

Supplementary Material

1 SUPPLEMENTARY METHODS

1.1 Derivation of the mechanistic model of functional response

The area searched (A ; km²) by a predator is expressed by the product of predator speed (s , km/h), the reaction distance to a prey item i (d_i , km), and the time spend searching (T_s , h):

$$A = s(2d_i)T_s \quad (\text{S1})$$

A potential encounter occurs when the predator comes within the distance (d_i) at which one can detect and react to the other. As not all prey within this area may be detected, attacked and subdued by the predator, we introduced the detection probability (z_i), the attack probability (k_i), and the success probability of an attack (p_i). Capture efficiency of a prey item i by the predator is expressed by:

$$\alpha_i = s(2d_i)z_ik_ip_i \quad (\text{S2})$$

The number of prey captured ($V_{\alpha i}$) during a search duration T_S for a density N_i is:

$$V_{\alpha i} = \alpha_i T_S N_i \quad (\text{S3})$$

The time spent searching (T_S) is defined as:

$$T_S = T_t - \frac{T_{ci}V_{\alpha i}}{p_i} - T_{mi}V_{\alpha i} \quad (\text{S4})$$

where T_t is the time available for feeding; $\frac{T_{ci}V_{\alpha i}}{p_i}$ is the time spent chasing prey once they are encountered (which includes successful and unsuccessful chases); and $T_{mi}V_{\alpha i}$ is the time spent manipulating prey if they are subdued (which includes time spent eating or hoarding the prey item).

By simplifying Eq. S4 we have:

$$T_S = T_t - V_{\alpha i}(\frac{T_{ci}}{p_i} + T_{mi}) \quad (\text{S5})$$

We can combine the chasing and manipulation time to produce an overall prey handling time (h_i):

$$h_i = \frac{T_{ci}}{p_i} + T_{mi} \quad (\text{S6})$$

Substituting T_s from Eq. S5 into Eq. S3, we arrive at:

$$V_{\alpha i} = \frac{\alpha_i N_i T_t}{1 + \alpha_i h_i N_i} \quad (S7)$$

The functional response of a predator ($f(i)$) is the number of prey captured per predator per unit of time (acquisition rate). This is expressed by dividing Eq. S7 by T_t :

$$f(i) = \frac{\alpha_i N_i}{1 + \alpha_i h_i N_i} \quad (S8)$$

1.2 Estimation of parameter values

1.2.1 Predator speed

A total of 16 foxes (7 females and 9 males) were equipped with a GPS collar (Radio Tag-14, Milsar, Poland) during the summers of 2018 and 2019. Of those, 7 were equipped during both years giving us a total of 23 fox-summers (8 foxes in 2018 and 15 in 2019). Reproductive females (2 out of 4 in 2018 and 6 out of 7 in 2019) spent substantial time nursing the pups in the den. Foxes were captured using Tomahawk cage traps #205 (Tomahawk Live Trap Company, Tomahawk, WI, USA) or Softcatch #1 padded leghold traps (Oneida Victor Inc. Ltd., Cleveland, OH, USA) as described in (Rioux et al., 2017). GPS fix intervals were fixed at 4 minutes (360 fixes per day), and data were downloaded to a hand-held receiver using UHF transmission. GPS location error was of 11 m (Poulin et al., 2021).

Average predator speed (km/day) was estimated by adding linear distances between successive locations, using the *adehabitatLT* library in R (R Core Team, 2019). Predator speed was extracted from June 5 to July 9 to focus on the incubation period of most birds. We removed from analyses all fixes obtained <48 hours after capture and days where the number of fixes was insufficient (<75% of all fixes). Predator speed was converted per hour and average speed was 1.52 km/h (sd = 0.59 km/h, $n = 123$ fox-days).

1.2.2 Goose parameters

Nest attendance probability

During goose incubation period, the time spent on the nest by females average 93% ($\mu = 93.6$, se = 1.6%, $n = 7$ females; Poussart et al. 2000 and $\mu = 93$, $n = 41$ females; Reed et al. 1995). During incubation recesses females usually remained close to their nests, and 90% of all records ($n = 183$) were within 20 m (Reed et al., 1995). Since there is uncertainty in the proportion of females within 10 m, we used 90% as the maximum and 50% as the minimum. By combining this information, we can estimate a minimum probability of nest attendance at 96.5.% and a maximum probability of nest attendance at 99.3%.

