Supplementary Material for "Incorporating uncertainty about species' potential distributions under climate change into the selection of conservation areas with a case study from the Arctic Coastal Plain of Alaska"

Species of Conservation Concern

Besides the polar bear and the caribou, nine species of bird were analyzed (Supplementary Material, Table 1).

Supplementary Material Table 1. **Birds of Conservation Concern on the Arctic Coastal Plain**.

Name	Records[1]	FWS[2]	IUCN[3]	Audubon[4]	SWG[5]
BB	88			X	
CA	76			X	X
CAP	105			X	X
GA	180			X	
NP	15			X	X
PL	84			X	
PD	114			X	X
PS	44	T	V	X	
SF	96	T		X	

"BB"=*Branta bernicla nigricans*,common name=Black Brant.
"CA"=*Calidris alba*,common name=Sanderling.
"CAP"=*Calidris alpina*,common name=Dunlin.
"GA"=*Gavia adamsii*,common name=Yellow–billed Loon.
"NP"=*Numenius phaeopus*,common name=Whimbrel.
"PD"=*Pluvialis dominica*,common name=
American Golden–Plover.
"PL"=*Phalaropus lobatus*,common name=
Red–necked Phalarope.
"PS"=*Polysticta stelleri*,common name=Steller's Eider.
"SF"=*Somateria fischeri*,common name=Spectacled Eider.

1. Number of longitude/latitude records used to develop the model of the species' distribution.
2. Classification of the species according to the United States Fish and Wildlife Service (FWS). "T" denotes "threatened", that is, likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range. "Endangered species" means any species that is in danger of extinction throughout all or a significant portion of its range.
3. Classification of the species according to the 2006 IUCN Red List of Threatened Species.
   "V" denotes "vulnerable", meaning that the Alaskan population of Steller's Eider has undergone an observed, estimated, inferred, or suspected population size reduction of at least 30% over the last 10 years (IUCN criterion A2b) and is projected to undergo a population size reduction of at least 30% within the next 10 years or three generations (criterion A3b).
4. "X" in this column denotes a species on the Audubon Watchlist 2002.
5. "X" denotes a species of "high conservation concern" according to the Alaska Shorebirds Working Group.

