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ARTICLE

Low vulnerability of Arctic fox dens to climate change-related geohazards on Bylot Island, Nunavut, Canada

Florence Lapierre Poulin, Daniel Fortier, and Dominique Berteaux

Abstract: Climate change increases the risk of severe alterations to essential wildlife habitats. The Arctic fox (*Vulpes lagopus* (Linnaeus, 1758)) uses dens as shelters against cold temperatures and predators. These dens, needed for successful reproduction, are generally dug into the active layer on top of permafrost and reused across multiple generations. We assessed the vulnerability of Arctic fox dens to the increasing frequency of geohazards (thaw settlement, mass movements, and thermal erosion) that is arising from climate change. On Bylot Island (Nunavut, Canada) we developed, and calculated from field observations, a qualitative vulnerability index to geohazards for Arctic fox dens. Of the 106 dens studied, 14% were classified as highly vulnerable, whereas 17% and 69% had a moderate and low vulnerability, respectively. Vulnerability was not related to the probability of use for reproduction. Although climate change will likely impact Arctic fox reproductive dens, such impact is not a major threat to foxes of Bylot Island. Our research provides the first insights into the climate-related geohazards potentially affecting Arctic fox ecology in the next decades. The developed method is flexible and could be applied to other locations or other species that complete their life cycle in permafrost regions.

Key words: Vulpes lagopus, vulnerability, geohazards, climate change, permafrost.

Résumé : Les changements climatiques augmentent les risques d'altérations sévères des habitats fauniques. Le renard arctique (*Vulpes lagopus* (Linnaeus, 1758)) utilise des tanières comme refuges contre le froid et les prédateurs. Ces tanières, creusées dans la couche active au-dessus du pergélisol, sont essentielles pour l'élevage des jeunes et sont réutilisées d'une génération à l'autre. Nous avons évalué la vulnérabilité des tanières de renards arctiques à l'augmentation de la fréquence des aléas géomorphologiques (tassement au dégel, mouvements de masse, érosion thermique) qui est engendrée par les changements climatiques. À partir d'observations de terrain sur l'île Bylot (Nunavut, Canada), nous avons développé et calculé un indice de vulnérabilité qualitatif des tanières à ces aléas. Parmi les 106 tanières étudiées, 14% ont été classées comme très vulnérables et 17% et 69% ont été classées comme modérément et faiblement vulnérables, respectivement. La vulnérabilité n'était pas reliée à la probabilité d'utilisation pour la reproduction. Les changements climatiques affecteront donc probablement les tanières de renards arctiques, mais sans constituer un risque majeur pour l'espèce à l'île Bylot. Notre recherche donne un premier aperçu de l'impact des aléas

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F. Lapierre Poulin* and D. Berteaux.† Canada Research Chair on Northern Biodiversity and Centre for Northern Studies, Université du Québec à Rimouski, Rimouski, QC G5L 3A1, Canada.
D. Fortier. Department of Geography and Centre for Northern Studies, Université de Montréal, Montréal, QC G1V 0A6, Canada.
Corresponding author: Florence Lapierre Poulin (e-mail: florence.lapierre.poulin@hotmail.com).
*Present address: Parks Canada Nunavut Field Unit, Iqaluit, NU X0A 0H0, Canada.

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géomorphologiques reliés aux changements climatiques sur l'écologie du renard arctique dans les prochaines décennies. La méthode proposée est flexible et pourrait être appliquée à d'autres sites ou d'autres espèces accomplissant leur cycle vital dans des régions à pergélisol.

Mots-clés : *Vulpes lagopus*, vulnérabilité, aléas géomorphologiques, changements climatiques, pergélisol.

