Predicting how climate change will affect terrestrial mammals' movement and habitat selection

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1 Abstract

2 To do

3 Introduction

Animals' energetic costs depend strongly on ambient temperature (Brown et al. 2004). Cold temperatures increase the metabolic costs of movement (Taylor, Heglund, and Maloiy 1982) and homeothermy (Melin et al. 2023), which can constrain an animal's ability to move (Schwerdt, De Villalobos, and Ferretti 2024), its fitness (Walker et al. 2019), and, ultimately, its odds of survival (Berger et al. 2018). Hot temperatures tend to lower energetic needs (Taylor, Heglund, and Maloiy 1982), but they also cause animals to overheat, which lowers their ability to move (Powers et al. 2017; Alston et al. 2020; Dyer et al. 2023).

Mammals reduce the adverse effects of extreme temperatures through both physiological and behavioral adaptations (Jessen 2001; Mota-Rojas et al. 2021), but their ability to respond through physiological adaptations is limited by their evolutionary history, since their optimal temperature and range of tolerable temperatures (Fig. 1) depend on the environment they live in (Levins 1974). In contrast, changes in movement rates and space use allow mammals to respond to stressors immediately (Alston et al. 2020, 2020; Dyer et al. 2023; Attias et al. 2018; Giroux et al. 2023; Verzuh et al. 2023).

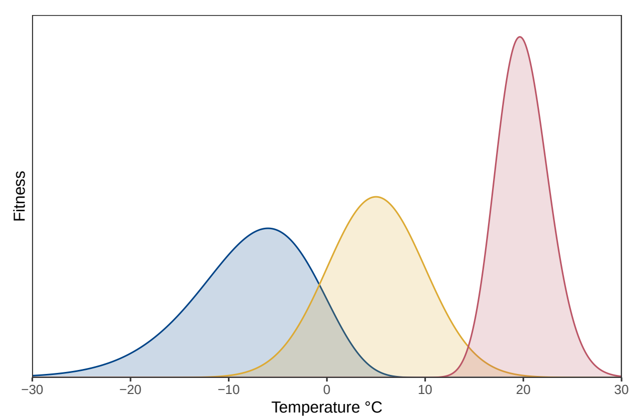

Figure 1: Hypothetical ranges in fitness as a consequence of ambient temperature for a cold-adapted mammal (blue), temperate-adapted mammal (yellow), and hot-adapted mammal (red). Contrast the differences in fitness gains at different temperatures, as well as differences in the height and spead of the three curves.

During the last century, changes in climate in British Columbia (BC), Canada, have resulted in widespread warming, milder and shorter winters, hotter and longer summers, and a greater risk of extremely high temperatures (Eberle, Higuera Roa, and Sparkes 2022).

These changes are expected continue over the next 100 years and compound their effects on mammals' fitness, movement behavior, and habitat selection as they cope with growing heat stress and human pressure (Deb, Forbes, and MacLean 2020; Woo-Durand et al. 2020; Weststrate et al. 2024).

This paper provides a BC-focused analysis on the effects of proximate weather and long-term climate on the movement of terrestrial mammal species. Using over two decades of telemetry data and proximal hourly weather data, we estimate how animals altered their movement frequency, movement speed, and habitat selection in response to air temperature. We then pair these responses with climate change projections to forecast changes mammals movement in the current century under different climate change scenarios (Riahi et al. 2017). The analyses include data from six species (*Canis lupus*, *Cervus elaphus*, *Oreamnos americanus*, *Puma concolor*, boreal and southern mountain *Rangifer tarandus*, and *Ursus arctos horribilis*; see Table 1) across a large spatial range of British Columbia (Fig. 2). We discuss the consequences of changes in mammalian movement in relationship to energetics, food encounter rates, and the incidences of human-wildlife.

Table 1: Start and end of the GPS telemetries along with the median sampling interval for each of the six species included in this study.

Dataset	Start	End	Median sampling interval (hours)
Canis lupus (boreal)	2013-01-27	2017-08-29	0.25
Elk in southwestern Alberta	2007-01-13	2013-11-20	2.00
Oreamnos americanus	2019-06-25	2023-10-05	6.24
Puma concolor	2006-02-05	2021-07-13	2.00
Rangifer tarandus (boreal)	2011-03-02	2018-01-04	12.99
Rangifer tarandus (southern mountain)	1998-03-21	2009-06-07	5.98
Ursus arctos horribilis	2004-09-30	2009-09-07	1.00

