Supplementary Materials

Article title: **Winter tick burdens for moose are positively associated with warmer summers and higher predation rates.**

Sarah R. Hoy[1]*, Leah M. Vucetich[1], Rolf O. Peterson[1] & John A. Vucetich[1]

[1] *College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, MI 49931, USA*

Correspondence: sarah.r.hoy@gmail.com

Keywords: climate warming, consumer-resource relationships, ectoparasite, host-parasite, predator-prey, summer temperatures, trophic interactions, predation, wolves

S1 – Assessments of hair loss for moose

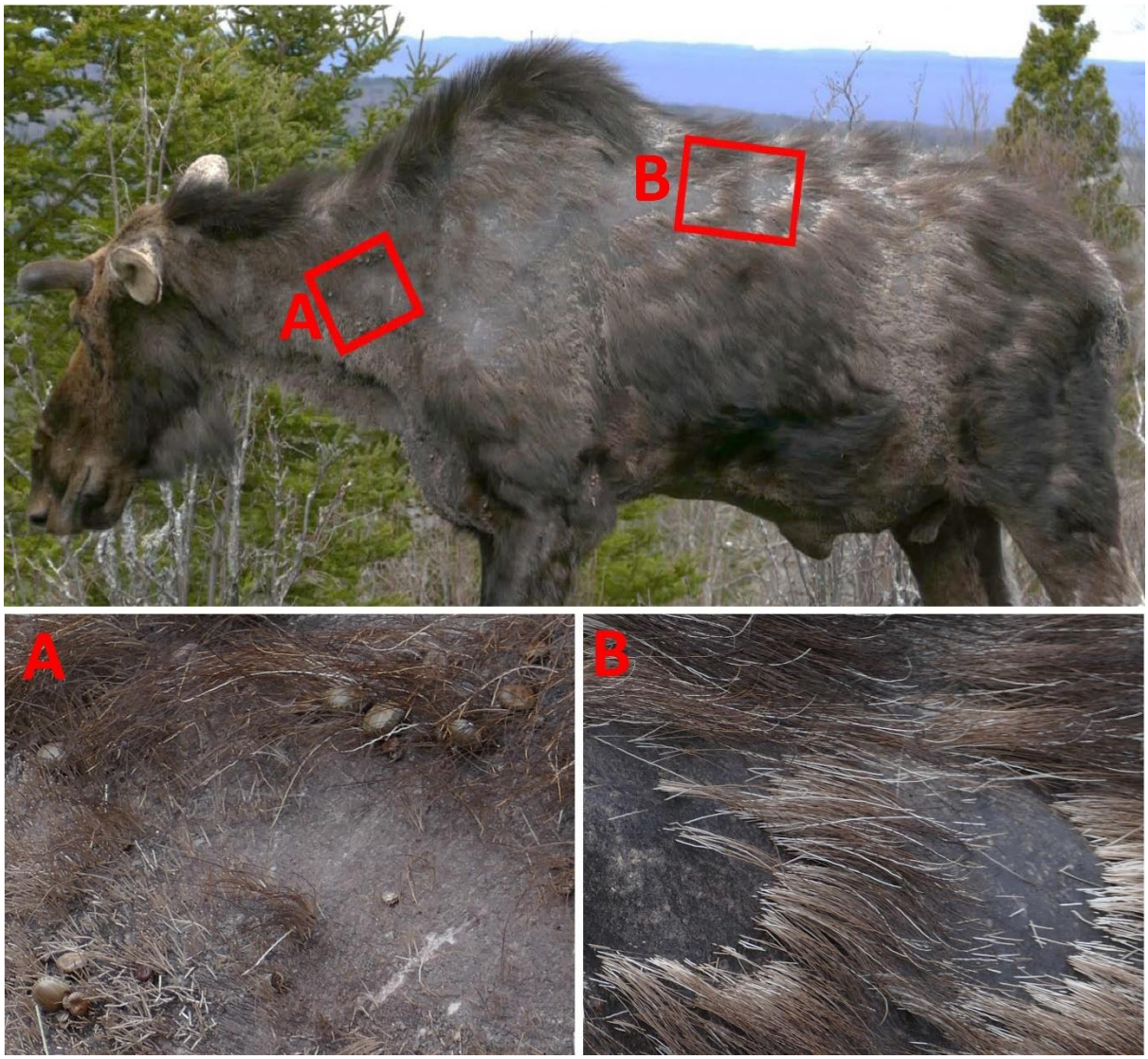

Fig. S1. Images of a bull moose taken at the end of April in Isle Royale National Park. The close-up image of the animal's neck (labelled A) shows a number of large engorged adult female ticks and smaller adult male ticks on their host. The close-up image of the animals back (labelled B) shows undamaged hair which appears brown in colour, damaged guard hairs which appear to be light grey or white, and areas where the hair has been completely removed which appear very dark brown or black in colour. Note that this particular individual has an abnormal growth on its stomach and such abnormal growths, in addition to other phenotypic characteristics, are used to distinguish between individual moose and reduce the likelihood of including repeat samples of the same individual in our dataset within a given calendar year.

