1195.82	64.35	<0.001
Saturated-Coast	Temperature + Ruggedness + Ruggedness ² + Precipitation + Coastal + %Cover	1205.55	74.08	<0.001
Topo	Elevation + Ruggedness + Ruggedness ²	1368.85	237.38	<0.001
Clim Bio	Temperature + Precipitation + %Cover	1376.58	245.10	<0.001
Bio	%Cover	1399.94	268.47	<0.001
Clim	Temperature + Precipitation	1404.14	272.67	<0.001
Coastal	Coastal	1499.44	367.97	<0.001
Null	1	1525.53	394.05	<0.001

Note: Models were calculated using all known occurrences and a random subset of pseudo-absences of equal number ($n = 550$). We ranked models by the lowest Akaike's Information Criterion (AIC), ΔAIC, and AIC weight. Models represent variables in competing hypotheses: "Clim" = climate variables, "Topo" = topographic variables, and "Bio" = proxy for prey availability. All variables except Coastal (which was binary) were centred on the mean and standardized by the standard deviation. For variable definitions, see Table 1.

in the Raster package (Hijmans 2017), which we then centred and standardized to match the habitat variables in the analysis. For the "coastal" layer, we classified cells as coastal (0, ≤ 15 km) or inland (1, > 15 km). The final map layer represented the coefficients and map layers transformed as log-odds following eq. (2.2) in Manly et al. (2004) using the Raster Calculator tool in ArcGIS [ESRI (Environmental Systems Resource Institute) 2013]. We calculated slope and the final prediction raster using ArcGIS, but all other calculations of data layers and analyses using R version 3.1.2 (R Core Team 2016) with the packages: sp, raster, rgeos, rgdal, and ROCR (Pebesma and Bivand 2005; Sing et al. 2005; Bivand and Rundel 2017; Bivand et al. 2017; Hijmans 2017; respectively).