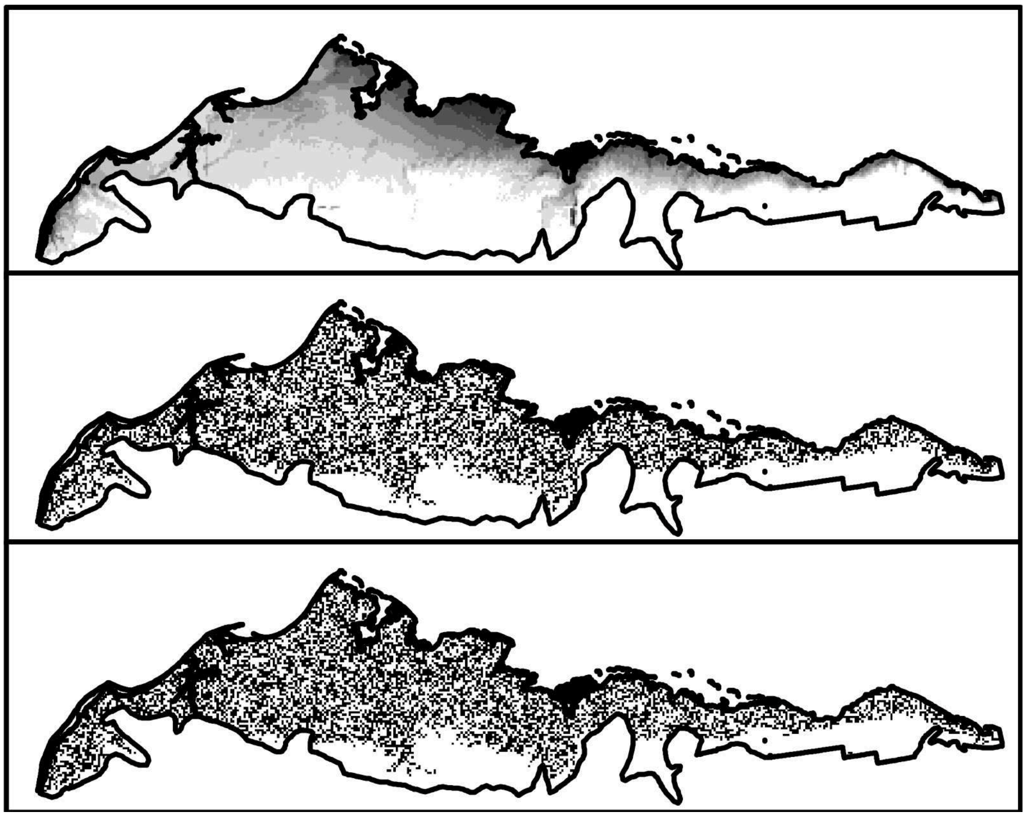

Fig. 1. **Construction of species' relocation scenarios via randomized rounding**. Top: Maxent model for the distribution of the Black Brant Goose *Branta bernicla* in 2040 under the B1 climate scenario. Sites on the Arctic Coastal Plain are classified into ten equal intervals of size 0.1. The color of each pixel represents the probability that the site will be potential Brant habitat according to the Maxent model. Black sites are predicted to be potential habitat with probability one, whereas white sites are predicted to be suitable with probability zero. The middle and lower panels were generated from the top panel via two separate iterations of the rounding procedure. Black pixels in the middle and bottom panels represent sites predicted to be potential Brant habitat with probability one after rounding. In the middle panel, there are 5824 such sites. In the bottom panel, there are 5868 such sites.

Supplementary Material Table 2. **Effect of Increasing the Extent of the Study Region on the AUC**

Species	AUC for Arctic Coastal Plain	AUC for Arctic Coastal Plain Plus Brooks Range
Branta bernicla	0.834	0.859
Calidris alba	0.818	0.855
Calidris alpina	0.864	0.865
Gavia adamsii	0.863	0.904
Numenius phaeopus	0.957	0.996
Pluvialis dominica	0.832	0.869
Phalaropus lobatus	0.831	0.853
Polysticta stelleri	0.871	0.985
Rangifer tarandus	0.872	0.869
Somateria fischeri	0.893	0.915
Ursus maritimus	0.768	0.843

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"PS"=*Polysticta stelleri*,common name=Steller's Eider.

"RT"=*Rangifer tarandus*,common name=caribou.

"SF"=*Somateria fischeri*,common name=Spectacled Eider.

"UM"=*Ursus maritimus*,common name=polar bear.

Comparison of Maxent to Random Forest

The accuracy of the Maxent models of the 11 species considered here was compared to models obtained using Random Forest, a machine–learning method that involves constructing multiple classification trees (Breiman, 2001; Berk, 2006). The application of Random Forest to presence–only data is inappropriate to the extent that classification trees require presence–absence data. Nevertheless, Random Forest has frequently been used to construct accurate models of species' distributions (Furlanello et al., 2003; Garzón et al., 2006; Lawrence et al., 2006) and species' responses to climate change (Iverson et al., 2004; Bunn et al., 2005; Candau and Fleming, 2005; Bunn and Goetz, 2006; Lawler et al., 2006; Prasad et al., 2006; Schwartz et al., 2006; Garzón et al., 2007). The objectives of the comparison were to assess the loss of accuracy, if any, that arises from treating pseudo–absences as true absences in Random Forest and to attempt to replicate the finding of Elith et al. (2006) that Maxent and Random Forest are comparable in accuracy.

The sensitivity of the Maxent models was the same as that of species' distribution models constructed using Random Forest (paired t–test: t=-0.671, df=10, p=0.518, Supplementary Material Table 3). However, Maxent obtained higher sensitivity for six of the 11 species, including the threatened sea ducks. To this extent, the performance of Maxent is intuitively better even if the difference between Maxent and Random Forest is not statistically significant.

