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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

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ABSTRACT

This analysis presents a conservation planning framework for decisions under uncertainty and applies it to the Arctic Coastal Plain of Alaska. Uncertainty arises from variable distributional shifts of species' ranges due to climate change. The planning framework consists of a two-stage optimization model that selects a nominal conservation area network in the first stage and evaluates its performance under the climate scenarios in the second stage. The model is applied to eleven at-risk species in Alaska including the threatened Spectacled Eider and Steller's Eider sea ducks and the polar bear. The 109th United States Congress and 2008 federal budget proposed opening for oil and gas development the "1002 Area" of the Arctic National Wildlife Refuge, which intersects the Plain. This analysis finds that, if Arctic Alaska experiences 1.5 °C of warming by 2040 (as predicted by the Intergovernmental Panel on Climate Change's A2 scenario), then potential habitat will decrease significantly for eight of these at-risk species, including the polar bear. This analysis also shows that there is synergism between oil and gas development and climate change. For instance, climate change accompanied by no development of the 1002 Area results in an increase of potential habitat for Steller's Eider. However, if development accompanies climate change, then there is a 20% decrease in that area. Further, this analysis quantifies the tradeoff between development and maintenance of suitable habitat for at-risk species.

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1. Introduction

Optimization models are often used to design conservation area networks, which are sites administered to protect threatened species and other components of biodiversity (reviewed in Sarkar et al., 2006). Traditionally, these models have been time-static insofar as they have assumed that all of the areas in a nominal conservation area network are put under a con-

servation plan at the same time, and deterministic in the sense that model parameters such as the locations of biodiversity surrogates (such as species or habitat types) and the budget for purchasing land do not have any explicit uncertainty associated with them. However, the importance of incorporating multi-stage predictions about future states of the landscape into conservation planning has been recognized since the mid-1990s. In 1994, an analysis of multi-decadal data on

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species' distributions in the Ingleborough limestone pavements in the United Kingdom demonstrated that if such predictions are not available to the decision-maker during the initial selection of conservation areas, by the final stage, species' turnover and extinction may have significantly decreased the biodiversity contents of areas put under a conservation plan at the first stage (Margules et al., 1994). In the last four years, the inclusion of future climate scenarios in the prioritization of conservation areas has also received increasing attention (Araújo et al., 2004; Pyke and Fischer, 2005; Hannah et al., 2007). The theoretical contribution of this study is to present a framework for multi-stage conservation decision-making under uncertainty that is tractable for problems of the size encountered in realistic planning exercises. The applied aspect of this study is to use this model to develop a nominal conservation plan for the Arctic Coastal Plain in Alaska's North Slope Borough. Uncertainties due to climate change-induced changes in species' distributions are incorporated into this analysis. Northern Alaska is a particularly appropriate setting for a planning exercise about climate change because annual mean climatic warming in the Arctic is predicted to exceed mean global warming and the effect of projected decreases in the extent and thickness of sea ice on fauna such as the polar bear may be profound (Schliebe, 2006; IPCC, 2007).

The Arctic Coastal Plain consists of 49,753 km² of drainage basins of rivers that flow from the Brooks Range into the Beaufort and Chukchi Seas (Duffy et al., 1999). The mammal fauna of the Plain includes the gray wolf *Canis lupus*, the brown bear *Ursus arctos*, four caribou *Rangifer tarandus granti* herds, including the Porcupine Herd with 123,000 individuals, and 1500 polar bears *Ursus maritimus*, which are classified as "vulnerable" by IUCN and proposed for listing as "threatened" by the United States Fish and Wildlife Service (Schliebe, 2006). From 10 May to 2 August the sun is never below the horizon on the Plain. During this time, hundreds of thousands of individuals of 230 bird species also migrate there from Africa, the Americas, and Asia to nest or molt (Troy, 1985; National Research Council, 2003). Two sea duck species that breed on the Plain are listed as "threatened" under the Endangered Species Act: the Spectacled Eider *Somateria fischeri* and Steller's Eider *Polysticta stelleri* (Petersen et al., 2000; Fredrickson, 2001). Ten of the bird species that breed on the Arctic Coastal Plain are also included in Audubon Watchlist 2002, a reliable system for ranking North American birds based on extinction risk (Dunn, 2002) that uses a methodology similar to the IUCN Red List for birds (Stattersfield et al., 2000). Five of these bird species are also classified as "species of high concern" by a working group of shorebird experts at the United States Fish and Wildlife Service and United States Geological Survey because of declining populations (Supplementary Material, Table 1 (Alaska Shorebird Working Group, 2000)).

