Appendix C: Temperature data

NARR ground temperatures

Current temperature profiles were based on modelled data from the North American Regional Reanalysis (NARR) dataset, downloaded from *https://psl.noaa.gov/data/gridded/data.narr.html* (accessed April 16, 2020). The variables are broken down into three groups: *pressure* (i.e., in the air column above ground), *mono-level* (for particular near-ground elevations), and *sub-surface* (below ground, specifically 0 cm, 10 cm, 40 cm, 100 cm, and 800 cm depth). We used the daily means for soil temperature from at 0 cm depth, which was the most relevant depth and measurement interval for the scale of our study. There were considerable differences between air and soil temperatures, which highlighted the importance of using soil temperatures for parasite larvae that are on the ground (Figure C1).

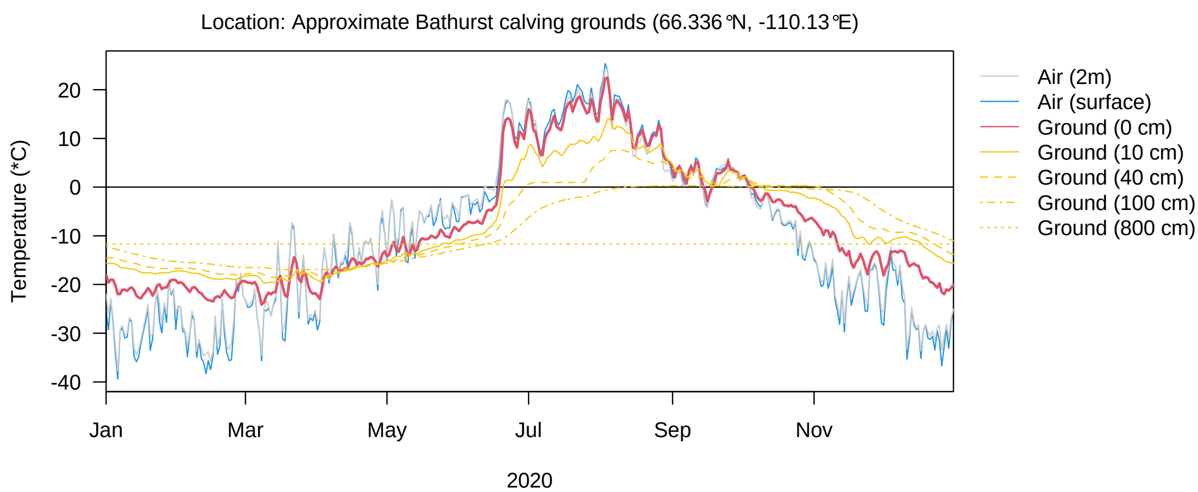


Figure C1. Summary of the daily temperatures for 2020 at different depths extracted from the NARR dataset for the grid cell corresponding to the Bathurst calving grounds.

We downloaded daily means from 2000 – 2020, and then smoothed these at each location to get an average annual temperature profile (see step (5) of the algorithm described below). The NARR data are provided on a spatial grid (*Lambert Conformal Format*). The total grid resolution of the NARR dataset is 349 x 277, which is approximately 0.3 degrees (32 km) resolution at the lowest latitude. We simulated hypothetical migration paths of Bathurst caribou in order to extract the ground temperatures for the relevant spatial points (see below).