Supplementary Material Table 3. **Sensitivity of Random Forest and Maxent**

	Sensitivity on the Test Set	
Species	Random Forest	Maxent
Branta bernicla	0.909	0.87
Calidris alba	0.9	0.91
Calidris alpina	0.867	0.864
Gavia adamsii	0.417	0.82
Numenius phaeopus	1	0.788
Pluvialis dominica	1	0.886
Phalaropus lobatus	0.667	0.8
Polysticta stelleri	0.5	0.849
Rangifer tarandus	0.722	0.864
Somateria fischeri	0.833	0.925
Ursus maritimus	1	0.712

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"UM"=*Ursus maritimus*,common name=polar bear.

Supplementary Material Table 4. **Running Time in Seconds for Optimization Model. Target: 50%**.

	Development of 1002 Area						
Budget	OD0	OD1	OD2	OD3	OD4	OD5	% Decrease (OD5)*
5×10^7	37.89	47.85	27.92	6.22	6.17	5.89	84.46
5.6×10^7	41.54	53.28	25.99	4.81	4.85	4.75	88.57
7.8×10^7	29.78	39.89	72.27	58.42**	4.63	4.75	84.05
10^8	30.48	31.47	25.86	9.05	7.84	8.05	73.59

* The % decrease in the running time for OD5 compared to OD0.

** Required 79 branch and bound nodes.

Supplementary Material Table 5. **Running Time in Seconds for Optimization Model. Target: 20%**.

	Development of 1002 Area						
Budget	OD0	OD1	OD2	OD3	OD4	OD5	% Decrease (OD5)*
5×10^7	33.16	27.74	9.07	5.88	5.96	5.95	82.06
5.6×10^7	30.73	25.65	7.93	4.8	4.78	4.79	84.41
7.8×10^7	26.42	24.16	7.82	7.81	4.71	4.8	81.83
10^8	31.93	25.32	7.22	7.2	7.84	7.79	75.6

* The % decrease in the running time for OD5 compared to OD0.

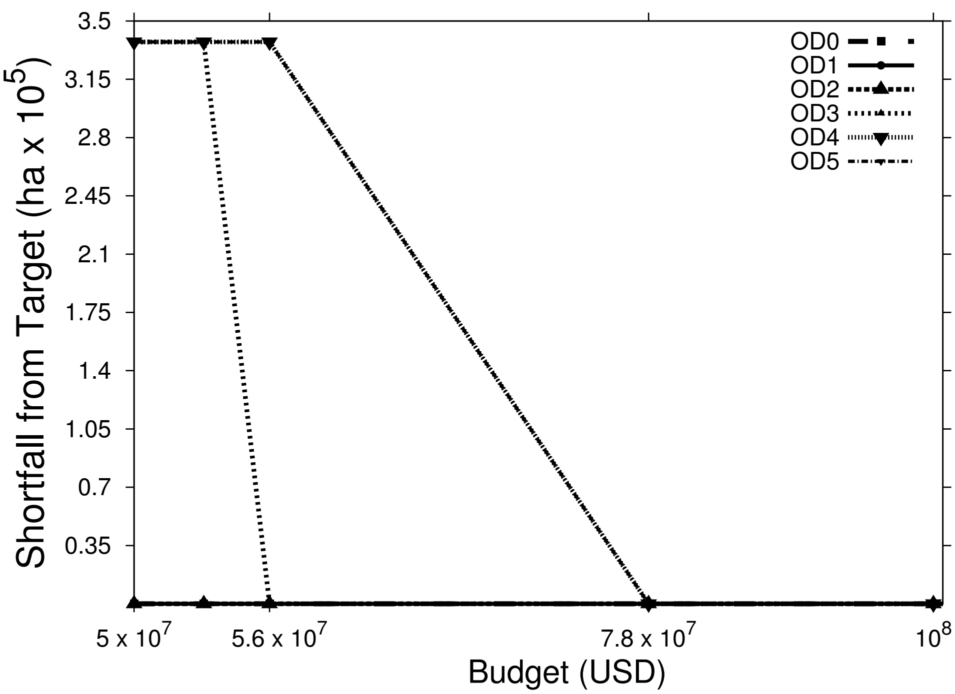

Fig. 2. **Effect of budget on the shortfall from the conservation target**. Target: 20% of the potential habitat sites for each species. The x-axis is plotted on a log scale but budgets are labeled in units of USD to facilitate interpretation.