Detection probability

We used artificial nests to assess experimentally the detection probability of unattended goose nests in summer 2019. Goose eggs were simulated with domestic hen eggs. Two eggs were placed in each artificial nest and covered with goose down collected from old goose nests. A total of 24 paired artificial nests were deployed randomly in the goose colony. The two paired nests were separated either by 10, 30, 60, 80 or 100 m. Movement-triggered cameras (model PM35T25, Reconyx) were set directly on the ground 5 m from each nest allowing to identify nest predators and to determine the exact time of nest predation. A successful detection was considered to have occurred when the two paired nests were predated by a fox in

the same time interval ($n = 9$ cases). An unsuccessful detection occurred when only one nest of the pair was depredated by a fox ($n = 6$ cases). When a nest was depredated by another species (e.g. gulls, ravens) or the event of predation was undetected by the camera, the pair was excluded from the analysis ($n = 9$ cases). We used a linear model with a binomial distribution to model detection probability in relation to detection distance (figure S1).

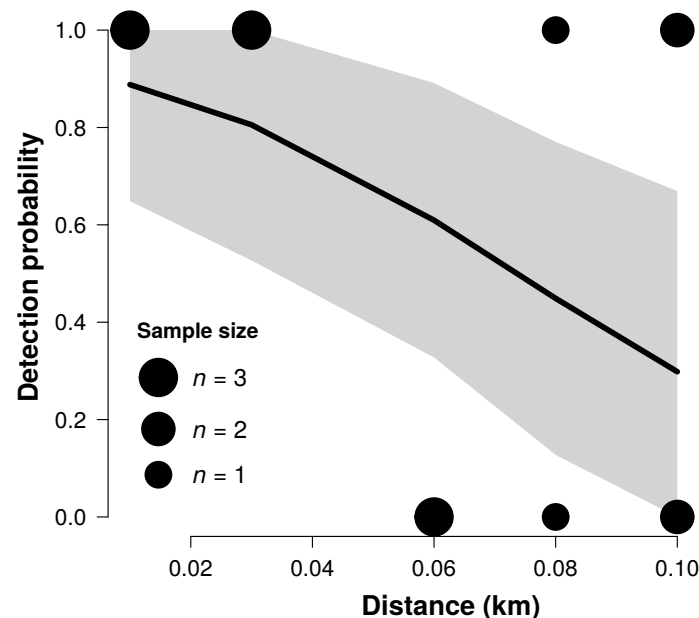


Figure S1. Probability that an artificial (unattended) goose nest was detected and depredated by an arctic fox as a function of the distance between paired nests. Each circle represents observed values and circle size is proportional to the number of observations. The curve represents the average detection probability and the gray band represents the 95% confidence interval of the regression.

Reaction distance

The reaction distance on attended nests was defined as the distance at which an attack can be initiated by the predator. This parameter was estimated with direct observations of foraging foxes in summer 2019 ($\mu = 0.0328$, $se = 0.007$, $n = 25$ attacks). On unattended nests, the reaction distance was defined as the maximum distance at which the predator can detect an unattended nest. We used a combination of direct observations combined with artificial nests (same experience as for the detection probability) to estimate the reaction distance on unattended nests ($\mu = 0.0365$ km, $se = 0.009$, $max = 0.1$ km, $n = 13$). We used 0.1 to 0.12 km as a range of maximum distance as the detection probability was still around 30% at 0.1 km (figure S1). As our sample size was limited for attended and unattended nests, we assigned a uniform distribution for both parameters.

Chasing time

By conducting direct observations of foraging foxes from a blind, we obtained the average chase time per egg attacked from a nest ($\mu = 23$ sec/egg, $sd = 29$, $n = 148$ attacks). To convert per nest, we subsampled the data set and summed up 4 individual values. This total was then adjusted to the average clutch size of 3.7 ($\mu = 0.02$, $se = 0.0024$ h per nest).