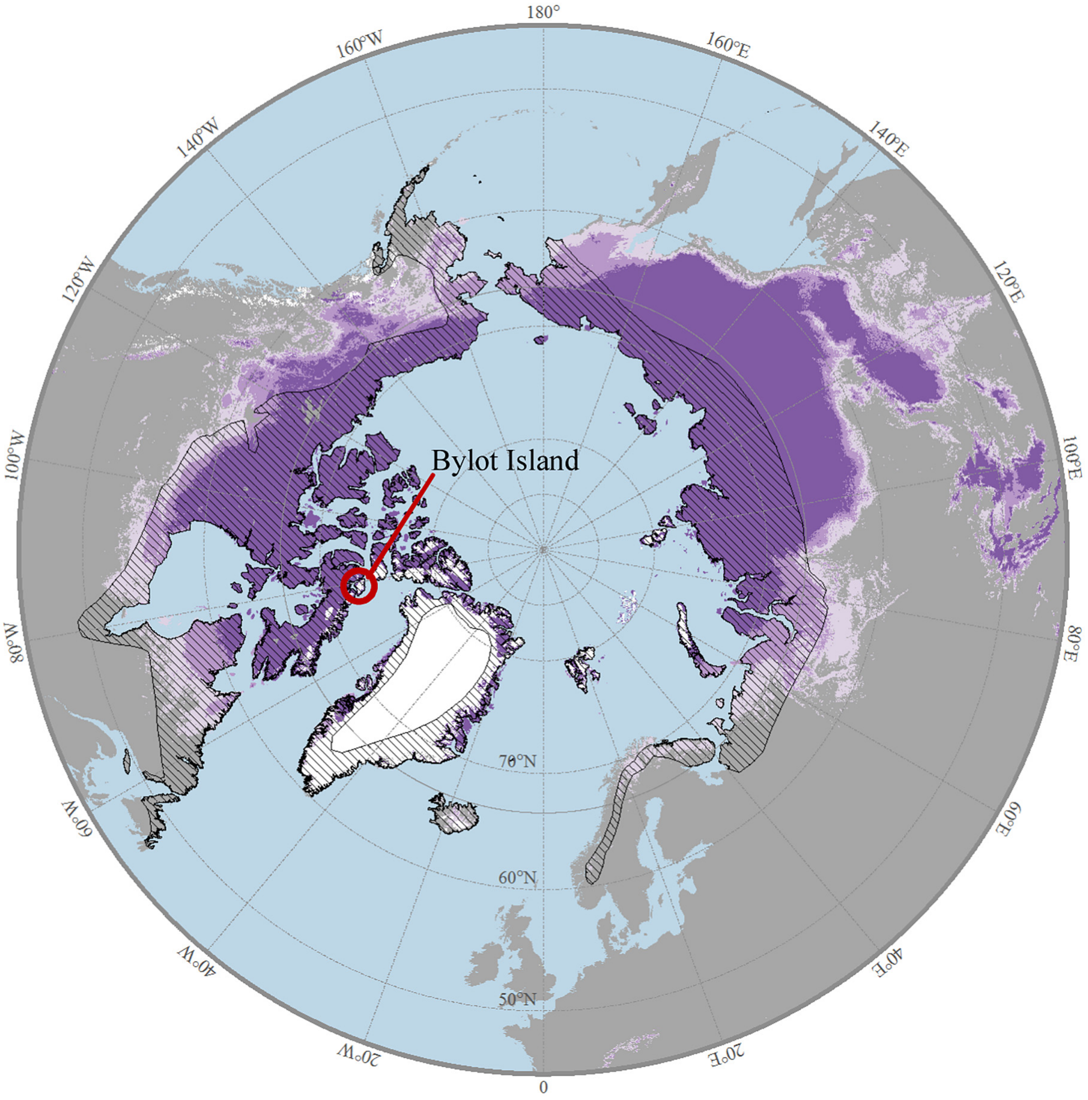
Introduction

Warming of the climate system is happening at an unprecedented rate and the ecological responses of a broad range of organisms are now visible (IPCC 2013). New threats to biodiversity have emerged (Secretariat of the Convention on Biological Diversity 2010), and although the direct effects of climate change on species have been extensively studied, there is still a need to investigate many indirect effects, including changes in food webs (Gilg et al. 2009), spreading of diseases (Parkinson and Butler 2005), novel interactions due to migration of competitive species (Elmhagen et al. 2017), and alterations of permanent structures used by animals (Beardsell et al. 2017; Berteaux et al. 2017*a*). This latter case is of particular concern in the Arctic, which experienced a warming twice as fast as the global average in the last decades (Bekryaev et al. 2010; AMAP 2017). The warming trend caused by the polar amplification is projected to continue, accompanied by increases in precipitation and storm frequency in some regions (ACIA 2005).

The Arctic fox (*Vulpes lagopus* (Linnaeus, 1758)) has a circumpolar distribution and was considered by the International Union for Conservation of Nature (IUCN) as one of ten flagship species representing the effects of climate change, because it can be impacted in multiple ways (Foden and Stuart 2009). Like most canids, the Arctic fox needs access to a den for a successful breeding (Tannerfeldt et al. 2003). Such dens consist of a network of tunnels measuring 15–20 cm in diameter and containing a few to >100 openings (Tannerfeldt et al. 2003). The persistence of dens is important in the life history of the species, which reuses the same dens year after year, sometimes over centuries (Macpherson 1969). Throughout most of its distribution, the Arctic fox lives in cold Arctic environments where permafrost is pervasive (French 2007) (Fig. 1). Permafrost stability directly depends on temperature and precipitation. It is now degrading due to climate warming, which increases the probability of geohazard occurrence (ACIA 2005; Arenson and Jakob 2015). More specifically, thaw settlement (subsidence of the ground due to thawing and subsequent draining of water), mass movements (downslope movements of masses of sediments or rocks on cliff and hillslope sections caused by gravity), and thermal erosion (combined thermal and mechanical action of running water on frozen ground) are related to permafrost degradation processes and are direct threats to the stability of physical structures established in the ground, such as dens.

Building from the long-term monitoring of >100 Arctic fox dens in the Canadian High Arctic, our first objective was to evaluate the vulnerability of Arctic fox dens to current and future climate change-related geohazards. Vulnerability can be defined as a function of exposure, sensitivity, and adaptive capacity (IPCC 2001). Due to the limited geographical scale of our study (600 km^2), all dens were considered similarly exposed to regional climate change. Sensitivity is the likelihood that a given climate change produces a recognizable landscape response (Brunsden and Thornes 1979; Brunsden 2001). This depends on local characteristics and geomorphology, and is highly heterogeneous across space, hence the potential source of considerable differences in vulnerability across dens. As for adaptive capacity, Arctic foxes can easily cope with slow changes in their den structure by compensatory digging; thus, we considered that slow action geohazards (e.g. solifluction and frost creeping causing slow downslope movements of only a few cm/year; Font et al. 2006) did

Fig. 1. Geographical distribution of continuous permafrost (dark purple), discontinuous permafrost (purple), sporadic permafrost (light purple), glaciers (white) and Arctic fox (hatched pattern). Map drawn using the packages OpenStreetMap (Fellows 2019) and rgdal (Bivand et al. 2020) in the R statistical environment (R Core Team 2020), and assembled from the following data sources: arctic coastline (Toolik – Arctic Geobotanical Atlas 2012); permafrost distribution (Obu et al. 2018); glacier distribution (Brown et al. 2002); Arctic fox distribution (IUCN 2014).