Species' distribution data UTM coordinates of occurrences of the 11 species were assembled from a recently–completed atlas (NOAA, 2005). In addition, 23 records for the polar bear were digitized from a study of movement data obtained from females instrumented with satellite radio collars from 1998 to 2004 (Fischbach et al., 2007). In total, there were 27 records for the polar bear and 35 for caribou. Table 1 of the Supplementary Material lists the number of records for each bird species. These ranged from 15 to 180 records. Data were projected to the Albers Equal Area coordinate system, which accurately represents the shape and proportional area of sites in the study region (Muller et al., 1999; Amstrup et al., 2000).

Performance tests for the Maxent models The accuracy of the Maxent models was assessed using the AUC and hypothesis tests. First, the AUC was computed on a subset of 25% of the occurrences of each species which were witheld from model training for this test. In this context, the AUC is the probability that a randomly selected site will be correctly classified as suitable or unsuitable habitat for the species (Rosner, 2006). Models with an AUC < 0.75 were rejected (Moffett et al., 2007; Pawar et al., 2007). The AUC has recently been criticized on the grounds that a higher AUC may be obtained by increasing the study region's geographical extent to include sites that are environmentally distant from the species' occurrences (Lobo et al., 2008). To analyze this criticism, the geographical extent of the data set was expanded to include the Brooks Range, which is known to be unsuitable as denning or nesting habitat for the species considered here due to its elevation and distance from the Beaufort Sea. When the Maxent analysis was repeated on the expanded data set, the mean increase in AUC was 3.42%, which is too small to be considered important (Supplementary Material Table 2). In addition, the Maxent models were assessed using a second criterion, the binomial test, which does not involve the AUC (see "Hypothesis Testing in Maxent" in the Supplementary Material). The binomial test was carried out at 11 different thresholds and a Maxent model was retained if the p–value for the test was significant at α=0.05 for at least one threshold.

Exploratory data analysis was conducted to identify the climatic variables for 2007 that provided the best fit to the data described in "Species' distribution data". First, models of the species' potential distributions were constructed using the annual means of the climatic variables in 2007 derived from the `GISS_AOM_SRESB1_1` and `UKMO_HADGEM_SRESA2_1` general circulation models. Next, a second set of models was constructed using the values of the climatic variables in July 2007 only, because the bird species analyzed here only occupy the Arctic Coastal Plain during the summer. In addition, July temperature is a good predictor of the diversity of arctic flora and avifauna (Chapin III et al., 1996; Matveyeva and Chernov, 2000). The species' distribution models with the highest AUCs were the models constructed from the July 2007 climate data associated with the `GISS_AOM_SRESB1_1` general circulation model. These distribution models were used to set the conservation targets for the Optimization Model formulated in Section 2.5.

Hypothesis Testing in Maxent

After generating a model of the distribution of a species, Maxent assesses the model's accuracy by conducting a binomial test on the species' occurrence records that were withheld during the construction of the model. Recall that the Maxent model is probabilistic, that is, it reports the probability that each species is present in each site. The binomial test requires the data to be zero, which represents a "failure", or one, which represents a "success" (Ross, 2002). A success means that the Maxent model predicts that a site is potential habitat for the species and the species has actually been recorded in the site. A failure means that Maxent predicts the site not to be suitable for the species but the species has been recorded in the site. In order to carry out the binomial test, Maxent must convert the probabilities to zero or one based on a threshold. Maxent analyzes 11 different thresholds and reports the results of the binomial test for each threshold (see below). Below are the names of the 11 different thresholds:

1. Fixed cumulative value: 1.
2. Fixed cumulative value: 5.
3. Fixed cumulative value: 10.
4. Minimum training presence.
5. 10^{th} percentile training presence.
6. Equal training sensitivity and specificity.
7. Maximum training sensitivity plus specificity.
8. Equal test sensitivity and specificity.
9. Maximum test sensitivity plus specificity.
10. Balance training omission, predicted area, and threshold value. This threshold minimizes six times the training omission rate plus 0.4 times the cumulative threshold plus 1.6 times the fractional predicted area (see below).
11. Equate entropy of thresholded and non-thresholded distributions.