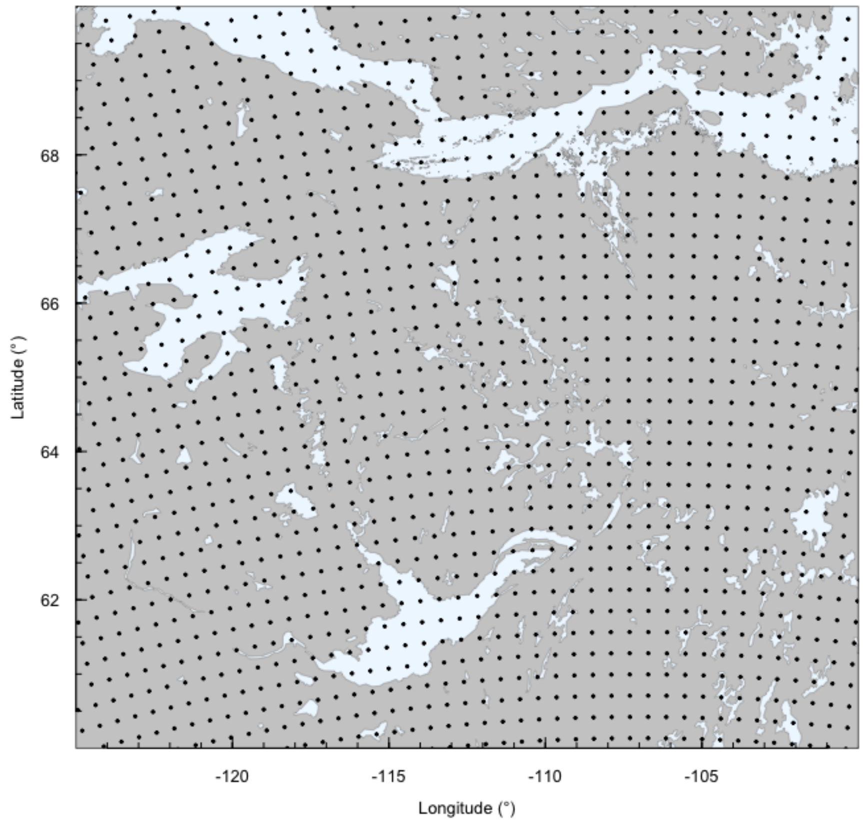


Figure C2. The spatial grid points of NARR data overlapping the Bathurst caribou range.

Climate change projections

Climate-change scenarios were based on spatially gridded projections of air temperature anomalies from the CMIP5 multi-model ensemble (Amman et al. 2018). As ground temperature projections were not available, we used the mean monthly air temperature anomalies for the period of 2080–99 compared to the model's reference period of 1986–2005 for a low emissions scenario (Representative Concentration Pathway (RCP) 2.6) and high emissions scenario (RCP 8.5). The spatial grid for the climate change projections was coarser than the spatial grid for the NARR data (see Figure 2 in the main text). As for the NARR data, the points in space that we used were based on the simulated migration path of Bathurst caribou; this process is described below.

Defining a migration path

Current annual temperature profiles and climate-change projections vary depending on geographic location. To ensure that the temperatures we applied in our simulations were representative of those experienced by *Ostertagia* larvae within Bathurst caribou range, we had to define the spatial migration routes of caribou. There is considerable interannual variability in these exact migration routes (Gunn et al. 2001; The Bathurst Caribou Range Plan 2018), but fairly high fidelity to calving grounds and a consistent move southward for overwintering. The spatial extent of winter, spring, calving, summer, and fall ranges has been defined by Russell et al. (2013) for the purpose of summarizing climatic variables across these different ranges. The shapefiles for these ranges were shared with us (Don Russell, *personal communication*) to facilitate the analysis of additional climatic variables, specifically ground temperatures and climate-change projections.

Rather than averaging variables across the different ranges, we generated migration paths that connected randomly selected points within each range. This approach avoided discontinuous jumps in temperature through space that would result when stitching together the different ranges, and also avoided having to decide which temperatures to apply in areas with multiple, overlapping ranges.

Steps to define migration path and extract temperature data

(1) **Randomly select a stopover point in winter, calving, summer, and fall ranges.** We excluded the spring migration range, which is very large – basically encompassing all the other ranges – and which is used by caribou just to move through, without much stopping. Randomly choosing a stopover point within the spring range often led to unrealistically tortuous spring migration routes.