not contribute to vulnerability. On Bylot Island (Nunavut, Canada), Arctic foxes have a strong propensity to excavate their dens on elevated topographical features, steep slopes, rims of low-centered polygons, and river banks (Szor et al. 2008), which are more likely to be impacted by permafrost degradation. Therefore, we predicted that a majority of Arctic fox dens was vulnerable to climate change-related geohazards. It is important to note that our vulnerability assessment strongly differs from an impact study in that we did not run a temporal analysis seeking evidence that the frequency of the geomorphic processes has changed, with induced impacts on den stability. We rather refer throughout the paper to expectations regarding future changes. The primary benefit of a vulnerability assessment is to identify potential threats before they occur, so that mitigation or adaptation plans can be discussed ahead of time.

Only a small fraction of dens available to foxes are frequently used for reproduction (Prestrud 1992*a*; Anthony 1996). The selection of reproductive dens seems to be mainly driven by the distribution of food resources, but other variables, such as spring snow cover, ground temperature, thickness of the active layer, and slope orientation are also at play (Szor et al. 2008). As reproductive dens have a crucial importance for the maintenance of populations, our second objective was to determine if reproductive dens were more vulnerable to climate change and their associated geohazards than other dens.

Methods

Study site

We worked in Sirmilik National Park, specifically on the southern lowland of Bylot Island (73° N, 80° W), Nunavut, Canada (red circle on Fig. 1). The northernmost part of our study area lies within the Qarlikturvik Valley, where massive ice is widespread and forms extensive fields of ice-wedge polygons (Fortier and Allard 2004). This type of ground ice is extremely sensitive to disturbance, and climate change is already affecting ice-wedge polygons on Bylot Island and at the circumpolar scale (Jorgenson et al. 2006; Fortier et al. 2007; Godin et al. 2014; Liljedahl et al. 2016). Elsewhere on the southern coastal plain of Bylot Island, the permafrost is generally considered as ice-rich with ground ice located near the surface due to a thin active layer (30–50 cm, Fortier et al. 2006). The study area is crossed by several rivers and streams that can reach high water levels during the spring melt. Previous work assessing terrain characteristics of denning sites suggested that fox dens on Bylot Island are typically located on mounds or slopes, which favour drainage, and that almost half of them are found near water courses (Szor et al. 2008).

Den monitoring

About 40 Arctic fox dens were discovered opportunistically between 1993 and 2002 on Bylot Island. In 2003, an extensive den survey was performed by foot and snowmobile to locate most dens ($n = 83$) in the study area (Szor et al. 2008). In 2007, the study area increased from 425 km^2 to 600 km^2 and more dens were found in the subsequent years for a total of 106 dens in 2015. Each year, from May until August, we visited all dens at least twice to assess their reproductive status and install motion-triggered infrared automatic cameras (Silent Image PM35C31, RapidFire Professional PC85, and HyperFire PC800; Reconyx, Holmen, Wisconsin, USA) that can further confirm our observations. Because den switching is common among canids (Tannerfeldt et al. 2003) and was observed many times in our population, both natal dens (where pup emergence was seen from cameras) and rearing dens (where first observation of cubs was done late in the breeding season) were considered as reproductive dens. They both play an essential role during the breeding season. Oblique aerial photographs of each den were taken from a helicopter (height of 10–100 m above the ground) during the summers 2014 and 2015 to describe the local geomorphology, and dens were also visited on foot to characterize their surficial deposit type.

Vulnerability assessment

We conducted a vulnerability assessment to evaluate the vulnerability of Arctic fox dens to three specific climate change-related geohazards: thaw settlement, rapid mass movements (e.g., active layer detachment slides, thaw slumps, and debris flows), and permafrost thermal erosion. These three processes were selected because of their moderate to fast rate of action. In fact, mass movements and thermal erosion are permafrost disturbance processes occurring rapidly, with important geomorphological changes that would significantly damage fox dens. Thaw settlement of ice-rich permafrost is slower but due to ground ice thawing, the accumulation of water over the permafrost table can inundate the floor of dens and make them unusable. These hazards were also considered relevant because they have been repeatedly found on Bylot Island over the last decade (Fortier et al. 2007; Godin and Fortier 2012; Godin et al. 2014, 2016; Beardsell et al. 2017; Bouchard et al. 2020). Among the different approaches to climate change vulnerability assessment (Tonmoy et al. 2014), we used the widely recognized indicator-based vulnerability assessment (IBVA), a method in which indicators are used as proxy measures of processes generating vulnerability (Tonmoy and El-Zein 2013). The choice of indicators can be based on empirical research, theory, or expert judgment (El-Zein and Tonmoy 2015). IBVAs are widely used because such qualitative assessments are flexible, easy to apply, and robust as they can combine indicators of different nature (Tonmoy et al. 2014). Furthermore, they are particularly suitable when working at local or regional scales (Hinkel 2011). We followed the steps suggested by Kappes et al. (2012), who have adapted to a multi-hazard context the vulnerability assessment in coastal areas proposed by Papathoma and Dominey-Howes (2003).

Selection of indicators

Following an extensive literature review, four indicators were initially identified as potentially having the greatest influence on the sensitivity of Arctic fox dens to climate change, namely drainage conditions around dens, ground ice content, slope gradient, and erosion. These indicators are closely linked to the three climate change-related geohazards of interest and they can be rather easily estimated, both in the field and from aerial photographs. Note that vulnerability indicators refer to a possible future harm that may or may not happen, as opposed to harm indicators that refer to a current state (Hinkel 2011; Tonmoy et al. 2014). We describe below our treatment of each indicator.