Development on the Arctic Coastal Plain consists largely of oil and natural gas extraction. Since 1977, 12 billion barrels of oil have been extracted from more than 2000 wells north of the Brooks Range, most near Prudhoe Bay. This constitutes 20–25% of United States oil production and provides taxes and royalties that make up 85% of the budget of the state of Alaska (Gilders and Cronin, 2000). On the Arctic Coastal Plain, 7011 ha of tundra are covered by gravel associated with oil

development and an additional 4300 ha are subject to this development's indirect effects, including flooding, dust-killed vegetation, and thermokarst (National Research Council, 2003). In March 2006, a 5000 barrel crude oil spill, the largest in North Slope history, occurred in the Western Operating Area of Prudhoe Bay (Marshall, 2006). The recovery of Alaskan tundra from such spills requires 600 years for mesic sites and up to 1200 years for marsh sites (National Research Council, 2003). Subsequent tests of the Eastern Operating Area led to the shutdown of Prudhoe's 400,000-barrel per day production on 6 August 2006. It is estimated that when oil production at Prudhoe Bay ceases to be economically feasible, around 2040, the cleanup of oil facilities will cost 10 billion USD (US Government Accountability Office, 2002).

The 1002 Area of the Arctic National Wildlife Refuge (627,300 ha) is the sole protected area that intersects the Arctic Coastal Plain. The United States Alaska National Interest Lands Conservation Act of 1980 prohibited oil development elsewhere in the Refuge but authorized study of the 1002 Area's potential for oil production, which is now estimated at 7.7 billion barrels (Schuenemeyer, 2002; Montgomery, 2005). The United States House of Representatives in HR 2491 in 1996, HR 4 in 2001, HR 6 in 2003, and HR 5429 in 2006, and Senate in S. 1932 in 2005 have passed bills to open the 1002 Area to oil development. In addition, the Fiscal Year 2008 budget proposed by the Executive Office of the President assumes 7 billion USD in oil lease revenues from the 1002 Area (Corn et al., 2007).

These proposals are inimical to biodiversity conservation in the Arctic Coastal Plain. Development of the 1002 Area may result in population declines in the polar bear, which shows greater preference for the 1002 Area for denning than other nearby areas, and may also reduce calf survival in the Porcupine Herd caribou (Stirling, 1990; Amstrup and Gardner, 1994; McCabe, 1994). Steller's Eider is susceptible to oil spills during molt because of its gregarious nature and because, as a bottom feeder, it is likely to become covered with oil each time it surfaces (Blood, 1977; Bustnes, 1997). The eastern Arctic Coastal Plain, which includes the 1002 Area, also includes breeding grounds for the Spectacled Eider *Somateria fischeri*, which is federally listed as "threatened" because of a 96% decline in the Alaska population since 1957 (Petersen et al., 2000). Oil development is also likely to impact negatively other birds of conservation concern on the Arctic Coastal Plain. The Black Brant Goose *Branta bernicla nigricans* experiences low nest success in oil fields and requires an undisturbed environment to regrow feathers during molt (Taylor, 1995; Sedinger and Stickney, 2000).

Assessment of the effects of oil and gas development in the future must also take climate change into consideration because the Arctic Coastal Plain is experiencing surface warming and concomitant increased vegetation greenness and shrub abundance (Lachenbruch and Marshall, 1986; Jia et al., 2003, 2006; Bunn and Goetz, 2006). This warming is predicted to result in population declines in both the Porcupine Herd caribou and the polar bear (Eastland and White, 1990; Stirling and Derocher, 1993; Stirling et al., 1999). The United States District Court for the state of Alaska recently ruled that there was insufficient scientific data on the combined effects of global warming and oil and gas development on the Plain