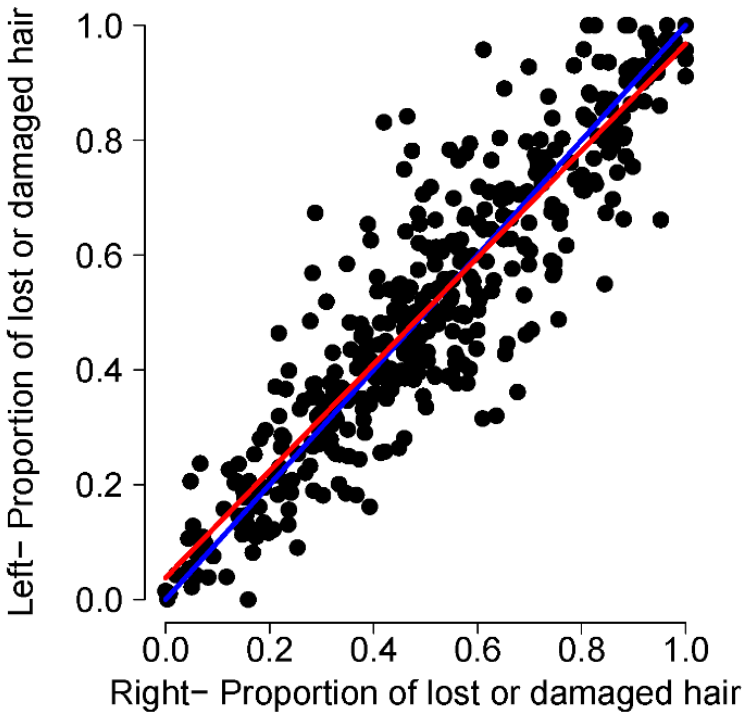

Fig. S2. The proportion of the left side of an individual's neck and torso with lost or damaged hair (hair loss) is closely correlated with the proportion of the right side of the body with hair loss for moose in Isle Royale National Park. Hair loss occurs when moose groom themselves intensively in response to being parasitized by winter ticks and was estimated from images of the side profiles of individual moose (see Fig. S1 and Fig. 1 in main text). Each point represents an individual for which we had images of both sides of the body. The red line is the best fit regression line for the data, whereas the blue line is for reference and depicts a 1:1 ratio.