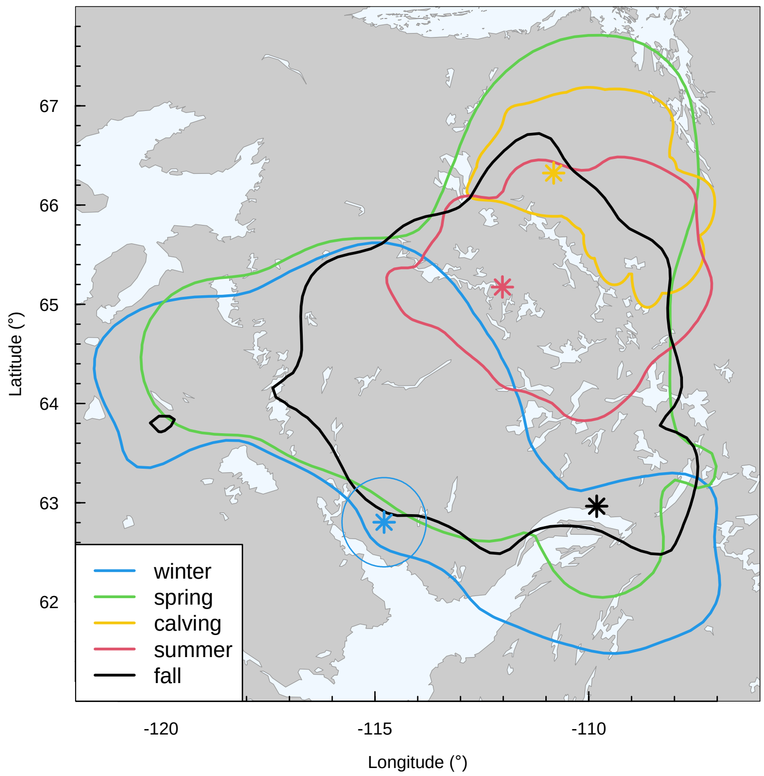


Figure C3. A map of the Bathurst caribou range, with different coloured polygons showing the seasonal ranges for Bathurst caribou as provided by D. Russell (Russell et al. 2013). Asterisks are the randomly chosen stopover points within each range. The grey points are the centroids of the NARR ground temperature grid.

(2) Starting with the winter range, choose a migration route between stopover points as follows:

a. Highlight NARR grid points within 50 km radius of current location (see blue circle in Figure C3 for an example). 50 km was chosen as a likely maximum for the distance travelled in a day.

b. Calculate distance d_i between each grid point i within that radius and the next stopover (e.g., the distance to the yellow asterisk = calving stopover in the above map). The vector of all these distances is **d**.

c. Select a point within the 50 km radius from the origin point to "move to", where the probability of selecting point i is weighted by a logistic form: $w_i = \frac{1}{1+\exp(3\,\hat{d}_i)}$, where $\hat{d}_i$ is the normalized distance: $\hat{d}_i = \left(d_i - \mathrm{mean}(\boldsymbol{d})\right)/\mathrm{sd}(\boldsymbol{d})$. The parameters in this logistic function were tuned to simulated migration paths that reflected observed movement of collared caribou, but were not fitted to any particular dataset. With this functional form, the probability of selecting a point declines with increasing distance to the next stopover point and directional selection is greatest (steepest slope in Figure C4) when animals are ~500 km from their next stopover (Figure C4).

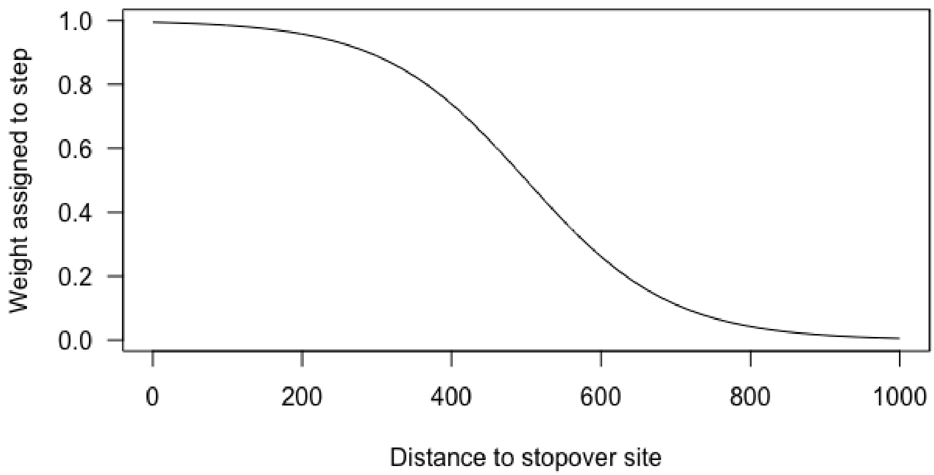


Figure C4. The weight assigned to steps based on their respective distances between the step and the desired final destination (i.e., stopover site).