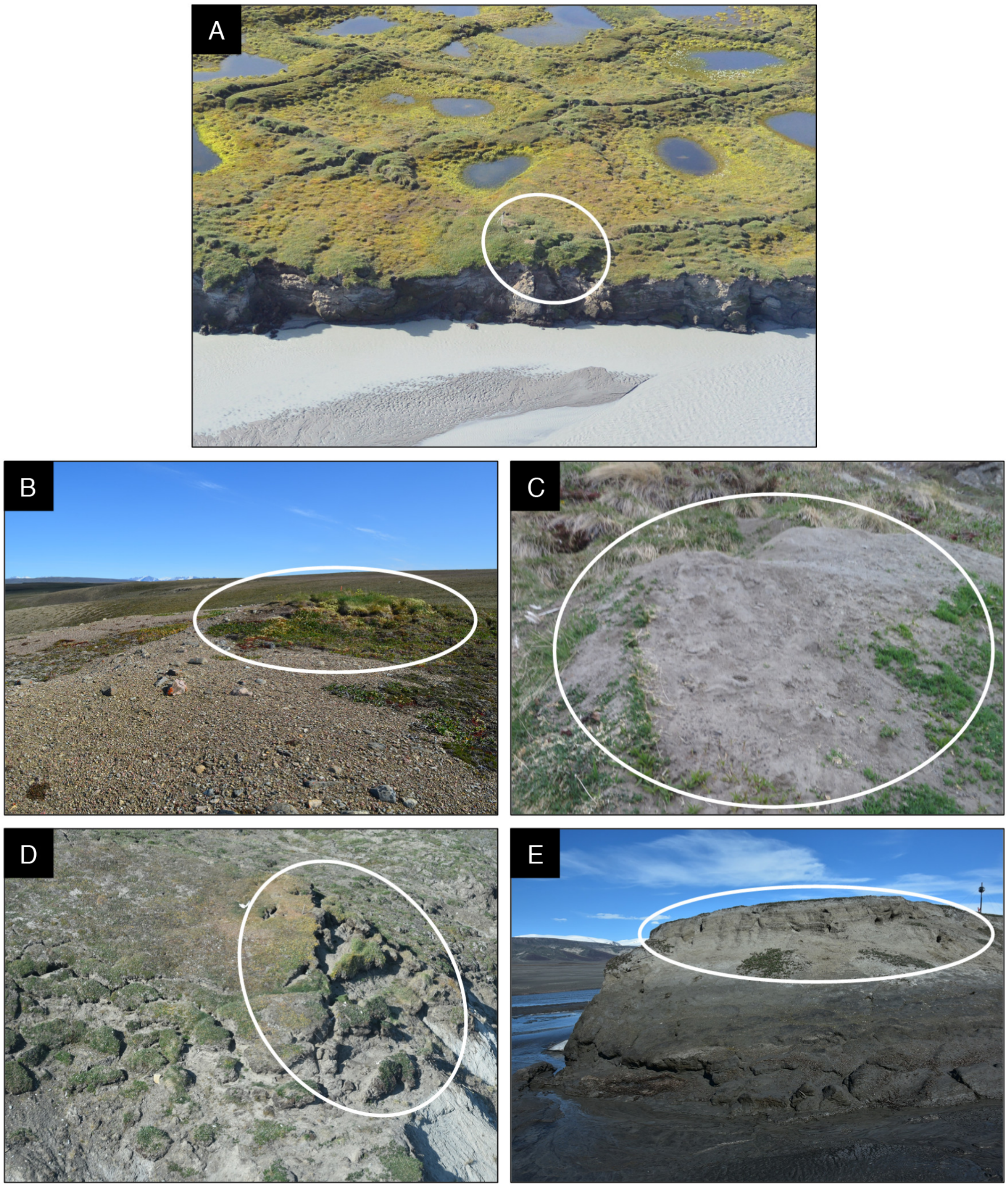
Drainage conditions

An essential indicator of thaw settlement and mass movement sensitivity in the Arctic is the drainage condition of the local terrain. Poorly-drained soils having a high water content favor frost heaving/thaw settlement on gentle sloping terrains and are conducive to high pore water pressure on slopes upon thawing, which is a prerequisite to rapid mass movements (Matsuoka 2001; French 2007). However, it was demonstrated on Bylot Island (Szor et al. 2008) and elsewhere (Macpherson 1969; Smits et al. 1988; Prestrud 1992*b*; Nielsen et al. 1994) that Arctic foxes establish their dens in dry habitats such as sandy mounds and well-drained slopes, therefore, we excluded drainage from our analysis.