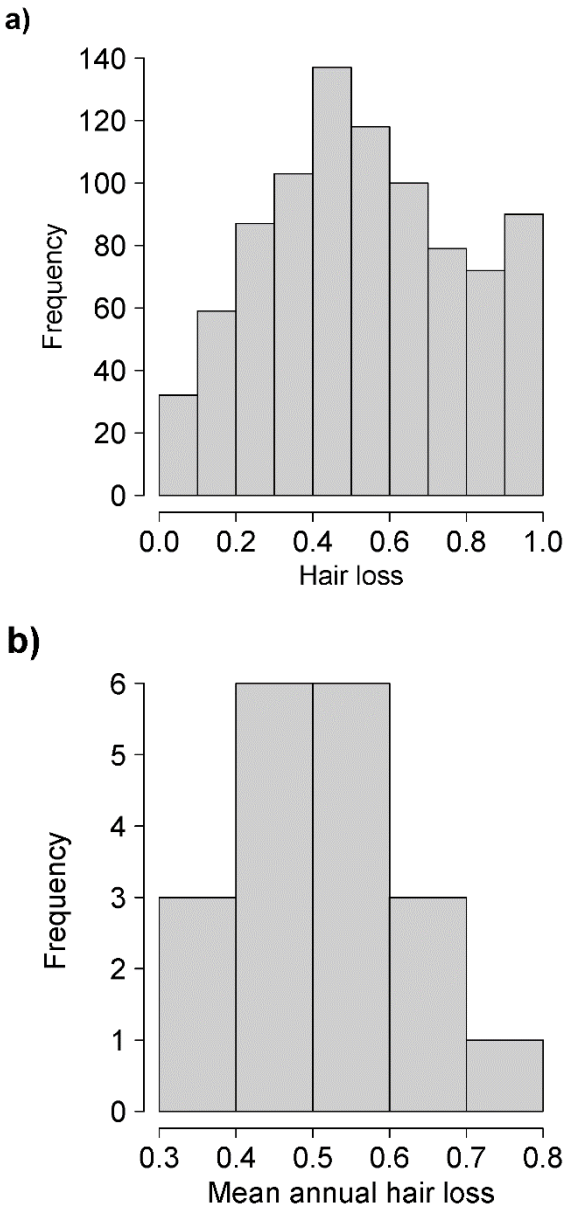

Fig. S3 Histograms showing the distribution of hair loss estimates (an indicator of winter tick burden) for moose in Isle Royale National Park. Hair loss was estimated from images of the side profiles of individual moose (see Fig. S1 and Fig. 1 in main text). We collected images of any individual moose for which we could get a clear view of its side profile, irrespective of the individual's age, sex or severity of hair loss. Panel (a) shows the distribution of hair loss for all individuals included in the dataset (i.e., the distribution of the response variable used in the individual-level analysis before being logit transformed). All observed individuals experienced at least some hair loss (>1%). That observation is consistent with observations from other study systems and suggests that "most, if not all moose …in southern Canada and northern United States have ticks every year of their life" (Samuel 2004, p. 43). Panel (b) shows the distribution of mean annual hair loss (i.e., the distribution of the response variable used in the population-level analysis before being logit transformed).

S2 – Candidate variables for predicting interannual variation in hair loss for moose

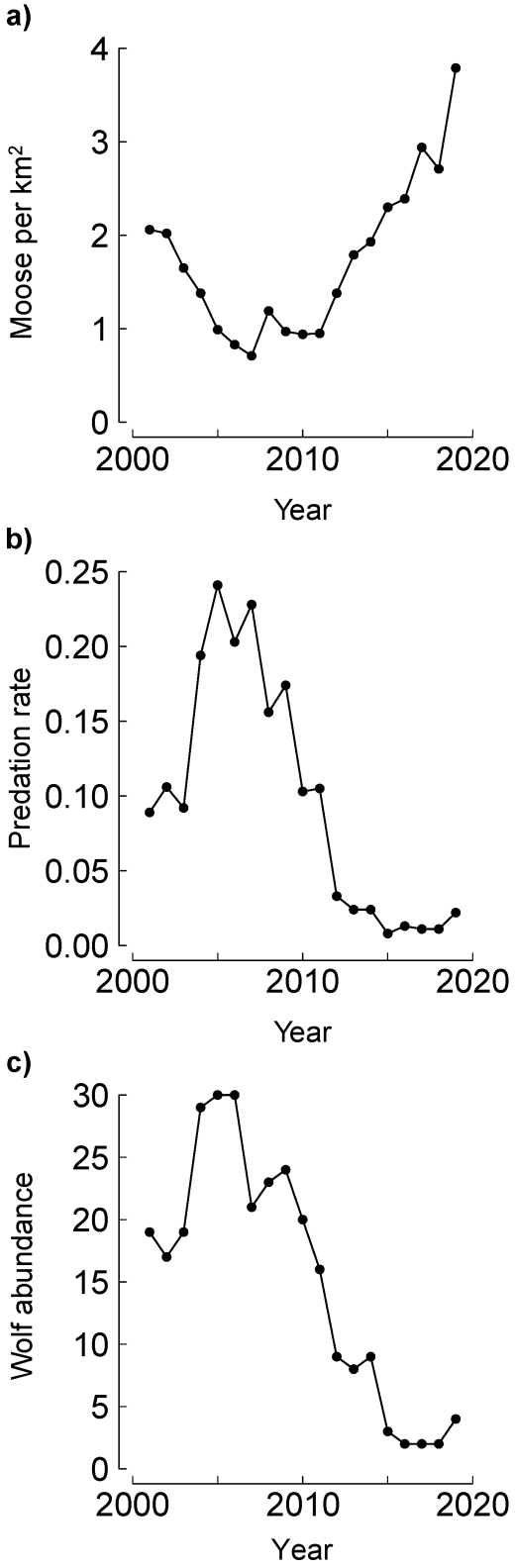

Fig. S4 Temporal variation in the non-climatic variables used to predict interannual variation in hair loss, an indicator of winter tick burdens, for moose in Isle Royale National Park over a 19-year period. A description of each variable and how it was estimated is provided in the main text (see *Statistical analyses*, and Table 1).