Manipulation time

By conducting direct observations of foraging foxes from a blind, we obtained the time required by the predator to manipulate one egg, which includes consumption or hoarding time ($\mu = 136$ sec/egg, $sd = 127$, $n = 207$). To convert per nest, we subsampled the data set and summed up 4 individual values. This total was then adjusted to the average clutch size of 3.7 ($\mu = 0.14$, $se = 0.009$ h per nest).

Attack probability of attended nests

Based on direct observations of foraging foxes from a blind, we estimated attack probability at 22% by using the proportion of attended nests attacked by a fox divided by the total number of possible attacks ($n = 215$). The total number of possible attacks is obtained by adding the number of attacks towards attended nests and the number of times the foxes are chased by the geese without having initiated an attack. The latter gives us an estimation of the number of opportunities to initiate an attack. This estimation of attack probability gives us the upper limit of attack probability as the total number of possible attacks is most likely underestimated. Thus, we used a wide range of values (from 0.01 to 0.22) and a uniform distribution for this parameter.

Success probability

Based on direct observations of foraging foxes from a blind, the probability of a successful attack was 93.4% on unattended nests ($se = 0.022$, $n = 137$ attacks) and 9.8% on attended nests ($se = 0.011$, $n = 701$ attacks).

Complete predation probability

Based on direct observations of foraging foxes from a blind, the probability of a complete clutch predation once an egg is subdued on unattended nests was 69% ($se = 0.12$, $n = 16$) and was 47% ($se = 0.13$, $n = 15$) on attended nests. The probability of complete clutch predation for an unattended nest is not 1 since a parent may detect a fox during incubation recess and return quickly to protect the nest.

1.2.3 Lemming parameters**Reaction distance and detection probability**

Based on direct observations, foxes generally initiate their attacks on lemmings within 5 m (on 29 attacks recorded in 1996-1999 and 2019). We assumed that the maximum reaction distance was twice that distance (10 m) and that detection probability followed a decreasing sigmoid function. Hence, detection probability was considered fairly high within 5 m radius (100-80%) and declined sharply between 5 and 10 m.

Chasing time

By conducting direct observations of foraging foxes, we estimated the average chase time per lemming attacked ($\mu = 88$ sec, $se = 7.1$, $n = 246$ attacks).

Success probability

By conducting direct observations of foraging foxes, we estimated the probability of a successful attack on a lemming at 51% ($se = 0.03$, $n = 268$ attacks).

Manipulation time

Based on direct observations of foraging foxes, we estimated the average manipulation time per lemming captured, which includes consumption and hoarding time ($\mu = 37$ sec, $se = 3.0$, $n = 93$).

1.2.4 Passerine parameters

Reaction distance

The reaction distance was defined as the maximum distance between an observer (a simulated predator) and the nest when the bird flushes the nest. To measure the reaction distance, a human observer approached nests from a random bearing at normal walking speed (~ 4 km/h). The observer made several approaches until the bird leaves the nest. At each approach the distance between the observer and the nest was noted. Flush distance was recorded for 45 different nests in summer 2019 and ranged from 0 to 20 m ($\mu = 2.8$ m, $sd = 3.6$ m, $n = 77$) The distance was measured either by pacing or with a GPS unit.

Detection probability

Detection probability was estimated by following the same method as reaction distance. Besides recording flush distances, the distance between the observer and the nest was noted even if the bird didn't flush. We used a linear model with a binomial distribution to model detection probability (0; the bird didn't flush, 1; the bird flushed) in relation to the minimum distance between the observer and the nest ($n = 167$, figure S2).

Manipulation time

By using movement-triggered cameras near the nest, we extracted manipulation time from 17 passerine nests monitored between 2006 and 2014. The average manipulation time was 31 sec ($sd = 30$ sec) and included consumption and hoarding time. Cameras (PM35T25 model) were set directly on the ground 5 m from the nest (for more details about camera features see McKinnon and Bêty (2009)).