Ground ice content

Thaw settlement, mass movements, and thermal erosion are all highly dependent on ground ice content (Nelson et al. 2002; Jorgenson et al. 2006; Pullman et al. 2007; Smith 2010; Dupeyrat et al. 2011; AMAP 2017). Whereas ground ice content is best determined through coring or inferred using geophysical techniques such as ground probing radar and electrical resistivity, these approaches were both too invasive and too logistically constraining to be used. In addition, most wildlife biologists do not have the expertise to implement these techniques. Instead, we evaluated the occurrence of excess ice close to the surface by identifying the presence of massive ice in the form of ice-wedge polygon networks that are easily recognizable on aerial photographs (Fortier et al. 2016) (Fig. 2A). However, the absence of such landforms does not necessarily mean that other forms of excess ice, such as segregated ice, are not present within the sediment. We thus also characterized in hand samples the predominant grain size fraction of the surficial deposit of each

Fig. 2. Examples of the indicators evaluated on each den: presence of ice-wedge polygons (A), surficial deposit as a proxy of ground ice content; (B), coarse sand and gravel, (C), fine sand and silt), presence of tension cracks (D), and presence of thermal erosion (E). Den burrow entrances are concentrated within the white ellipses. A den usually consists of many burrows, but only a few of them are visible on each picture. In (C), some burrow entrances are hidden by the top of sand piles. Photo Credit: Florence Lapierre Poulin.



den using three categories (coarse sand and gravel, sand and till, fine sand and silt), assuming that grain size was consistent within the top meter of permafrost. Grain size was used as an indirect indicator of ground ice as coarse deposits, such as sand and gravel (Fig. 2B), are ice-poor, whereas fine deposits, such as fine sand and silt (Fig. 2C), tend to be ice-rich

(Kaplar 1974; Andersland and Ladanyi 2004; Grandmont et al. 2012*b*). To validate our visual estimates, 20 surficial deposit samples of approximately 400 g were collected on randomly selected dens, and analyzed in the lab with the dry sieving granulometry method (Head 2006).

Slope gradient

Mass movements are often triggered by natural events such as heavy rainfalls or earthquakes (ACIA 2005), but they chiefly depend on the geomorphological characteristics of the terrain. As they are driven by gravity, mass movements occur preferentially on steep slopes. Tension cracks resulting from a first mass movement event are starting points for further mass wasting (Huscroft et al. 2004; Slaymaker et al. 2009; Gao et al. 2015), because they shorten the length of the slip surface. This reduces resistance to failure, and increases pore water pressure by generating water infiltration, which lowers strength properties (Baker 1981; Lewkowicz and Harris 2005; Lewkowicz 2007). As the threshold slope angle beyond which mass movements occur is highly variable among deposit types and may be difficult to assess, we instead used the presence of tension cracks (Fig. 2D) and recent landslide scars within 25 m of the den, evaluated through oblique aerial photographs, as proxies of slope instability.

Erosion

Water levels in streams and rivers are projected to rise in the Arctic due to an increasing release of water from melting glaciers and snowmelt (ACIA 2005). Furthermore, much of the Arctic coastline is ice-rich, making it sensitive to global warming (AMAP 2011; Forbes 2011). Mass movements and thermal erosion are thus more likely to increase close to shorelines, stream and rivers banks, where failures already happen frequently due to erosion of the toe of the slope (Dyke 2000). We used the presence of coastal or fluvial erosion (Fig. 2E) as our last indicator in the vulnerability assessment.

Normalization and weighting of indicators

To minimize uncertainties and errors originating from the observer's judgment when assigning values to qualitative variables (Grandmont et al. 2012*a*), we allowed only two or three value levels for each indicator (Fig. 3). We then used an aggregation method to represent the differential importance of the indicators for each geohazard and combine them into a single vulnerability index (Tonmoy et al. 2014). To determine the weight of each indicator in relation to each geohazard, we compared indicators pairwise and used our judgment (mostly the expert judgement of D. Fortier who has studied Bylot geomorphology since the late 1990s) of their perceived relative importance on a 1–9 scale (1 = equally important, 5 = strongly more important, 9 = extremely more important), thus producing a single set of weights (Supplementary Table S1[1]). This method is called the analytical hierarchy process (AHP), and is one of the most used methods to obtain criteria weights (Saaty and Vargas 1991). The normalized principal eigenvector of the matrix gives the relative importance of the indicator measured on a ratio scale (Supplementary Table S1[1]). Figure 3 shows the weights of indicators towards thaw settlement, mass movements, and thermal erosion, as well as the scores associated with value levels of indicators. After multiplying each score by its weight and adding up the result for each indicator, we obtained a relative vulnerability index (RVI) for each geohazard for each den, as follows:

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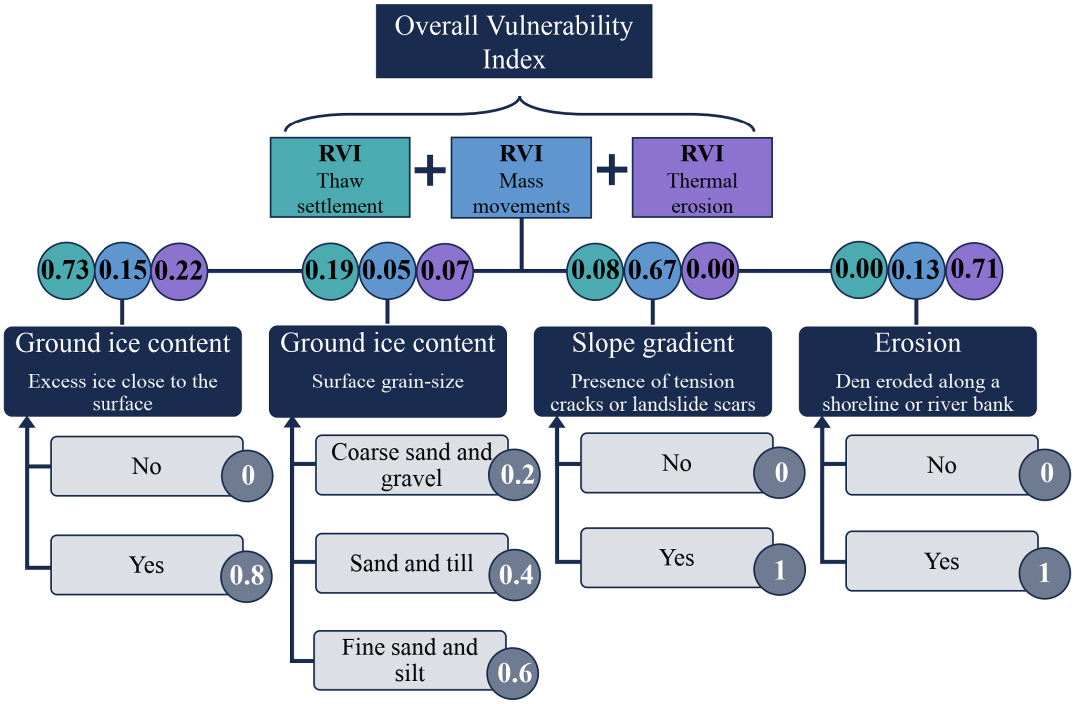
[1] Supplementary material is available with the article at https://doi.org/10.1139/as-2019-0007.