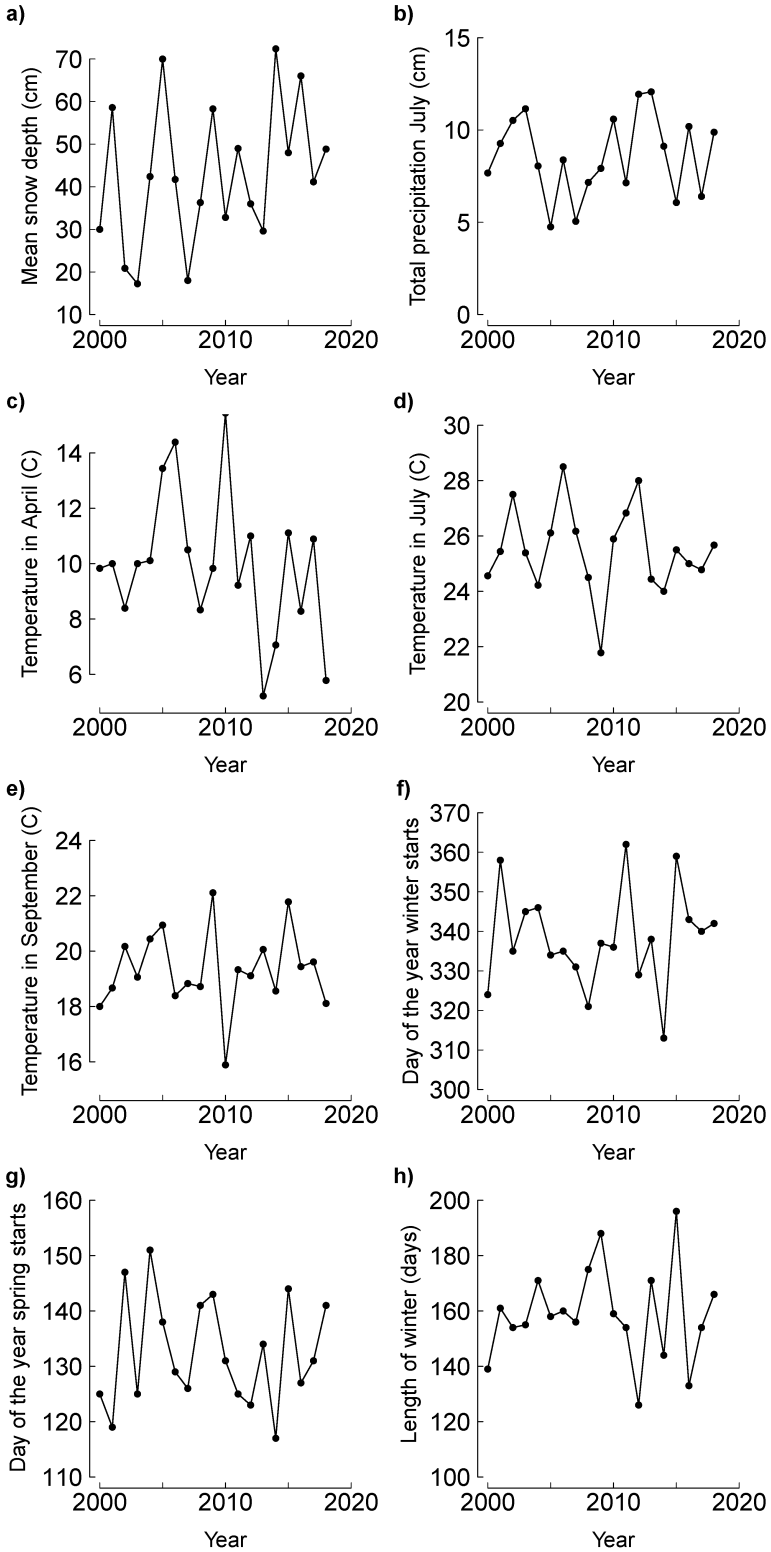

Fig. S5 Temporal variation in the eight climatic variables used to predict interannual variation in hair loss, an indicator of winter tick burden, for moose in Isle Royale National Park over a 19-year period. A description of each variable is provided in the main text (see Table 2). We obtained daily, and mean monthly temperatures and precipitation from a weather station in Grand Portage, north-eastern Minnesota, located approximately 40-60 km from Isle Royale. Specifically, data came from the following resources: https://wrcc.dri.edu/spi/divplot1map.html and https://www.ncdc.noaa.gov/cdo-web/search?datasetid=GHCND.