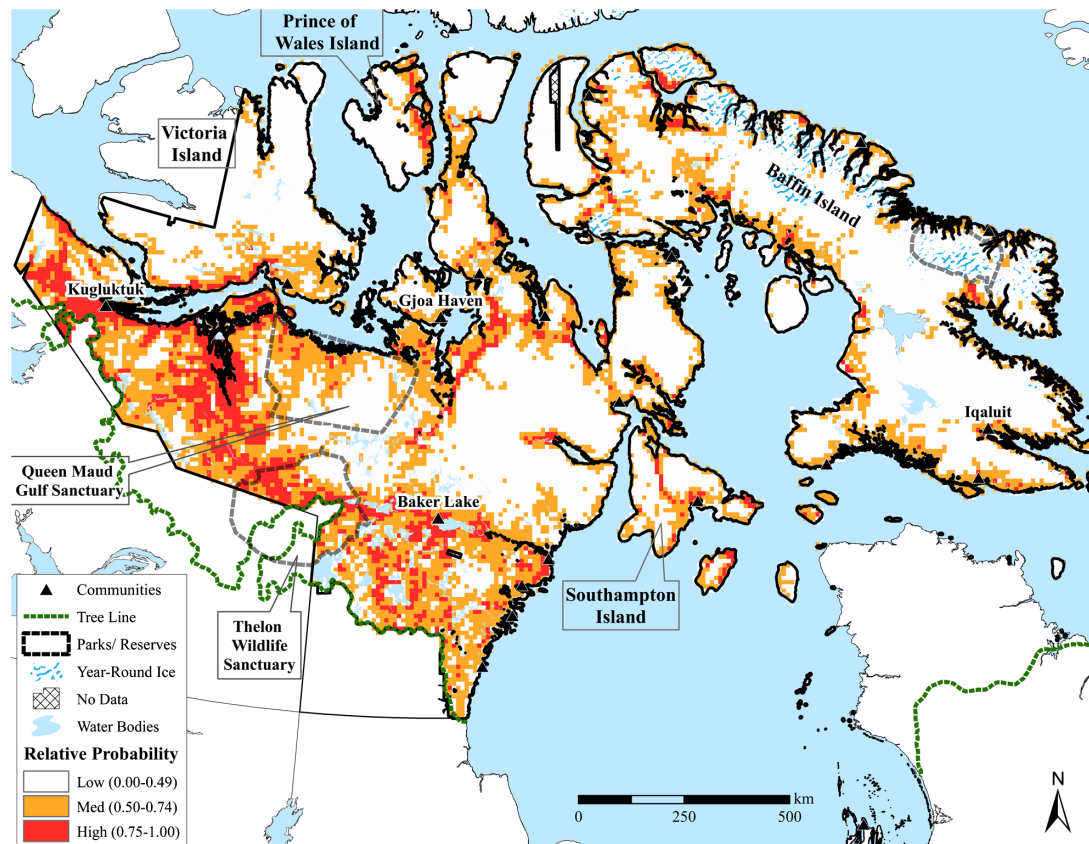
Results

The saturated-elevation model (average AUC = 0.81 \pm 0.02 SD; Supplementary Fig. S5¹) best explained the breeding occurrence of peregrine falcons in the eastern Canadian Arctic (Table 2). In this model, Ruggedness, Elevation, Temperature, and Cover had the greatest influence on the relative probability of occurrence of peregrine falcons (Supplementary Fig. S4¹). Peregrines were most likely to nest in areas with intermediate Ruggedness (standardized coefficient = 1.45 \pm 0.14 SE), low Elevation (standardized coefficient = -0.96 \pm 0.12 SE), greater Cover (standardized coefficient = 0.79 \pm 0.13 SE), and warmer summer Temperature (standardized coefficient = 0.65 \pm 0.14 SE). A negative effect of Ruggedness² (standardized coefficient = -0.26 \pm 0.08 SE) meant that peregrines avoided areas with extremely rugged or flat terrain, and resulted in a response at medium-high Ruggedness values (Supplementary Fig. S4¹). Areas with the highest ruggedness (e.g., the mountainous northeast coast of Baffin Island) did not have a higher relative probability of being occupied than medium-rugged areas (e.g., Bathurst Inlet in the Kitikmeot region). To a lesser degree, peregrines avoided breeding in areas with relatively high Precipitation (standardized coefficient = -0.20 \pm 0.11 SE).

Peregrine falcon distribution

Predicted peregrine relative nesting probability was highest in the southern and western regions of mainland Nunavut (Fig. 2). In particular, there was a band of high relative occurrence probabilities in inland Nunavut from the Thelon Wildlife Sanctuary to the village of

Fig. 2. Predicted relative probability of nesting occurrence of the peregrine falcon (*Falco peregrinus*) throughout the majority of Nunavut, Canada. Nesting probabilities were derived from the best model explaining peregrine nest habitat selection based on the lowest Akaike's Information Criterion (AIC) (Table 2). Year-round ice with an area $\geq 1 \text{ km}^2$ (stippled white), areas lacking environmental data (grey) and large water bodies $\geq 200 \text{ km}^2$ (blue) were excluded from the prediction area.



Kugluktuk in the northwest. In the southern region, relative nesting probability of peregrines was also high around lakes from the village of Baker Lake southward. Peregrines had an overall lower relative probability of occurrence in the northernmost regions of Nunavut, where predicted occurrence was mainly coastal.

Some areas that, to the best of our knowledge, were not previously surveyed in Nunavut were predicted to have a high relative probability of peregrine occurrence. These areas include south of the village of Gjoa Haven on the mainland, the east coast of Prince of Wales Island, and the south coast of Victoria Island. Areas with a low predicted occurrence included inland on the northwest mainland and inland Baffin Island. Overall, ca. 10% of the study area ($159\,327 \text{ km}^2$) had a relative probability of occurrence of nesting peregrine falcons greater than 75%, or what we classified as “high”. Some areas predicted by our model to have peregrine breeding populations matched up well with known nest locations while others did not (Fig. 1).

Discussion

By using nest data gathered from diverse sources and relating these data to remotely-sensed information, we estimated the relative probability of occurrence of a widespread

raptor breeding in the eastern Canadian Arctic. Our model predicted peregrine occurrence in similar areas as previous assessments based on expert knowledge and known nesting sites in Nunavut (Fyfe 1969; Campbell et al. 2012), but our predictions additionally included areas where nests are not yet known to occur. Some of the areas of high relative probability of peregrine occurrence exist in wildlife reserves, bird refuges, or parks (e.g., Thelon Wildlife Sanctuary and Queen Maud Gulf Bird Sanctuary), but many high relative probability areas are in the vicinity of active or potential mining activities (e.g., see Bigio et al. 2015).