Fig. 3. Vulnerability computation framework for Arctic fox dens facing climate change-related geohazards on Bylot Island, Nunavut. An overall vulnerability index (OVI) is calculated by adding the relative vulnerability index (RVI) associated with each of three geohazards, namely thaw settlement (green), mass movements (blue), and thermal erosion (purple). Each RVI is calculated from three to four indicators reflecting ground ice content, slope gradient, and erosion. Weights (0 = no importance, 1 = very high importance) attributed to the various indicators for each geohazard appear in the coloured circles, whereas scores (0 = no relevance to vulnerability, 1 = high relevance to vulnerability) attributed to the various levels of each indicator appear in the grey circles. Adapted from Kappes et al. (2012).



$$(1)\quad RVI = \sum_{1}^{i} W_i \times I_i S_j$$

where W_i are the weights for the different indicators (I_i), and S_j is the score associated with the indicator's value level.

Finally, we calculated an overall vulnerability index (OVI) for each den by adding up the RVIs calculated for the three geohazards. We divided the output results in three categories of vulnerability: low (OVI < 0.5), moderate ($0.5 \leq \text{OVI} \leq 1.5$), and high (OVI > 1.5).

Data analysis

We used a generalized linear mixed-effects model with a binomial distribution (presence or absence of reproduction at the den) to analyze the probability of den use for reproduction in relation to the vulnerability index. We used reproduction data from 1993 to 2019, merging together natal and rearing dens as explained above. Year was included as a random effect to control for variation in reproductive success between years due to cyclic food resources. Den identity was also included as a random effect as the same dens were monitored over several years. The parameters were estimated using the "lme4" package with the Laplace approximation (Bates et al. 2015) in the R Statistical Environment (R Core Team 2020).

Results

We characterized 106 dens for which we obtained 1640 pictures in total (Supplementary Table S2[1]). Dens excavated in ground that contained evident excess ice were rare ($n = 9$), and almost exclusively limited to the Qarlikturvik Valley located in the northern part of the study area (only F152 was located south of this valley). The surficial deposits were mainly categorized as coarse ($n = 44$) and medium ($n = 39$), although fine deposits were also found in 23 dens, of which 48% were also situated in the Qarlikturvik Valley. We observed tension cracks or landslide scars on 20 dens, as well as thermal erosion on 19 dens, with no distribution bias across the study area.

The OVI ranged from 0.060 to 1.907. Of the 106 studied dens, 73 (69%) were in the "low vulnerability" category, whereas 18 (17%) and 15 (14%) were in the "moderate vulnerability" and "high vulnerability" categories, respectively. The large OVI values of highly vulnerable dens mostly arose from a high RVI to thermal erosion ($n = 4$) or a combination of high RVI to thermal erosion and mass movements ($n = 11$). Highly vulnerable dens tended to be mostly found close to the coast and in the Qarlikturvik Valley (Fig. 4). This spatial clumping to the distribution of erosion intensity was associated with the coastline and with the important proglacial river in the center of the Qarlikturvik valley. Also, the surrounding plateaus and rolling hills (up to 500 m above sea level) have steep slopes, hence the importance of the RVI to mass movements in the OVI.

Reproduction in a given year was assessed 1757 times for the 106 dens monitored between 1993 and 2019 in the study area. There was no significant effect of our OVI on the probability of den use for reproduction ($\beta = -0.06$, 95% CI = −0.58 −0.46, $n = 1757$; Fig. 5).

Discussion

Contrary to our predictions, most dens in the study area (69%) showed a low vulnerability to climate change-related geohazards. This could be partly explained by the fact that despite selecting mounds, steep slopes, and streamside cutbanks to excavate their dens, Arctic foxes also prefer sandy substrates, which are better drained and less likely to contain excess ice than finer deposits. Furthermore, dens located close to streams or on slopes were often found on fluvial terraces, which partially protect them against erosion and mass movements. Still, 14% of the dens were found to be highly vulnerable, and this would have been of concern if these dens were those selected for reproduction. Such was not the case, however, and thus we conclude that climate change-related geohazards are not a major threat over the next decades for the Bylot Island population of Arctic foxes.