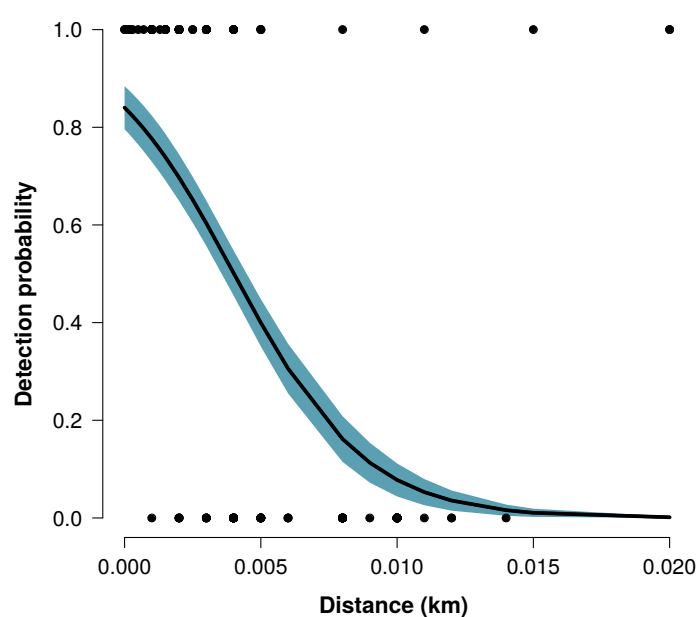


Figure S2. Detection probability of a passerine nest in relation to the distance between the observer and the nest. The gray band represents the \pm standard error of the regression.

1.2.5 Sandpiper parameters

Reaction distance and detection probability

Reaction distance was estimated by Smith and Edwards (2018) following the same method as described for passerines reaction distance. The mean reaction distance was 15.3 m (sd = 18.8 m, $n = 104$ nests, max = 85 m) for White-rumped Sandpiper (*Calidris fuscicollis*; Smith and Edwards (2018)). We used the same detection probability function as for passerines (figure S2).

Manipulation time

By using movement-triggered cameras near real and artificial sandpiper nests, we extracted manipulation time from 5 sandpiper and 18 artificial nests monitored between 2006 and 2016. An artificial nest consisted of four Japanese quail (*Coturnix japonica*) eggs placed in a small depression made in the ground, similar to the simple nest scrapes used by sandpipers. Quail eggs resemble those of sandpipers in colouration and size. The average manipulation time was 250 sec (sd = 189 sec) and includes consumption and hoarding time. Cameras (PM35T25 model) were set directly on the ground 5 m from the nest (for more details about camera features see McKinnon and Bêty (2009)).

Table S1. Parameter values and distribution used in the functional response model of arctic fox to goose nests, lemmings, passerine and sandpiper nests.

Parameter name	Value	Distribution
Predator speed	$\mu = 1.52$ km/h, $sd = 0.59$, $n = 123$ fox-days	Normal-truncated
Goose nests		
Nest attendance probability	min = 0.965, max = 0.993	Uniform
Chasing time	$\mu = 0.02$, $se = 0.0024$ h per nest	Normal-truncated
Manipulation time	$\mu = 0.14$, $se = 0.009$ h per nest	Normal-truncated
Goose attended nests		
Reaction distance	min = 0.026, max = 0.040 km	Uniform
Attack probability	min = 0.01, max = 0.22	Uniform
Success probability	$p = 0.098$, $se = 0.011$	Normal-truncated
Complete predation probability	$p = 0.47$, $se = 0.13$	Normal-truncated
Goose unattended nests		
Reaction distance	min = 0.10, max = 0.12 km	Uniform
Detection probability	Cumulative detection probability at the reaction distance. See figure S1	NA
Success probability	$p = 0.934$, $se = 0.022$	Normal-truncated
Complete predation probability	$p = 0.69$, $se = 0.12$	Normal-truncated
Lemmings		
Reaction distance	min = 0.005, max = 0.010 km	Uniform
Detection probability	Cumulative detection probability at the reaction distance. See figure S4	NA
Chasing time	$\mu = 0.024$, $se = 0.0019$ h per ind.	Normal-truncated
Success probability	$p = 0.51$, $se = 0.03$	Normal-truncated
Manipulation time	$\mu = 0.010$, $se = 0.0008$ h per ind.	Normal-truncated
Passerine nests		
Reaction distance	0.02 km	NA
Detection probability	Cumulative detection probability at 0.02 km (0.24). See figure S2	NA
Manipulation time	$\mu = 0.0086$, $se = 0.0005$ h/nest	Normal-truncated
Sandpiper nests		
Reaction distance	0.085 km	NA
Detection probability	Cumulative detection probability at 0.085 km (0.059). See figure S2	NA
Manipulation time	$\mu = 0.069$, $se = 0.0023$ h/nest	Normal-truncated

Note: Reaction distance refers to the detection distance for all prey, except for attended goose nests, where reaction distance refers to the attack distance.