The non-climatic variables that we considered were all highly correlated with one another (i.e., moose density, wolf abundance, and predation risk Table S1). Despite moose density being highly correlated with predation rate, these two variables should not be viewed as being interchangeable because they represent two separate hypotheses with distinct mechanisms (i.e., moose density is an indicator of host availability for ticks, whereas predation rate is an indicator of predation risk, see Table 1 in main text). Also, although predation rate and moose abundance tend to be inversely related, fluctuations in predation rate can arise from any combination of changes in: (i) per capita kill rate (*KR*), which quantifies the rate at which predators acquire food on a per capita basis and is considered to be a behavioural phenomenon; (ii) survival and reproduction of wolves, which would lead to changes in wolf abundance, (iii) recruitment and adult survival of moose (possibly due to changes in predation rate or tick burdens during the previous year), which would lead to changes in moose abundance. It is plausible that any one of those three processes may influence tick burdens. However, the influence of any one of those processes on its own may be difficult to detect with statistical confidence, whereas the combined effect of those three processes on hair loss may be manifest with predation rate.

Table S1. Matrix of correlations between all variables used in the analysis predicting hair loss in the main text. Values in the lower left half of the table are correlation coefficients (*r*) and values in upper right half of the table are the associated p-values. Correlations that are statistically significant are indicated with bold font. A description of each variable is provided in Table 1 and 2 in the main text. Note that in the statistical analysis there is a 1-year time lag for all weather variables (*precipitation, snow, $temp_{APR}$, $temp_{JUL}$, $temp_{SEPT}$, autumn, spring, winter*) and for $Moose_{lag}$, $Predation_{lag}$ and $Wolf_{lag}$.

Variables	Hair loss	*Snow*	*Precip*	*$temp_{APRIL}$*	*$temp_{JULY}$*	*$temp_{SEPT}$*	*Autumn*	*Spring*	*Winter*	*Moose*	*Predation*	*wolf*	*$Moose_{lag}$*	*$Predation_{lag}$*	*$Wolf_{lag}$*
Hair loss	-	0.26	0.98	0.06	**0.001**	0.78	0.60	0.73	0.65	**0.04**	**0.005**	**0.03**	0.07	**0.02**	0.12
Snow	-0.27	-	0.35	0.88	0.23	0.29	0.77	0.69	0.93	0.36	0.34	0.19	0.54	0.70	0.54
Precip.	0.01	-0.23	-	-0.31	0.12	0.19	0.83	0.46	0.18	0.36	0.27	0.38	0.39	**0.03**	0.20
$temp_{APRIL}$	0.44	-0.04	0.19	-	0.12	0.48	0.78	0.83	0.96	**0.01**	**0.04**	0.12	**0.04**	**0.04**	**0.04**
$temp_{JULY}$	**0.69**	-0.29	0.62	0.37	-	0.20	0.62	0.43	0.09	0.67	0.67	0.98	0.48	0.73	0.92
$temp_{SEPT}$	-0.07	0.26	-0.32	-0.17	-0.31	-	0.23	**0.02**	**0.04**	0.77	0.97	0.84	0.79	0.63	0.84
Autumn	0.13	0.07	-0.05	0.07	0.12	0.29	-	0.57	0.15	0.58	0.70	0.60	0.48	0.59	0.41
Spring	0.08	-0.10	-0.18	-0.05	-0.19	**0.51**	0.14	-	**0.002**	0.59	0.29	0.29	0.93	0.31	0.61
Winter	-0.11	0.02	-0.32	-0.01	-0.40	**0.48**	0.34	**0.66**	-	0.42	0.42	0.51	0.72	0.38	0.68
Moose	**-0.47**	0.22	0.22	**-0.57**	-0.10	-0.07	0.14	-0.13	-0.20	-	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Predation	**0.62**	-0.23	-0.27	**0.47**	0.10	-0.01	-0.09	0.26	0.20	**-0.76**	-	**<0.001**	**0.005**	**<0.001**	**<0.001**
Wolf	**0.50**	-0.31	-0.21	0.37	0.01	0.05	-0.13	0.25	0.16	**-0.78**	**0.94**	-	**0.03**	**<0.001**	**<0.001**
$Moose_{lag}$	-0.43	0.15	0.21	**-0.48**	-0.17	0.06	0.17	0.02	-0.09	**0.90**	**-0.61**	**-0.63**	-	**<0.001**	**0.003**
$Predation_{lag}$	**0.52**	-0.09	-0.50	**0.48**	0.09	0.11	-0.13	0.25	0.21	**-0.83**	**0.86**	**0.85**	**-0.80**	-	**<0.001**
$Wolf_{lag}$	0.37	0.15	-0.31	**0.48**	0.03	-0.05	-0.20	0.12	0.10	**-0.83**	**0.86**	**0.89**	**-0.73**	**0.87**	-

S3 – Additional figures and tables supporting the analysis of interannual variation in hair loss.