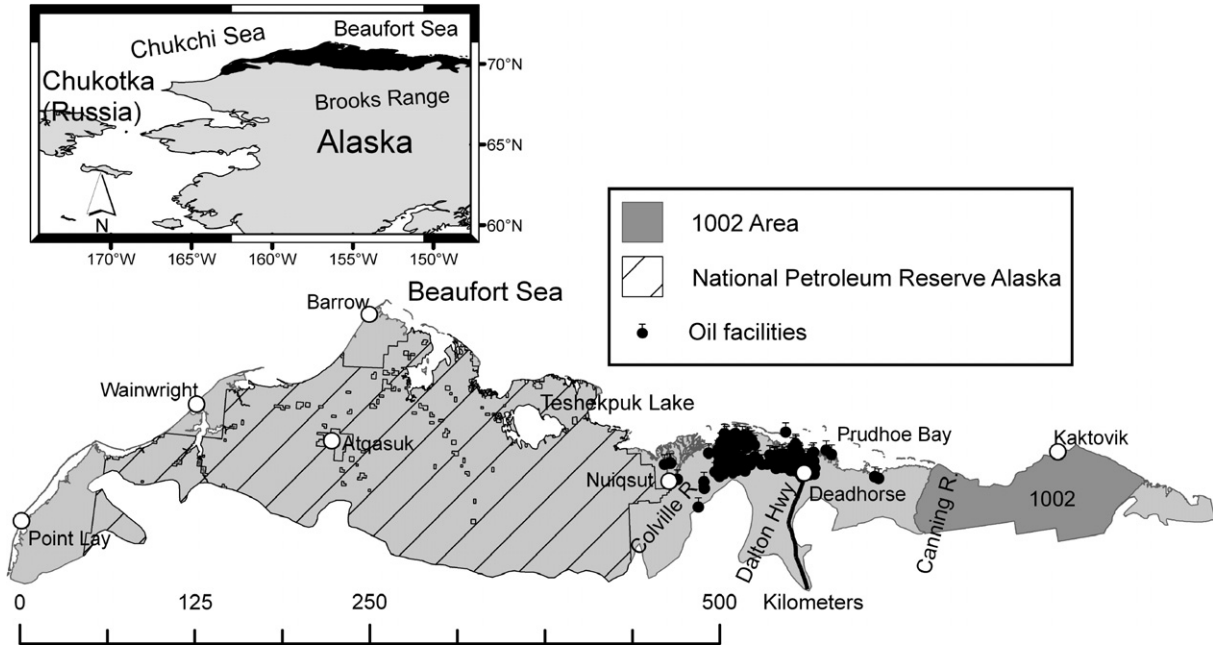


Fig. 1 – The Arctic Coastal Plain. Inset: Location of the Arctic Coastal Plain, shown in black, in northern Alaska.

to justify halting oil and gas extraction near Teshekpuk Lake (Singleton, 2006). To date, there have been relatively few studies of the interaction between climate change and oil and gas development, though this interaction is forecast to decrease forage quality and access to forage for lactating caribou in the Alaskan Arctic (Gerhart et al., 1996; Klein, 1999; Griffith et al., 2002). One objective of this paper is to quantify these combined effects by applying and analyzing solutions of a two-stage stochastic optimization model.

Stage one of the model selects nominal sites in 2007 to serve as potential conservation areas in the Arctic Coastal Plain. This study then simulates shifts in the potential distributions of species due to climate change in 2040, which is the second stage of the model. Next, the optimization model determines if the conservation areas selected in the first stage still represent the targeted amount of habitat after climate-induced shifts in the species' distributions in the second stage (Fig. 2). The conservation areas designated by the model in 2007 are "optimal" to the extent that they minimize the shortfall of the species' habitat from their conservation targets in 2040, averaged over scenarios representing shifts in the potential distributions of the species. The model assumes that there is an effect of climatic warming and other climatic and topographic variables on the potential distributions of the species and analyzes the outcomes of several probabilistic scenarios representing differing amounts of warming. In the model, the budget for establishing conservation areas is deterministic, but 11 different budget sizes were separately analyzed.

This study makes the following contributions. First, it provides techniques for analyzing the interaction between climate change and habitat transformation due to development. Second, this study presents a modeling framework for conservation planning in the presence of shifts in species' potential