Table S2. List of equations to derive the functional response of arctic fox to each prey species.

Model	Form
Goose nests (G)	
Acquisition rate	$f(G) = f(G_a) + f(G_{ua})$
Goose attended nests (G_a)	
Capture efficiency - Complete predation	$\alpha_{Gac} = s(2d_{Ga})k_{Ga}p_{Ga}P_{cGa}$
Capture efficiency - Partial predation	$\alpha_{Gap} = \frac{s(2d_{Ga})k_{Ga}p_{Ga}(1 - P_{cGa})}{3.7*}$
Handling time	$h_{Ga} = \frac{T_{cG}}{p_{Ga}P_{cGa}} + T_{mG}$
Acquisition rate	$f(G_a) = \frac{(\alpha_{Gac} + \alpha_{Gap})wN_G}{1 + (\alpha_{Gac} + \alpha_{Gap})h_{Ga}wN_G}$
Goose unattended nests (G_{ua})	
Capture efficiency - Complete predation	$\alpha_{Guac} = s(2d_{Gua})z_{Gua}p_{Gua}P_{cGua}$
Capture efficiency - Partial predation	$\alpha_{Guap} = \frac{s(2d_{Gua})z_{Gua}p_{Gua}(1 - P_{cGua})}{3.7*}$
Handling time	$h_{Gua} = \frac{T_{cG}}{P_{cGua}} + T_{mG}$
Acquisition rate	$f(G_{ua}) = \frac{(\alpha_{Guac} + \alpha_{Guap})(1 - w)N_G}{1 + (\alpha_{Guac} + \alpha_{Guap})h_{Gua}(1 - w)N_G}$
Lemmings (L)	
Capture efficiency	$\alpha_L = s(2d_L)z_Lp_L$
Handling time	$h_L = \frac{T_{cL}}{p_L} + T_{mL}$
Acquisition rate	$f(L) = \frac{\alpha_L N_L}{1 + \alpha_L h_L N_L}$
Passerine nests (P)	
Capture efficiency	$\alpha_P = s(2d_P)z_P$
Handling time	$h_P = T_{mP}$
Acquisition rate	$f(P) = \frac{\alpha_P N_P}{1 + \alpha_P h_P N_P}$
Sandpiper nests (S)	
Capture efficiency	$\alpha_S = s(2d_S)z_S$
Handling time	$h_S = T_{mS}$
Acquisition rate	$f(S) = \frac{\alpha_S N_S}{1 + \alpha_S h_S N_S}$

Note: *This value refers to the average clutch size of the greater snow goose (Gauthier et al., 2013).

1.3 Exploration of density dependence in capture efficiency components

We incorporated density dependence into the goose and the lemming models within the range of densities observed in our study system. For each parameter in which density dependence was incorporated, the minimum (p_{min}) and the maximum (p_{max}) parameter values were associated respectively with the minimum (N_{min}) and the maximum (N_{max}) prey density in order to calculate the slope and the intercept of the density-dependence relationship:

$$slope = (p_{max} - p_{min}) / (N_{max} - N_{min}) \quad (S9)$$

$$intercept = p_{max} - (slope * N_{max}) \quad (S10)$$

In the goose model, we modified attack and success probabilities for nests attended, and reaction distance and detection probability for nests unattended (e.g. figure S3). In the lemming model, we added density dependence in reaction distance, detection and success probabilities (e.g. figure S4).