Raptors have been proposed as a sentinel species in other ecosystems, signaling overall environmental changes due to their top-predator status (Sergio et al. 2006; Smits and Fernie 2013). Our study identified nesting habitat features that will remain stable as well as those likely to change within the next century due to predicted climate changes. Stable habitat features such as rugged terrain and low elevation were likely selected by peregrines because they provide a combination of nesting locations and access to productive environments. Selection for areas with medium to high terrain ruggedness at the regional scale is consistent with studies investigating peregrine nest site selection at the fine scale (Gainzarain et al. 2000; Wightman and Fuller 2005; Brambilla et al. 2006). Higher occurrence probabilities at low elevations could mean that peregrines prefer to nest in areas close to large bodies of water, where the elevation usually declines. Indeed, we found high probabilities of falcon occurrence around the lakes in the south-central part of Nunavut, as well as in coastal areas (Fig. 2). These areas may be attractive to peregrines for a number of reasons, from maintaining a favourable microclimate, potentially greater access to a varied and potentially abundant prey base such as bird colonies (Forbes 2011), microtopography to serve as hunting perches, or combination of these factors. In both the case of rugged topography and lower elevations, these features will likely maintain their importance even with changes in regional climate.

Unlike elevation and ruggedness, summer temperatures, precipitation and, to a lesser extent, land classes will be altered by climate changes in the future. Climate is one of the major drivers of species distributions at the continental scale (Pearson and Dawson 2003). We found that peregrines preferred to nest in areas with relatively high mean summer temperatures and, to a lesser degree, areas with relatively low mean summer precipitation. Our study area is at the northern limit of peregrine distribution, thus the selection for warmer temperatures is not surprising, but this is the first study to identify broad-scale precipitation patterns as important in peregrine nesting habitat. Both warmer temperatures and less precipitation during the nesting period have been linked to greater nest success in small-scale studies (Olsen and Olsen 1989; Anctil et al. 2014; Bruggeman et al. 2016), and our results suggest that they also prefer these conditions when selecting nesting habitat at a regional scale. The combined influence of temperature and precipitation on peregrine occurrence may be particularly important in the future monitoring of this species due to projected warming of the Arctic and predicted increase in variation in precipitation regimes (Larsen et al. 2014). Examining the relative importance of temperature and precipitation on the breeding of this top predator will be a key research topic for its future management and conservation.

With our analysis and distribution map, wildlife managers can compare the relative importance of different areas for strategic management of peregrines in Nunavut. Moreover, deviations in model predictions to genuine falcon occurrence in some areas could outline the importance of interspecific interactions at a regional scale. For instance, the presence of large goose colonies can negatively affect the availability of falcon prey species, such as shorebirds (Lamarre et al. 2017), and this could partly explain the relatively low occurrence of nesting falcons reported in some areas (e.g., Bylot Island; see Gauthier et al. 2013). As our study focused on the relative peregrine falcon occurrence at a regional scale, further investigations of habitat selection at finer scales would also be needed to fully

inform operational, small-scale management. Though we conducted this study with the best available environmental data in Nunavut, our analysis should also be re-visited as better environmental datasets become available in this remote northern area.

This study used a simple yet robust model to provide both a useful tool for the regional management of this species and an example of the utility of species distribution models for describing the relationship of species to their environments in the Arctic. It also highlights some important areas for future research efforts. For instance, we included the mean summer precipitation as a predictor of peregrine occurrence, but for this species climate extremes may be more important during the breeding period. In an experimental study at a site in southeast Nunavut, [Ancil et al. \(2014\)](#) found that the number of extreme rain events during the chick-rearing stage, rather than the mean precipitation, decreased nest productivity. [Robinson et al. \(2017\)](#) similarly found that more days of precipitation during the early brood-rearing period at another site in Nunavut was negatively related to nestling survival. Modeling climate extremes requires long-term, widespread weather station data ([Easterling et al. 2000](#)), something that needs improvement in most places in the Arctic.

Conclusion

This study demonstrates the utility of species distribution models for estimating species occurrence in a remote area with disparate survey information. With data sharing and project collaboration, many studies of local populations or occupancy could translate into regional scale distribution information. Together, single-species distributions could also potentially turn into overall biodiversity estimates or serve as tools for studying species interactions (e.g., [Hof et al. 2012](#)) throughout large and remote areas. To help move forward with the predictions of future distribution of Arctic top predators, better resolution of climate information and prey species current distribution would be needed. More studies like ours would help respond to calls for greater information on species biodiversity in the Arctic ([Ims et al. 2013](#)) and help define future research goals for both individual species biology and of overall Arctic ecosystems.

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