It is important to note that there are at least twice as many dens as there are Arctic fox breeding pairs in our study area. Indeed, 52 out of the 106 (49%) known dens were used for reproduction during the most intensive reproductive year, but that number usually varies between 2 and 30 (Juhasz et al. 2020). In addition, Macpherson (1969) found in the Northwest Territories that 15% of Arctic fox dens had collapsed burrows and were abandoned. Yet these partially destroyed dens were later brought back into use after the den site had stabilized, suggesting that Arctic foxes are resilient to structural modifications of their dens. Taken together, the presence of supernumerary dens and the apparent resilience of foxes to den collapse reinforce our conclusion that climate change-related geohazards do not currently threaten the Bylot Island Arctic fox population. Moreover, it is not excluded that despite potential threats to Arctic fox dens, climate change could also create new suitable habitats for the species. For example, a thicker active layer in ice-poor grounds could provide more sites allowing digging, which could help to overcome losses due to geohazards.

Fig. 4. Distribution of Arctic fox dens ($n = 106$) on the south lowland of Bylot Island, Nunavut, Canada. Colors of dots show the vulnerability of dens to climate change-induced geohazards (green = low vulnerability, yellow = moderate vulnerability, red = high vulnerability). Map drawn using the package rgdal (Bivand et al. 2020) in the R statistical environment (R Core Team 2020), and assembled from the following data sources available under the Open Government Licence – Canada: coastline, elevation, and hydrographic features (Natural Resources Canada 2020); Sirmilik National Park's boundaries (Parks Canada 2018).

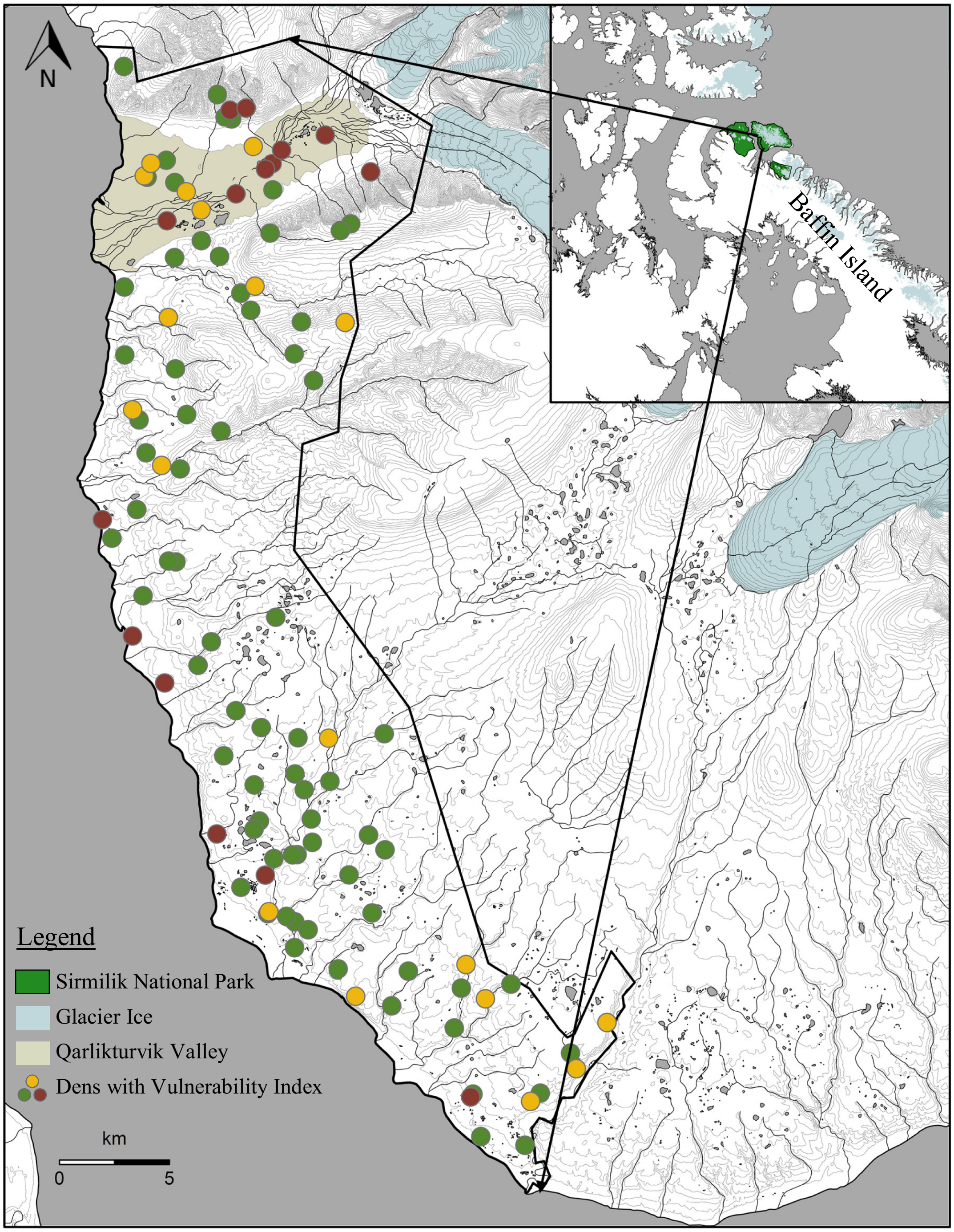
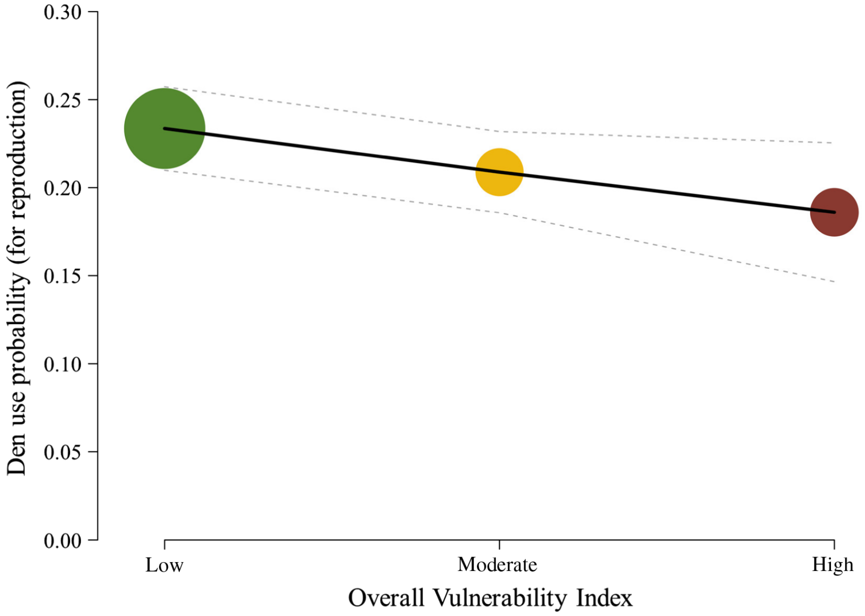