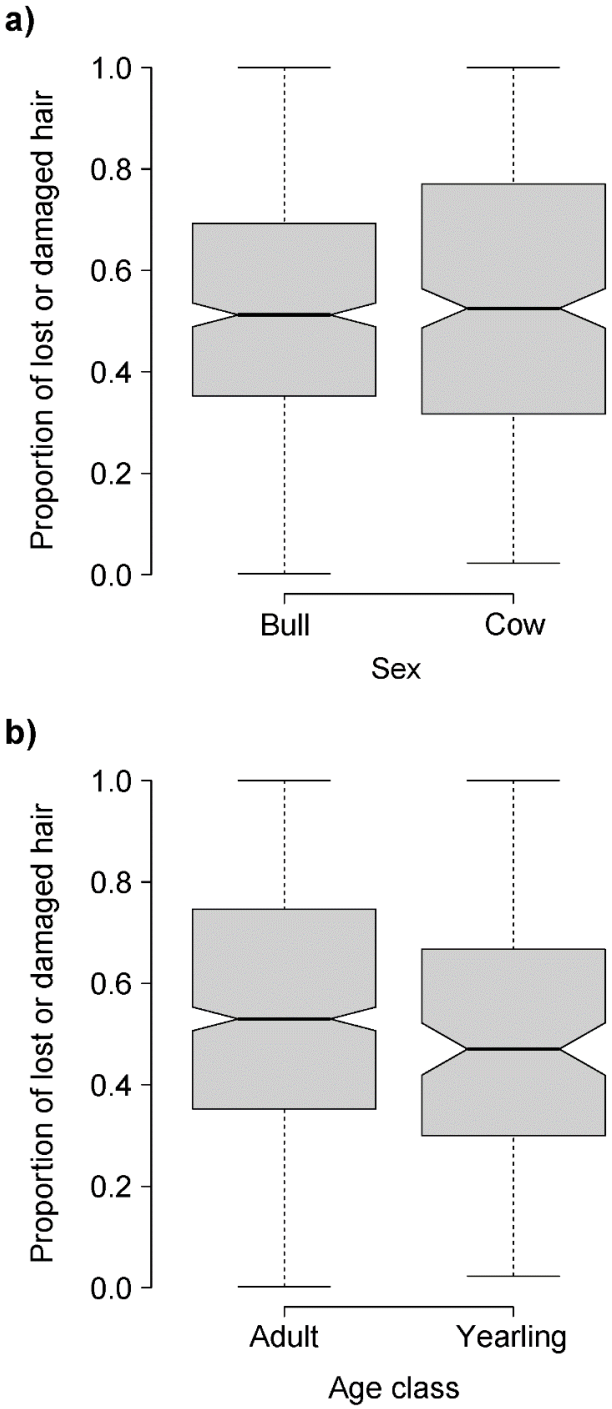

Fig. S6. The proportion of an individual's neck and torso with missing or damaged hair (hair loss) for different demographic classes of moose in Isle Royale National Park observed over a 19-year period (2001-2019). Hair loss did not differ significantly between sexes (sample size of 518 bulls and 338 cows). There was a small, but statistically significant difference in hair loss between age-classes with hair loss being 5% lower on average for yearling moose as opposed to adults (sample size of 126 yearlings and 709 adults).

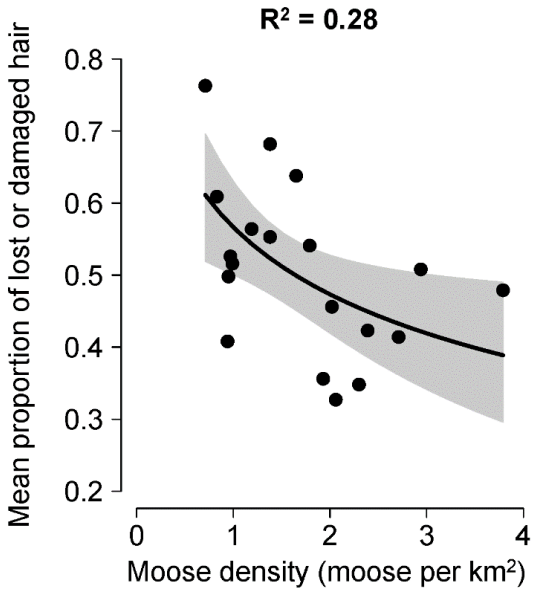

Fig. S7 Mean annual values of hair loss due to winter ticks for moose in Isle Royale National Park over a 19-year period (2001-2019). Mean annual hair loss is shown in relation to the moose density (estimated in Jan-Feb a few months before hair loss was estimated (in May to early-June). The line depicts predictions from a linear model where the response variable hair loss was logit transformed and the predictor variable moose density was log transformed. Grey shaded area indicates the 95% upper and lower confidence intervals around predictions.