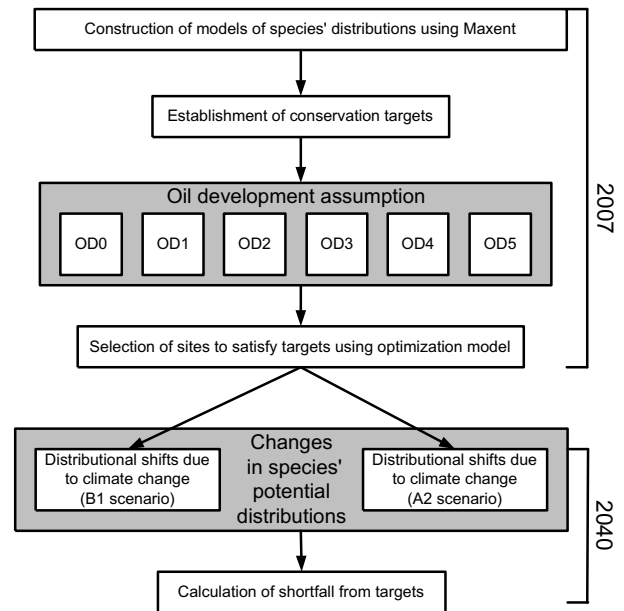


Fig. 2 – Flowchart of the simulation and optimization framework for conservation planning under uncertainty used in this study. OD0, OD1, . . . , OD5 represent the six cases of oil and gas development of the 1002 Area that were examined. The extent of oil and gas activity increases with the case number. In OD0, it is assumed that the 1002 Area is intact. In OD1, there is development in the Canning River Delta only. In OD5, the entire 1002 Area is developed. The cases of oil development are deterministic whereas the species' responses to climate change have explicit uncertainty associated with them.

distributions and habitat loss. This framework, which selects the optimal set of sites in 2007 given uncertain future scenarios, can accommodate a much larger number of sites than previously-published techniques for the prioritization of areas under uncertainty. Finally, this study quantifies the conservation significance of the 1002 Area.

2. Methods

2.1. Study area

Located in northern Alaska (latitude: 69°14'–71°14'N, longitude: 141°16'–163°5'W), the Arctic Coastal Plain is a physiographic province characterized by prostrate graminoid shrubs in the warmer, wetter half west of the Colville River and a calcium-rich non-acidic tundra complex in the eastern half (Muller et al., 1999) (Fig. 1). 49% of the Plain lies within the Arctic Circle, which begins at 66°32'N. For this analysis, the Arctic Coastal Plain was divided into 15,470 sites at the 2 × 2 km resolution because at this scale: (i) polar bears are sensitive to the effects of oil exploration (Amstrup, 1993) and (ii) the optimization model, developed in Section 2.5, remains computationally tractable (see below). The 1002 Area, which is the section of the Arctic National Wildlife Refuge that intersects the Arctic Coastal Plain, comprises 1696 sites at the 2 × 2 km resolution and is located at latitude 69°27'–70°4'N and longitude 142°17'–146°33'W.

2.2. Climate scenarios

Two climate scenarios were examined, the Intergovernmental Panel on Climate Change (IPCC)'s B1 and A2 scenarios, because they represent the extremes of the range of projected temperature change for northern Alaska in 2040. Thus results that hold when both scenarios are included should be robust if intermediate ones occur. The B1 scenario is the coolest scenario for the region, with a projected increase in temperature of 4–6 °C, and the A2 scenario is the hottest scenario, with a projected increase of 4–11 °C (IPCC, 2007). There are several general circulation models for each scenario. The IPCC's Fourth Assessment Report was consulted to identify the three models with the lowest projected temperatures for the B1 scenario and the three models with the highest projected temperatures for the A2 scenario. Model selection was based on temperature rather than precipitation because the latter is predicted to increase in the study region by only 10% by the 2040s and this increase will be offset by increased evapotranspiration (Oechel et al., 1997; Plumer et al., 2006). This study used the GISS_AOM_SRESB1_1 model for the B1 scenario, because, of the three lowest temperature models for the B1 scenario, this model had the largest number of climatic variables available for download from the World Data Center for Climate. Similarly, the UKMO_HADGEM_SRESA2_1 model was used for the A2 scenario because, of the three highest temperature models for the A2 scenario, this model had the largest number of variables available for download. The climate models were downloaded in GRB format and converted to ESRI shapefiles using the NDFD Grib2 Decoder ver 1.9. The shapefiles were interpolated to a 2 × 2 km grid using ordinary kriging (Haining, 2003).

2.3. Oil development assumptions

This study examined six spatial cases of development of the 1002 Area based on expert opinion (for details, see Tussing and Haley, 1999; Kruse et al., 2004). Case OD0 assumes that the 1002 Area is intact. Cases OD1, ..., OD5 involve oil and gas activity in the 1002 Area that ranges from the development of 508 km² of the Canning River Delta in OD1 to the development of the entire 6273 km² of the 1002 Area in OD5. The cases are hierarchically cumulative in the sense that OD2 includes the development in OD1 as well as additional development.