d. Move to that next point.
e. Repeat a-d until the next stopover is reached.
f. Repeat a-e until back at the original winter stopover.

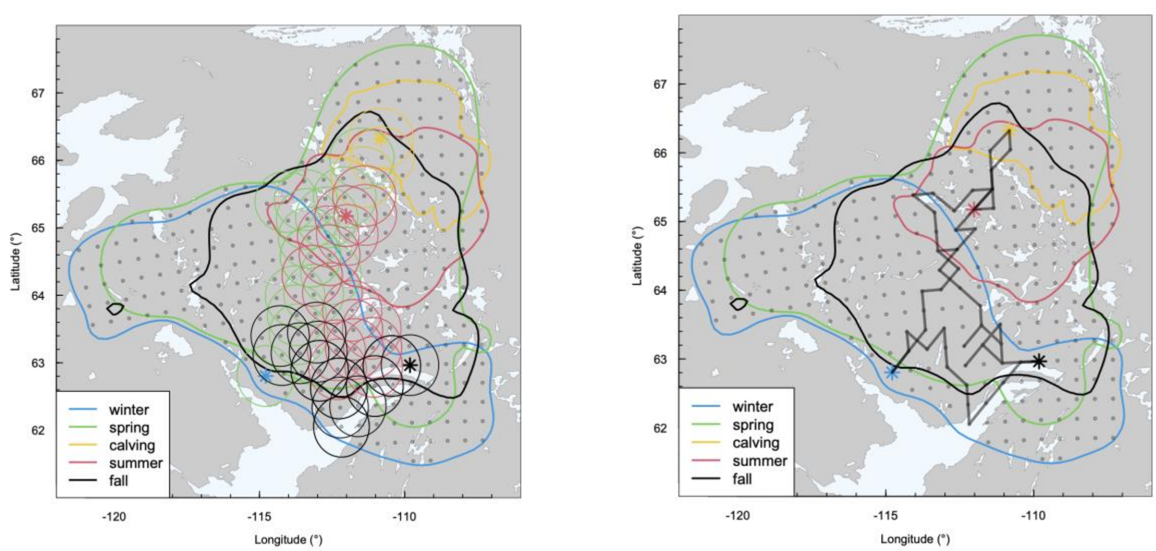
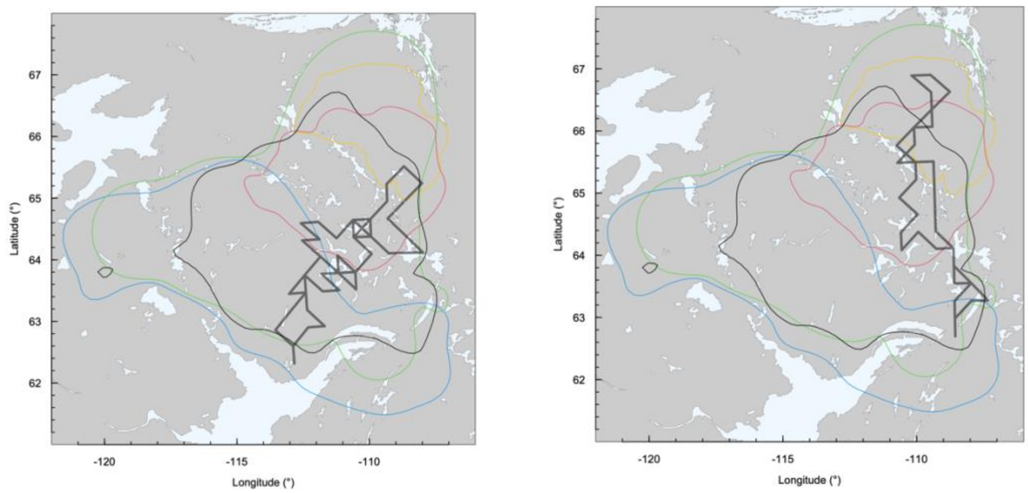
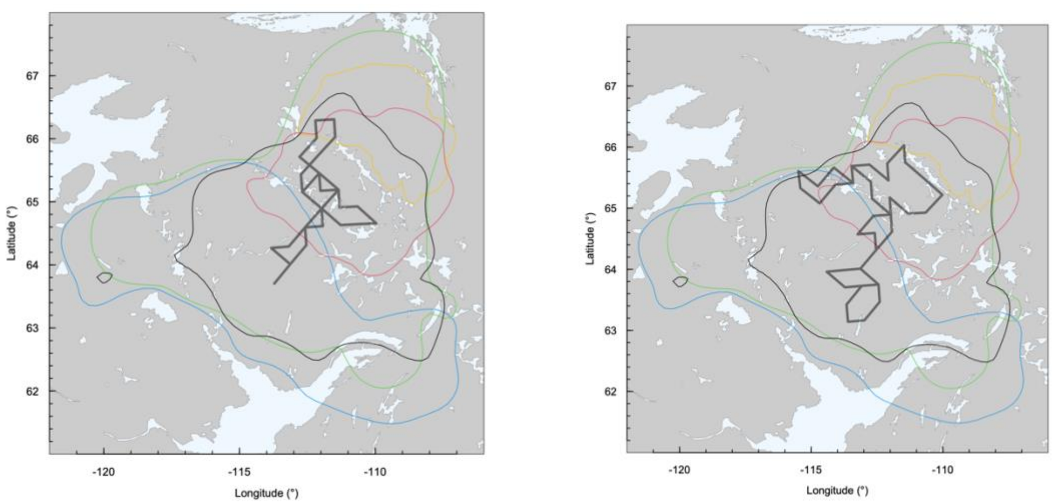