Table S2. Results of model selection predicting *hairloss*, an indicator of winter tick burdens for moose in Isle Royale National Park. All models were linear mixed-effect models with year fitted as a random effect. Below we present all models within 2 AICc units of the top model identified by the *dredge* function in the MuMIn package in program-R. The response variable *hairloss* was logit transformed because it is a proportion. Predictor variables are described in Table 1 and Table 2 in the main text. Note that these are the results of an individual-level analysis, as opposed to the population-level analysis presented in the main text. Also, note that the variables $wolf_{lag}$, *moose* and $moose_{lag}$ are highly correlated with *predation* (see Table S1).

Predictors	Coefficients	SE	ΔAICc
$temp_{JULY}$, *predation*, $wolf_{lag}$	0.24, 5.88, -0.02	0.03, 1.44, 0.01	0
$temp_{JULY}$, predation	**0.24, 3.98**	**0.04, 0.71**	**0.15**
$temp_{JULY}$, *predation*, *precipitation*, $temp_{SEPT}$	0.25, 4.21, 0.04, 0.07	0.04, 0.66, 0.03, 0.04	0.58
$temp_{JULY}$, *predation*, $wolf_{lag}$, $temp_{SEPT}$	0.26, 5.81, -0.02, 0.05	0.04, 1.40, 0.01, 0.04	0.64
$temp_{JULY}$, *predation*, $temp_{SEPT}$	0.26, 3.94, 0.05	0.04, 0.69, 0.04	0.83
$temp_{JULY}$, *predation*, *precipitation*, $wolf_{lag}$	0.24, 5.86, 0.02, -0.02	0.04, 1.39, 0.03, 0.01	1.26
$temp_{JULY}$, *predation*, *wolf*, $wolf_{lag}$	0.25, 4.59, 0.02, -0.02	0.04, 2.04, 0.02, 0.01	1.34
$temp_{JULY}$, *predation*, *autumn*	0.24, 4.03, 0.004	0.04, 0.70, 0.005	1.38
$temp_{JULY}$, *predation*, *moose*, $wolf_{lag}$	0.24, 5.88, -0.09, -0.02	0.04, 1.44, 0.14, 0.02	1.62
$temp_{JULY}$, *predation*, *autumn*, $wolf_{lag}$	0.24, 5.74, 0.003, -0.02	0.04, 1.45, 0.005, 0.01	1.67
$temp_{JULY}$, *predation*, *snow*, $wolf_{lag}$	0.25, 6.11, 0.002, -0.02	0.04, 1.49, 0.004, 0.01	1.70
$temp_{JULY}$, *predation*, $moose_{lag}$	0.25, 4.36, 0.08	0.04, 0.88, 0.11	1.72
$temp_{JULY}$, *predation*, $temp_{APRIL}$	0.25, 4.23, -0.02	0.04, 0.79, 0.03	1.73
$temp_{JULY}$, *predation*, $predation_{lag}$	0.24, 4.71, -0.87	0.04, 1.34, 1.38	1.80
$temp_{JULY}$, *predation*, $predation_{lag}$, $temp_{SEPT}$	0.26, 5.10, -1.42, 0.05	0.04, 1.29, 1.35, 0.04	1.86
$temp_{JULY}$, *predation*, *winter*, $wolf_{lag}$	0.23, 6.00, -0.001, -0.02	0.04, 1.48, 0.004, 0.01	1.90
$temp_{JULY}$, *predation*, $wolf_{lag}$, $temp_{APRIL}$	0.25, 5.89, -0.02, -0.01	0.04, 1.43, 0.01, 0.03	1.92
$temp_{JULY}$, *predation*, $wolf_{lag}$, $moose_{lag}$	0.24, 5.97, -0.02, -0.04	0.04, 1.48, 0.02, 0.14	1.96
$temp_{JULY}$, *predation*, $wolf_{lag}$, $predation_{lag}$	0.24, 5.76, -0.02, 0.45	0.04, 1.53, 0.01, 1.68	1.96
$temp_{JULY}$, *predation*, *moose*	0.24, 4.35, 0.05	0.04, 1.09, 0.11	1.99
$temp_{JULY}$, *predation*, $wolf_{lag}$, *spring*	0.24, 5.93, -0.02, -0.001	0.04, 1.48, 0.01, 0.01	2.02