To illustrate the meanings of these thresholds, consider threshold one, "fixed cumulative value: 1". As one of the steps in the process of constructing a model for each species, Maxent creates a probability density function $\widehat{\pi}$ that estimates the probability of occurrence of each species in each site. $\widehat{\pi}$ has the property that the sum of the probabilities of occurrence over all of the sites equals one. Now suppose that a cumulative distribution function, $\overline{\pi}$, is computed from $\widehat{\pi}$. The probability associated with each site under $\overline{\pi}$ equals the probability associated with the site under $\widehat{\pi}$ plus the probability of all other sites of equal or lower probability (Phillips et al., 2006). Under the threshold "Fixed cumulative value: 1", any site with a cumulative probability less than 0.1 is set equal to zero and any site with a cumulative probability greater than or equal to 0.1 is set equal to one. After the Maxent predictions have been converted to zero and one using the "Fixed cumulative value: 1" threshold or one of the other ten thresholds, the accuracy of the Maxent model can be assessed with the binomial test.

To explain the binomial test, the following notation is required:

t: the number of test localities; $t > 0$.

r: the omission rate for a given threshold ($0 \geq r \geq 1$). This is the number of sites in which the species occurs that are classified by Maxent as unsuitable habitat for the species. (1-r) is the sensitivity or true positive rate.

a: proportional predicted area ($0 \geq a \geq 1$). This is the percent of the study region predicted to be potential habitat for the species.

After the data have been converted to zero or one, Maxent tests the following null hypothesis: H_0: the Maxent model is no better than a model selected at random from the set of all models with proportional predicted area a. H_0 is evaluated via the one–tailed binomial test. If H_0 is rejected at a given threshold, then there is evidence that the Maxent model is accurate. If H_0 is rejected at most or all of the 11 thresholds, then the evidence in favor of the accuracy of the model is more compelling. In the present analysis, H_0 was rejected at least eight of the 11 thresholds for the Maxent model of each species (see Supplementary Material Table 6).

Determining whether to reject H_0 requires computing a binomial probability $\widetilde{p}$. Recall that the binomial test computes the probability of k successes in n trials when the probability of success in each trial is p (Ross, 2002). In the context of modeling the potential distribution of a species, the number of successes is $t(1-r)$, the number of trials is t, and the probability of success in each trial is a (Phillips et al., 2006). According to the binomial formula, the probability $\widetilde{p}$ of observing the data if the null hypothesis were true equals $\binom{t}{t(1-r)} a^{t(1-r)}(1-a)^{rt}$. If $\widetilde{p} \leq 0.05$, then H_0 is rejected. Maxent reports the exact value of $\widetilde{p}$ if the number of test samples is at most 25. This is true of the Black Brant, caribou, polar bear, Red-necked Phalarope, Sanderling, Spectacled Eider, Steller's Eider, and Whimbrel. Otherwise Maxent uses an approximation of $\widetilde{p}$ based on the normal distribution due to the computational effort required to calculate $\binom{t}{t(1-r)}$. The following species had more than 25 records in the test set: the Dunlin, Yellow-billed Loon, and American Golden-Plover.

Supplementary Material Table 6a. **Significance of Threshold–Dependent Tests of Maxent Models**.