Figure C5. An example of the selected points along a migration route (left) and the resulting migration path (right).

(3) Repeat 1-2, 100 times to yield 100 different migration paths (4 shown below).





(4) For each migration path, expand the selected points to yield 1135 locations along the route (simulations have a 2 km grid spacing, so the 1135 points equal the 2270 km long migration route). The number of points selected between stopovers emerges from the algorithm described above and is not pre-determined or constrained. We therefore replicate points to make up the necessary number of kilometres between each location. For example, there might only be 20 grid points selected between winter and calving range in a given simulation, but those 20 grid points need to translate to a ~600 km migration in the model (the total annual migration is 2270 km, but we are considering just a portion in this example). In the model simulations, we assumed a spatial domain in increments of 2 km, meaning that the 600 km migration happens over 300 spatial steps. Given that we have selected only 20 grid points using our algorithm, we replicate

each of those 300/20 times = 15 times along our spatial domain. This accounts for the fact that caribou don't migrate "as the crow flies", and the distance travelled between one grid point and another is not necessarily equal to the spherical ("great earth") distance between the two.

(5) For each of the 1135 points in the spatial domain, extract and smooth the annual ground temperature profile from the NARR data, yielding a 365 x 1135 matrix of temperatures for each day of year (DOY) and location for each migration route. The smoothing over time was done to average over the 21 years (2000 – 2020) of NARR ground temperature data that were downloaded to yield an average temperature profile.

(6) For each of the 1135 locations/grid points, extract and smooth the projected climate change anomaly under low (RCP 2.6) and high (RCP 8.5) emissions scenarios. Here, the smoothing is done because the projections are on a monthly time scale, so there are discontinuous jumps from month to month (see below) that would lead to problems (sharp jumps) in the numerical simulation of the PDEs. For both the projected temperature anomalies and the NARR data, the difference between any two points in space was relatively small so there was no need to smooth along the spatial migration route.