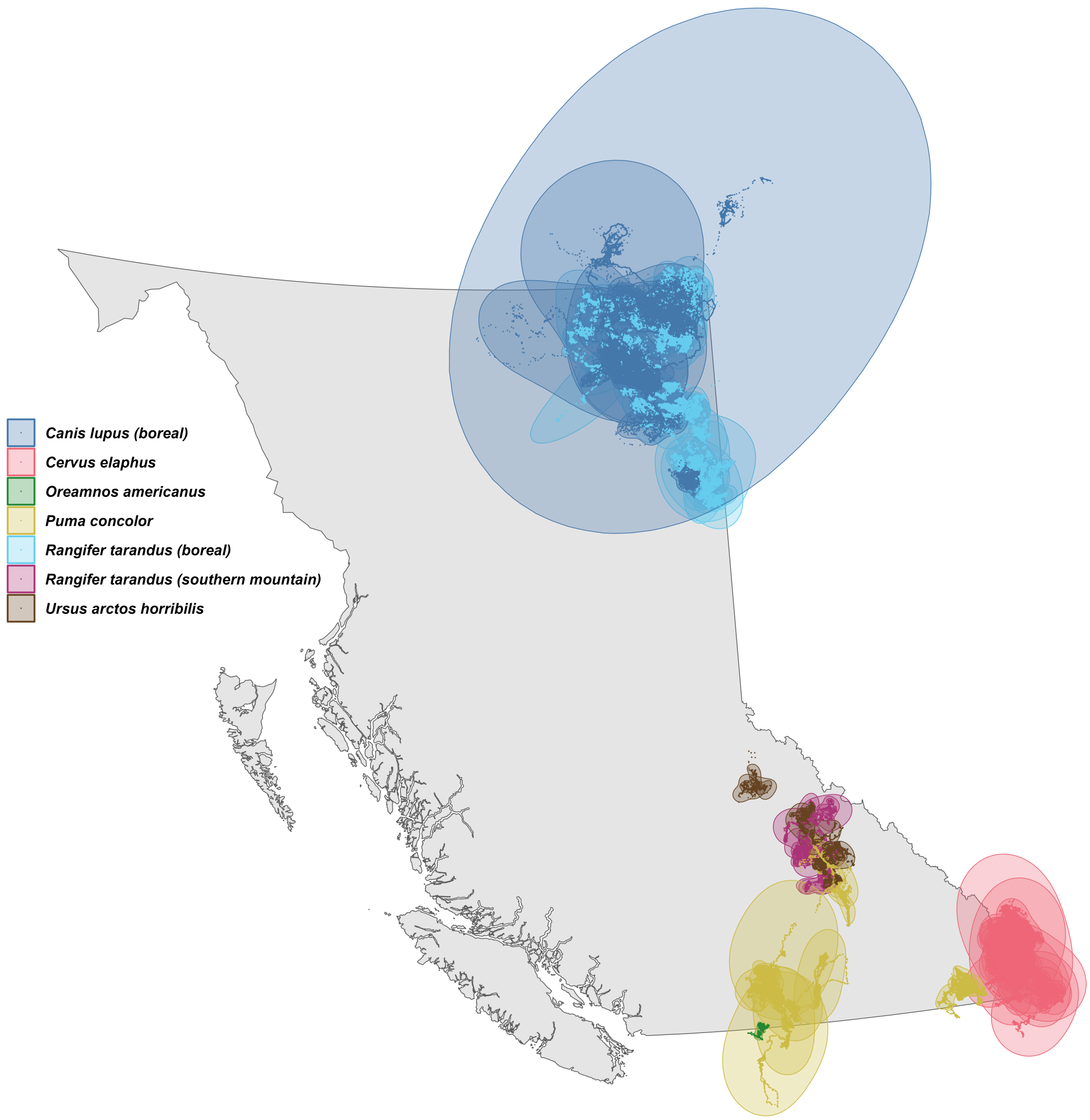

Figure 2: GPS telemetry data and autocorrelated kernel density utilization distributions for the six species included in this study.

4 Methods

4.1 GPS telemetry data

Elk (*Cervus elaphus*) data from Ciuti et al. (2012) were downloaded from Movebank (study name: Elk in southwestern Alberta, see Kays et al. 2022), while boreal caribou (*Rangifer tarandus*) and wolf (*Canis lupus*) telemetries were acquired via a public BC Oil and Gas Research and Innovation Society repository (https://www.bcogris.ca/projects/boreal-caribou-telemetry-data/), and the mountain goat (*Oreamnos americanus*) locations were provided by BC Parks. All other tracking data were obtained from private collaborators. Outlier GPS locations were removed following diagnostic analyses of the distance from the median location as well as straight-line displacement, turning angle, and time interval between consecutive points. Particular attention was paid to points with large turning angles ($\gtrapprox 170°$) and high straight-line displacement, especially if antecedent and subsequent points indicated stationary behavior. The script used to clean the data and all custom functions used are available on GitHub (https://github.com/QuantitativeEcologyLab/bc-mammals-temperature).