	Species						
Threshold	BB	CA	CAP	GA	NP	PD	PL
1	**1.72×10^{-4}**	5.57×10^{-2}	**7.42×10^{-3}**	**5.1×10^{-8}**	**3.25×10^{-3}**	**5.78×10^{-3}**	**2.97×10^{-2}**
2	**1.37×10^{-5}**	**8.03×10^{-4}**	**3.11×10^{-4}**	**2.26×10^{-12}**	**2.71×10^{-2}**	**3.09×10^{-5}**	**1.29×10^{-3}**
3	**2.33×10^{-6}**	**1.96×10^{-5}**	**3.34×10^{-4}**	**2.23×10^{-12}**	**1.6×10^{-2}**	**4.54×10^{-6}**	**9.21×10^{-4}**
4	**2.01×10^{-4}**	6.87×10^{-1}	5.85×10^{-1}	**1.89×10^{-6}**	**1.4×10^{-2}**	1.29×10^{-1}	5.46×10^{-1}
5	**1.3×10^{-6}**	**1.25×10^{-5}**	**2.48×10^{-4}**	**2.07×10^{-13}**	**2.58×10^{-3}**	**6.72×10^{-7}**	**1.1×10^{-3}**
6	**1.32×10^{-5}**	**2.52×10^{-6}**	**1.68×10^{-6}**	**1.08×10^{-17}**	**1.4×10^{-2}**	**6.59×10^{-10}**	**8.71×10^{-5}**
7	**1.32×10^{-5}**	**6.37×10^{-7}**	**3.39×10^{-6}**	**5.77×10^{-28}**	**1.4×10^{-2}**	**1.34×10^{-8}**	**1.39×10^{-4}**
8	**8.9×10^{-4}**	**1×10^{-5}**	**5.95×10^{-7}**	**8.41×10^{-14}**	**1.79×10^{-3}**	**5.71×10^{-9}**	**1.67×10^{-3}**
9	**9.55×10^{-7}**	**1.41×10^{-7}**	**6.02×10^{-7}**	**3.12×10^{-31}**	**1.79×10^{-3}**	**8.47×10^{-9}**	**7.94×10^{-6}**
10	**2.01×10^{-4}**	**5.05×10^{-3}**	**2.68×10^{-3}**	**2.43×10^{-7}**	**3.08×10^{-3}**	**1.36×10^{-3}**	**1.77×10^{-3}**
11	**5.86×10^{-6}**	**2.63×10^{-5}**	**1.01×10^{-5}**	**8.47×10^{-15}**	**1.61×10^{-2}**	**3×10^{-7}**	**6.06×10^{-4}**

The table lists the p–value for each binomial test. Values in bold are significant at α=0.05 and entail the rejection of H_0.

"BB"=*Branta bernicla nigricans*,common name=Black Brant.

"CA"=*Calidris alba*,common name=Sanderling.

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"PL"=*Phalaropus lobatus*,common name=Red–necked Phalarope.

Supplementary Material Table 6b. **Significance of Threshold–Dependent Tests of Maxent Models**.

	Species			
Threshold	PS	RT	SF	UN
1	$\mathbf{1.94 \times 10^{-2}}$	7.83×10^{-2}	$\mathbf{3.09 \times 10^{-5}}$	8.34×10^{-2}
2	$\mathbf{5.97 \times 10^{-4}}$	$\mathbf{3.37 \times 10^{-3}}$	$\mathbf{6.46 \times 10^{-8}}$	$\mathbf{1.71 \times 10^{-2}}$
3	$\mathbf{3.9 \times 10^{-5}}$	$\mathbf{4.46 \times 10^{-3}}$	$\mathbf{1.07 \times 10^{-9}}$	$\mathbf{4.6 \times 10^{-2}}$
4	$\mathbf{7.99 \times 10^{-4}}$	2.8×10^{-1}	$\mathbf{1.52 \times 10^{-4}}$	$\mathbf{4.39 \times 10^{-2}}$
5	$\mathbf{5.64 \times 10^{-4}}$	$\mathbf{6.14 \times 10^{-4}}$	$\mathbf{6.16 \times 10^{-10}}$	$\mathbf{5.71 \times 10^{-3}}$
6	$\mathbf{1.18 \times 10^{-4}}$	$\mathbf{1.82 \times 10^{-4}}$	$\mathbf{2.62 \times 10^{-11}}$	$\mathbf{5.13 \times 10^{-3}}$
7	$\mathbf{2.28 \times 10^{-5}}$	$\mathbf{6.14 \times 10^{-4}}$	$\mathbf{3.05 \times 10^{-9}}$	$\mathbf{9.55 \times 10^{-3}}$
8	$\mathbf{4.67 \times 10^{-4}}$	$\mathbf{1.71 \times 10^{-3}}$	$\mathbf{3.5 \times 10^{-12}}$	7.85×10^{-2}
9	$\mathbf{3.04 \times 10^{-5}}$	$\mathbf{1.26 \times 10^{-4}}$	$\mathbf{1.32 \times 10^{-13}}$	$\mathbf{3.52 \times 10^{-3}}$
10	$\mathbf{7.99 \times 10^{-4}}$	$\mathbf{1.13 \times 10^{-2}}$	$\mathbf{3.32 \times 10^{-7}}$	$\mathbf{2.58 \times 10^{-2}}$
11	$\mathbf{3.68 \times 10^{-5}}$	$\mathbf{6.47 \times 10^{-3}}$	$\mathbf{7.48 \times 10^{-9}}$	6.66×10^{-2}