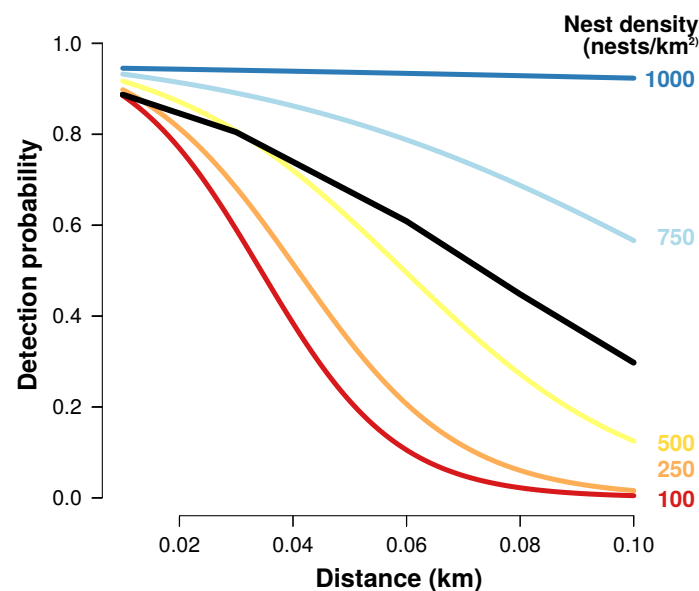


Figure S3. Probability that an artificial (unattended) goose nest was detected and depredated by the arctic fox as a function of distance along a gradient of goose nest density. The color gradient indicates the range of detection functions used to explore density dependence in detection probability.

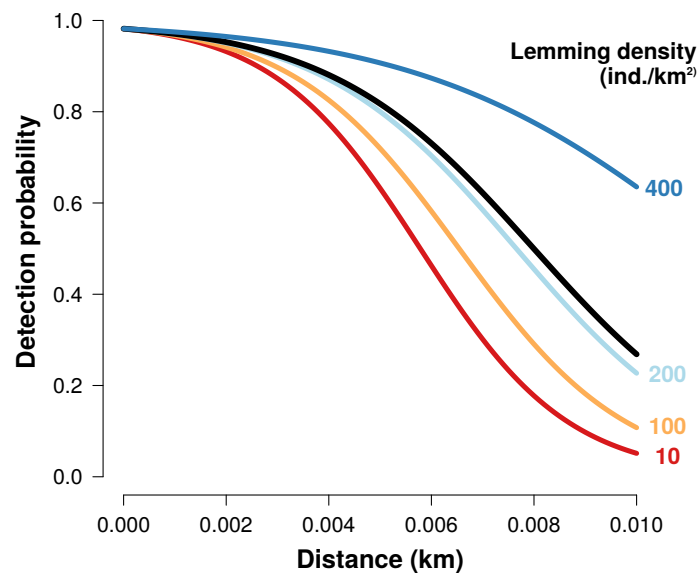


Figure S4. Probability that a lemming is detected by an arctic fox along a gradient of lemming density. The black line represents the average detection probability. The color gradient indicates the range of detection functions used to explore density dependence in detection probability.

2 SUPPLEMENTARY TABLES

Table S3. Empirical data used to evaluate the performance of the mechanistic model of functional response of arctic fox to goose nests and lemmings on Bylot Island, Nunavut. Data are listed by year.

Year	Observation length (h)	Average clutch size	Goose density range (nests/km ²)	Goose nest acquisition rate (nests/fox/h)	Lemming density (ind./km ²)	Lemming acquisition rate (ind./fox/h)
1996	3.1	3.7	79-100	1.82	414	0.32
1997	4.7	3.9	219-264	0.33	166	0.21
1998	9.5	3.8	283-358	0.28	247	2.32
1999	4.2	3.1	15-110	0.92	11	0
2004	29.8	3.6	85-110	0.19	325	2.85
2005	43.6	3.6	257-390	0.76	32	0.64
2015	3.4	3.5	713-926	0.34	365	0.30
2016	3.3	3.4	401-550	0.97	253	2.40
2017	10.1	3.5	456-814	0.20	19	0.10
2019	12.7	4.0	381-465	0.30	137	0.24

Table S4. Empirical data used to evaluate the performance of the mechanistic model of functional response of arctic fox to passerine and sandpiper nests on Bylot Island, Nunavut. Data are listed by year.