4.2 Historical temperature data

Rasters of hourly reanalyzed air temperature data were downloaded from the ERA5 dataset (Hersbach et al. 2023) from the European Center for Medium-range Weather Forecasting server (ECMWF; www.ecmwf.int; https://cds.climate.copernicus.eu). Proximal weather conditions were estimated for each location by extracting the values from the corresponding raster cell from the temporally nearest raster using the `extract()` function from the `terra` package (version 1.7-46, Hijmans 2023) for `R` (R Core Team 2024).

4.3 Estimating mammals' instantaneous speeds

We estimated modeled each animal's movement using continuous-time movement models (Chris H. Fleming et al. 2014) via the `ctmm` package (version 1.2.0, Christen H. Fleming and Calabrese 2023) for `R`. We then estimated mammals' instantaneouus speeds by applying the `ctmm::speeds()` function on all models with finite speed estimates (416 of 433, see Chris H. Fleming et al. 2014; Noonan et al. 2019). All 17 telemetries with insufficiently fine sampling were for caribou (15 boreal and 2 southern mountain). Since `ctmm`'s movement models assume stochastic but non-zero speeds (i.e., a single, stochastic moving state), speeds were set to zero if they were not significantly different from zero ($\alpha = 0.05$), under the assumption of a χ-distributed speeds. ***NOT SURE IF THIS IS CORRECT*** The function used is available on GitHub (https://github.com/QuantitativeEcologyLab/bc-mammals-temperature/blob/main/functions/detrend_speeds.R). To avoid artifacts due to excessively small, non-zero speeds, we determined whether an animal was moving or not by applying the `stats::kmeans()` function with 2 centers (Appendix A).

4.4 Estimating the effects of temperature on mammals' movement

We estimated the effects of temperature on mammals' state (moving or not) and speed (given that it was moving) using two Hierarchical Generalized Additive Models (HGAMs, see Pedersen et al. 2019) via the `mgcv` package for `R` (version 1.9-1, Wood 2017). The first HGAM had a binomial family of distribution and estimated the probability of a mammal moving as a function of time of day, day of year, and temperature, with separate smooths (but common smoothness parameter) for each species (model S in Figure 4 of Pedersen et al. 2019). In addition, the model also included a random effect for each animal, a tensor interaction product of time of day and day of year to account for changes in day length, and a tensor interaction product of time of day and temperature to account for changes in daily activity levels with temperature, for each species. Due to the substantial latitudinal separation between boreal and southern mountain caribou, we considered the two gropus as separate species for the sake of modeling. The model accounted for the cyclicity of time of day and day of year using cyclic cubic splines, which provide continuity in the smooth term by ensuring the function and its slope (first derivative) and curvature (second derivative) are continuous between consecutive cycles. The second HGAM had the same structure, but it used a Gamma family of distributions to estimate the speed of an animal, given that it was moving. Together, the two HGAMs inform us on an animal's long-term speed (i.e., distance traveled per unit time), since it is the product of probability that the animal is moving and its average speed when moving. Additional details are provided in Appendix A.

We estimated the effects of temperature on each species' selection for percent forest cover, elevation, and distance from fresh water using an HGAM with a Poisson family of distributions (Appendix B, also see Aarts et al. 2008; Alston et al. 2022). While we recognize there are other important drivers of habitat selection, we decided to only use these three proxies to ensure results were relatively comparable between species and to make province-wide predictions simpler.

4.5 Predicting changes in animal movement during the current century

HERE

Rasters of projected monthly average temperature in BC during the next 80 years were obtained via the `climatenaR` package (version 1.0, Burnett 2023) for `R`. Since the climate projections did not provide a measure of variation in temperature within each month due to weather, we estimated within-month variance by fitting a Generalized Additive Model with a Gamma family of distributions to the square-root precision ($\sqrt{\rho}$) in temperature for each month using the ERA5 data for BC during 1998-2024. The model included… (Appendix C).

model currently uses weights = sqrt(n); fitting a new one with uniform weights

5 Results

5.0.1 Effects of temperature on mammals' movement

5.0.2 Effects of temperature on mammals' habitat selection

should predict for the area the animals are in only

6 Discussion

6.0.1 Effects of temperature on mammals' movement

6.0.2 Effects of temperature on mammals' habitat selection

- energetics
- encounter rates (lower encounter rates with food (Hou et al. 2020))
- HWI

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