Sensitivity of temperature profiles to selected migration path

We simulated the above algorithm repeatedly to assess the sensitivity of our temperature profiles to the specific migration route we used. Although there were some differences depending on the route, these were small in comparison to the seasonal and spatial differences in temperature that were common across all the different migration routes. We therefore show results in the main paper for a single migration route only, as the outcomes and conclusions were not affected by the particular migration route.

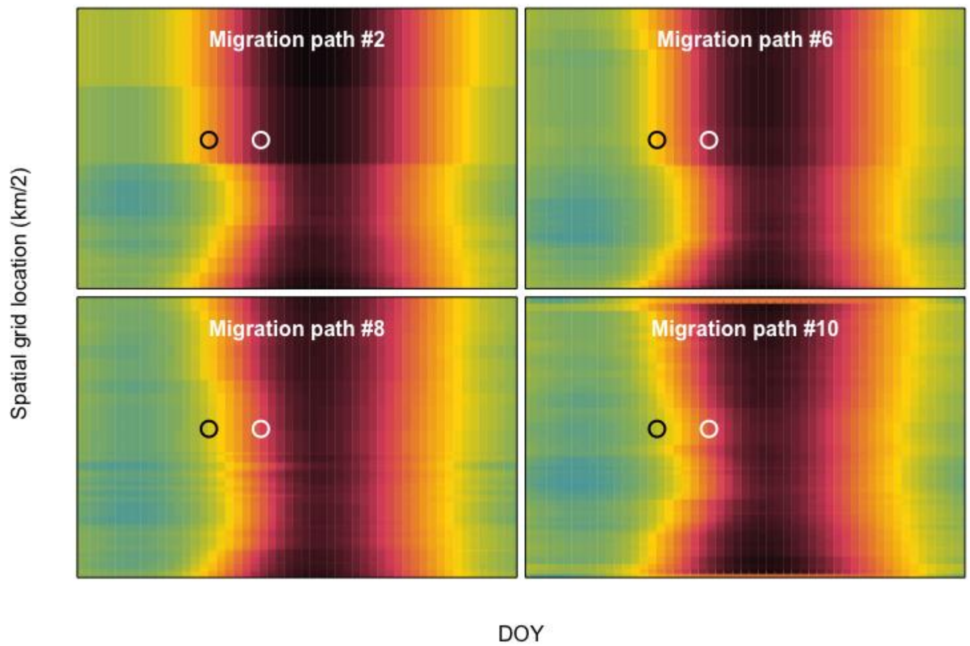


Figure C6. The spatiotemporal temperature grids constructed from four independent simulations of a migration path as described above. Red colours are warmer temperatures and blue colours are cooler temperatures. The day of year (DOY) is along the x-axis from 1 (far left) to 365 (far right) and the distance along the migration route is along the y-axis from 0 km (bottom) to 2270 km (top), starting and ending at the overwintering grounds. While there are some differences in temperature depending on the migration route (e.g., see the black point that is DOY = 110 at the calving grounds), the main patterns are the same and the important windows in space and time (e.g., white point at DOY 153 at the calving grounds, when hosts are present) are the same.

References

Amman, C., Boehnert, J., and Wilhelmi, O. 2018. World Climate Data CMIP5 Multi Model Ensemble.

Gunn, A., Dragon, J., and Boulanger, J. 2001. Seasonal movements of satellite-collared caribou from the Bathurst herd. Final Rep. to West Kitikmeot Slave Study Soc. Yellowknife, NWT **80**.

Russell, D.E., Whitfield, P.H., Cai, J., Gunn, A., White, R.G., and Poole, K. 2013. CARMA's MERRA-based caribou range climate database. Rangifer **33**(2): 145. doi:10.7557/2.33.2.2535.

The Bathurst Caribou Range Plan. 2018. Supporting Report: Caribou Range Assessment and Technical Information. Yellowknife, NT. Available from https://www.enr.gov.nt.ca/sites/enr/files/resources/draft_-_caribou_range_assessment_and_technical_information.pdf.