Year	Passerine nest density (nests/km²)	Passerine nest acquisition rate (nests/fox/h)	Sandpiper nest density (nests/km²)	Sandpiper acquisition rate (nests/fox/h)
2005	7.3	0.15	4.4	0.051
2006	10.3	0.28	5.9	0.169
2007	6.1	0.03	2.1	0.004
2008	7.3	0.06	1.0	0.002
2009	6.9	0.04	1.1	0.002
2010	6.8	0.04	4.5	0.014
2011	6.8	0.03	2.3	0.004
2012	12.3	0.19	4.0	0.060
2013	7.3	0.13	2.6	0.029

3 SUPPLEMENTARY FIGURES

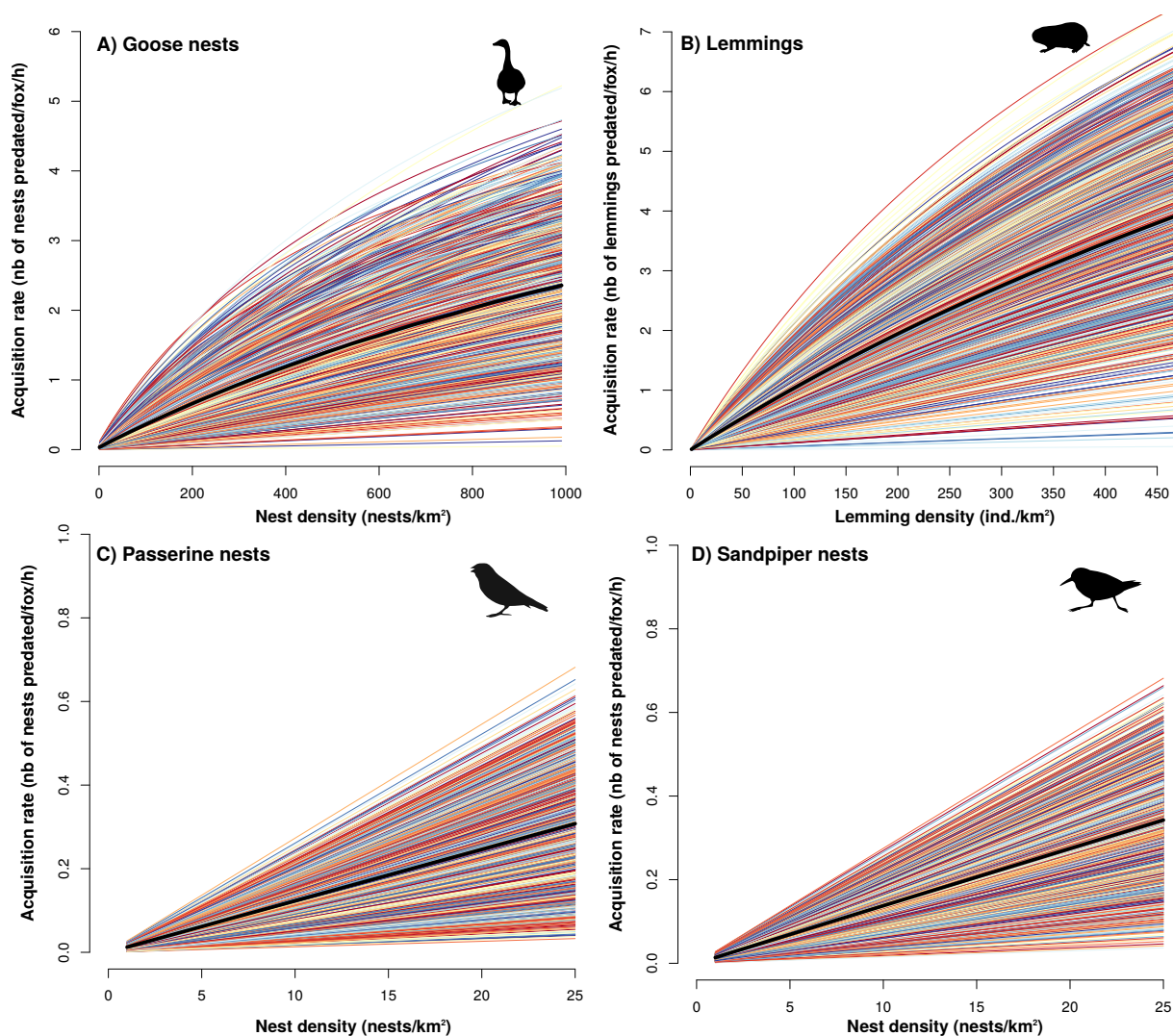


Figure S5. Functional response of arctic fox to density of goose nests (A), lemmings (B), passerine nests (C), and sandpiper nests (D). Each line represents a simulation and the solid black line represents the model median ($N = 1000$ simulations).