The table lists the p–value for each binomial test. Values in bold are significant at α=0.05 and entail the rejection of H_0.

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Targets and budgets The solution to the optimization model depended on the target, budget, and the sites available for selection. These data were deterministic, but a range of targets and budgets and budgets were examined. Two targets of species' representation were examined: 20% and 50% of the potential distributions of the species in 2007. Targets of representation of 10–12% have often been used in conservation planning exercises (Margules and Sarkar, 2007). Many of these exercises were conducted in tropical ecosystems where conflicts frequently arise between agricultural land uses and the establishment of protected areas and there is a high density human population. For planning in the Arctic, targets of up to 100% of the distributions of at–risk species have previously been used (Sarakinos et al., 2001). The targets used here attempt to balance species' persistence, which is typically assumed to increase with increasing targets, and conflicts with competing land uses, which may also increase as the targets increase. Due to the remoteness of the Arctic Coastal Plain from urban areas, conflicts with some types of extractive land use may arise less frequently than in tropical ecosystems. Thus, it is reasonable to examine targets larger than the conventional 10% target of representation.

In addition, 11 budgets were analyzed from 50 million USD to 10 billion USD. The lower budget is the estimated cost to clean up one site with oil facilities and the upper budget is the estimated cost to clean up all sites with oil facilities in the study region. Six cases of site availability were assessed, corresponding to the six cases of oil and gas development (OD0, OD1,…, OD5). Under each case of oil and gas development, the sites designated as containing oil and gas facilities were assumed to be unavailable for selection as conservation areas.

Climatic scenarios and oil and gas development Accuracy assessment of the climate variable interpolation indicated low error rates (-0.158 $\leq$ mean standardized error $\leq$ 0.04029, 0.9202 $\leq$ r.m.s. standardized error $\leq$ 1.075, McCoy and Johnston, 2002). Compared to the July 2007 climate for the Arctic Coastal Plain, precipitation and temperature were predicted to be significantly different in 2040. For each climatic variable: Wilcoxon signed rank $V \geq 1.19 \times 10^8$, $p < 2.2 \times 10^{-16}$. Constructing a GIS representation of the cases of oil and gas development required registering digital images of each case. The total r.m.s. error associated with the control points for the image registration was $\leq$ 341.41 m, which was less than the pixel size of each image. Under OD0, all 15 470 sites on the Arctic Coastal Plain were available for selection as conservation areas. Under OD1, 127 sites or 508 km^2 in the Canning River Delta were assumed to contain oil facilities and to be unavailable for selection as conservation areas. OD2 had 1416 km^2 of oil and gas development, OD3 had 2624 km^2, and OD4 had 4576 km^2. OD5 had 6273 km^2 of development, that is, it was assumed that the entire 1002 Area was developed and no site in the 1002 Area could serve as a conservation area.

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