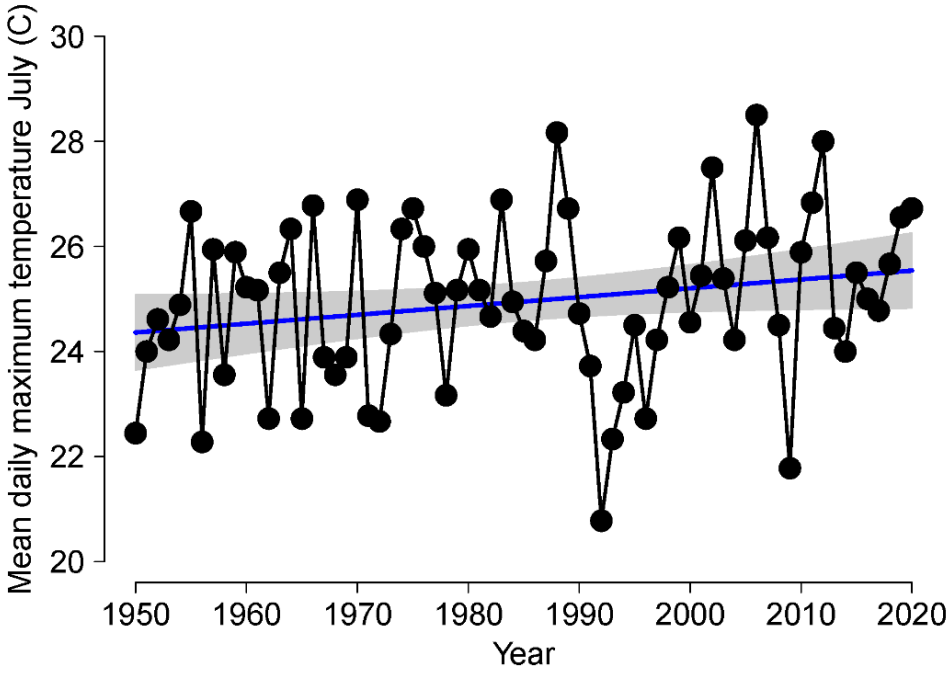

Fig. S8. Temporal variation in the mean daily maximum temperature in July over a 70-year period (1950-2020) for a weather station in Grand Portage, northern Minnesota, which is the nearest weather station to Isle Royale National Park. The blue line represents fitted values from a linear model with year as a predictor which explains 5% of the interannual variation in mean daily maximum temperatures and has an estimated slope of 0.02 ± (SE) 0.01. Grey shaded area indicates the 95% upper and lower confidence intervals around predictions.

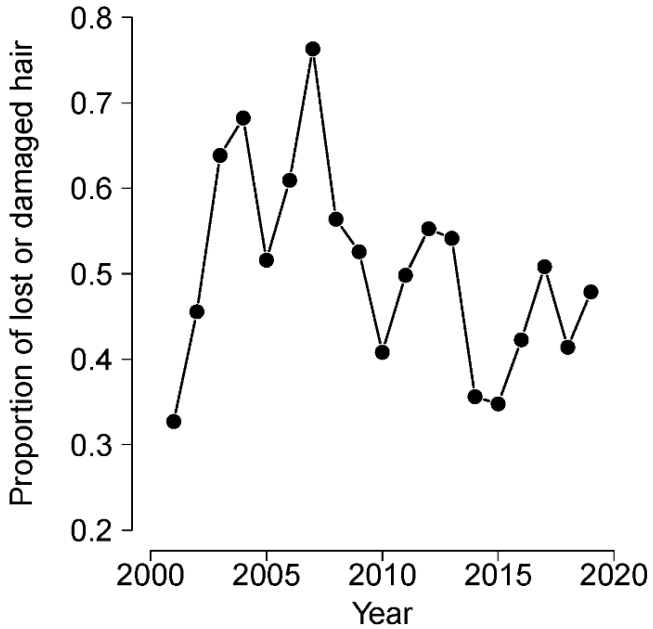

Fig. S9. Temporal variation in mean annual values of the proportion of a moose's neck and torso that had either lost or damaged hair (hair loss) over a 19-year period (2001-2019) for the moose population in Isle Royale National Park. The average number of individuals sampled each year was 46 (range 17-80).