Fig. 5. Probability of den use for reproduction in relation to the overall vulnerability index (β = −0.06, 95% CI = −0.58 −0.46, *n* = 1757). Dashed lines are the 95% confidence interval. Each disk represents the proportion of used dens grouped by the same vulnerability index (disk size is proportional to the number of observations: green = 1167, yellow = 291, red = 299).



We have proposed a qualitative indicator-based method to assess the physical vulnerability of Arctic fox dens to climate change-related geohazards. Climate change vulnerability assessments are often applied to socio-ecological systems (Tonmoy et al. 2014), although they can also be used to assess vulnerability in natural ecosystems, including vulnerability of species to climate change (Williams et al. 2008). To our knowledge, our study represents the first attempt to evaluate the vulnerability of animal den structures to permafrost degradation in a context of climate change. Our proposed method has many benefits. First, it considers characteristics of the dens themselves as well as their surroundings (Kappes et al. 2012). In general, vulnerability mapping is computed for a rather large scale (e.g. regional or national scale), and is thus assumed to be uniform within an exposed area (Tonmoy et al. 2014). However, vulnerability depends on a series of parameters of the element at risk (here the den) that should be considered at a local scale (Kienberger et al. 2013). Second, the method is very flexible and can easily be applied to different systems and species by adapting our proposed steps, namely identification of relevant hazards, selection of indicators, and normalization and weighting of indicators. Third, the method allows input of qualitative data (generated here from aerial photos and field surveys) to calculate a vulnerability index. Qualitative approaches are simple and may further be very useful as a first screening tool for analyses at larger spatial scales, or to rank the elements at risk when implementing a conservation plan (Gallina et al. 2016).

Despite its benefits, our proposed approach still contains uncertainties and could be improved in a number of ways. First, we normalized the indicators using a linear scoring (Steele et al. 2009), yet non-linear relationships may at times be more appropriate. For example, the scores associated with the different sizes of surficial deposits (0.2, 0.4, 0.6), which were based on expert appraisal, could have been different (e.g., 0.2, 0.3, 0.8) if the link between grain size and its associated hazards is not linear. A better documentation of the correlation between surficial deposits and their below ground ice content and frost susceptibility would allow us to set more accurate scores. Second, the weighting of indicators, determined by the analytical hierarchy process (AHP), was based on the expertise of a single geomorphologist (D. Fortier). This process entails some subjectivity, but it does lead to accurate results in many environmental decision-making studies (Saaty 2008; Steele et al. 2009). Saaty (1980) gives psychometric reasons for using the 1–9 scale in pairwise comparisons and suggests that the AHP process is the best way to minimize the impact of inconsistencies when assigning weights to indicators. However, having a panel of experts coming to an agreement when conducting pairwise comparisons of indicators may have minimized subjectivity related to weight attribution. Third, we considered hazards as being independent and equally harmful for dens, which explains why the OVI was an addition of the RVIs. Better knowledge of how these hazards interact together to affect Arctic fox dens could possibly lead to multiplicative instead of additive effects between hazards (Kappes et al. 2012). Finally, the determination of thresholds for classifying the dens in three categories was based on the frequency distribution of the OVI, from which three classes emerged (Supplementary Fig S1[1]). It would have been better to determine these classes after associating OVI scores to the measured degradation of dens following climate change (the verification step of the approach), but this will only be possible after a significant amount of climate change has occurred. Nonetheless, our categories still remain reliable in terms of ranking dens according to their vulnerability to climate change-induced geohazards.

Conclusion

Although climate change has the potential to adversely affect Arctic foxes in a number of ways (e.g. through a loss in the seasonal sea ice acting as a foraging platform; Berteaux et al. 2017*a*), we showed that climate change-related geohazards are not a major threat for the Bylot Island population. Our approach is based on visual indicators, but potential threats that have not yet become apparent are not excluded (e.g., the presence of anti-syngenetic ice wedges, see Mackay 1990, 1995) and should be investigated to have a more comprehensive understanding of the environment in which Arctic foxes evolve. It would be important to replicate similar assessments in other parts of the species range, as the Arctic fox is a focal model species to study Arctic animal ecology, and many other populations are studied across the circumpolar world (Berteaux et al. 2017*b*). Interestingly, these other populations are distributed along several gradients of environmental conditions, thus providing ideal conditions for testing how the vulnerability of dens to climate change-related geohazards vary across space in a polar species.

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