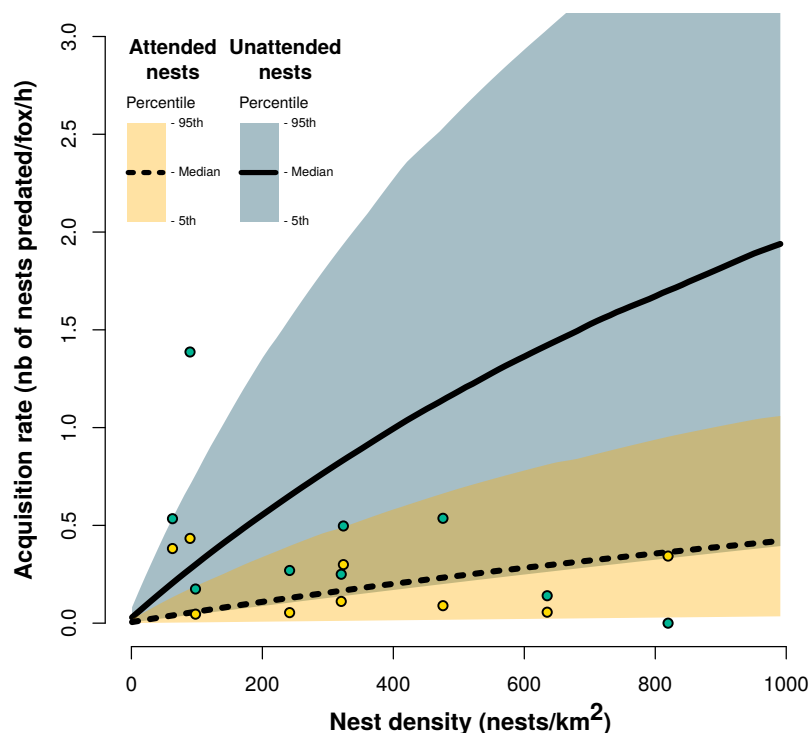


Figure S6. Functional response of arctic fox to density of goose nests for attended and unattended nests. The black lines represent the model median and the color bands represent the 95th percentiles based on 1000 simulations. Empirical data for attended and unattended nests obtained from direct observations of foraging foxes are represented by yellow and blue dots respectively.

REFERENCES

- Gauthier, G., Bêty, J., Cadieux, M.-C., Legagneux, P., Doiron, M., Chevallier, C., et al. (2013). Long-term monitoring at multiple trophic levels suggests heterogeneity in responses to climate change in the Canadian Arctic tundra. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 368. doi:10.1098/rstb.2012.0482
- McKinnon, L. and Bêty, J. (2009). Effect of camera monitoring on survival rates of High-Arctic shorebird nests. *Journal of Field Ornithology* 80, 280–288. doi:10.1111/j.1557-9263.2009.00231.x
- Poulin, M.-P., Clermont, J., and Berteaux, D. (2021). Extensive daily movement rates measured in territorial arctic foxes. *Ecology and Evolution* In press
- Poussart, C., Larochelle, J., and Gauthier, G. (2000). The thermal regime of eggs during laying and incubation in greater snow geese. *The Condor* 102, 292–300. doi:10.2307/1369640
- [Dataset] R Core Team (2019). R: A language and environment for statistical computing
- Reed, A., Hughes, R. J., and Gauthier, G. (1995). Incubation behavior and body mass of female greater snow geese. *The Condor* 97, 993–1001. doi:10.2307/1369538
- Rioux, M. J., Lai, S., Casajus, N., Bêty, J., and Berteaux, D. (2017). Winter home range fidelity and extraterritorial movements of Arctic fox pairs in the Canadian High Arctic. *Polar Research* 36. doi:10.1080/17518369.2017.1316930
- Smith, P. A. and Edwards, D. B. (2018). Deceptive nest defence in ground-nesting birds and the risk of intermediate strategies. *PLoS ONE*, 1–12