Sites currently containing oil facilities were identified from the atlas in NOAA (2005). If a site currently contains oil facilities, the cost of selecting that site for conservation was set equal to the expense of restoring the site to wildlife habitat, which includes the cost of gravel decontamination, well plugging and abandonment, and revegetation. Such restoration is estimated to cost 1.85 × 10⁶ USD per ha on the average (Gilders and Cronin, 2000; National Research Council, 2003). If a site does not currently contain oil facilities, the cost of the site was set equal to the cost to lease the site calculated as the mean price per ha in the 58 competitive lease sales in Alaska between 1984 and 2003 plus the per ha premium for leases in the North Slope region. This computation gives an average cost of 236.83 USD per ha (Haas, 2005).

Oil and gas development was modeled only through 2040 because oil production at Prudhoe Bay is predicted to cease by this date, requiring the state of Alaska to begin habitat restoration. In addition, the Arctic Sea is predicted to be free of ice in the summer by 2040 (Holland et al., 2006; Serreze et al., 2007). Moreover, sea level rise resulting from the breakup of multi-year pack ice by 2040 may adversely affect fauna by inundating low-lying islands near the coast. Multi-year ice is ice that forms in winter and survives at least one summer (Davis, 2000). Such ice is >2 m thick, blue, and has low conductivity and salinity. Changes in the mass of shelf ice do not effect sea level because the shelf is floating. However, sea ice serves as a buffer against the discharge of inland ice into the ocean. Thus, the melting of sea ice may result in sea level rise by increasing the discharge of ice into the ocean (Massom and Lubin, 2005). These islands (mean elevation: 1.83 m) are used by the Black Brant for nesting and by the caribou for the avoidance of insect harassment (Gavin, 1976). Thus, climate change is likely to impact Alaskan fauna within the time-span of the model reported here.

2.4. Models of species' ecological niches

2.4.1. Overview of maxent

A model of the potential distribution of the 11 species under consideration was constructed using a maximum entropy algorithm implemented in the Maxent 3.1 software package (Phillips et al., 2004, 2006). For each species, the input for the algorithm was the set of sites in which the species occurred (see "Species' distribution data" in Supplementary Material). Associated with each such site are "features", which are linear and quadratic functions of the explanatory variables and their products (see Section 2.4.2). Maxent computes a probability density function $\hat{\pi}$ that is as close as possible to a maximum entropy distribution subject to the constraints that the mean and variance of each feature under

$\hat{\pi}$ are close to the mean and variance of the feature at the sites at which the species was recorded as present. In addition, the covariance of any pair of features under $\hat{\pi}$ is required to be close to the covariance of the features in the sites at which the species was present. If a set of ecological parameters is used as the “features”, then the biological interpretation of $\hat{\pi}$ is that it represents the potential distribution or fundamental niche of each species. Maxent was used for this study because it is among the best performing machine-learning methods for modeling species’ distributions and can accommodate presence-only data (Elith et al., 2006). The settings for Maxent were the same as those described in Pawar et al. (2007). The Maxent models were compared to models obtained using the Random Forest algorithm (see “Comparison of Maxent to Random Forest” in Supplementary Material). Following published guidelines, the accuracy of each Maxent model was assessed using two criteria including the AUC (area under the receiver operating characteristic curve) and a binomial test of model performance (Moffett et al., 2007; Pawar et al., 2007) (see “Performance tests for the Maxent models” in Supplementary Material).

2.4.2. Explanatory variables in the maxent model

The following explanatory variables were included in the distributional models for all 11 species: aspect, elevation, meridional surface wind speed, sea level pressure, slope, surface downwelling shortwave radiation, total precipitation, 2 m surface air temperature, and zonal surface wind speed. The models of the species’ distributions in 2007 were constructed from climatic variables derived from the GISS_AOM general circulation model. GISS_AOM was used for 2007 rather than UKMO_HADGEM because the former resulted in models with higher AUC values (see “Performance tests for the Maxent models” in Supplementary Material). Models of the species’ distributions in 2040 were constructed by refitting the 2007 model with the predicted values of the climatic variables in 2040 according to the GISS_AOM and UKMO_HADGEM general circulation models (see Section 2.4.3).

Climatic and topographic variables are routinely used to model potential habitat for a species and to predict species’ responses to climate change (reviewed in Peterson et al., 2005). Some of the other explanatory variables used here were selected because they may directly influence habitat selection by birds, caribou, and the polar bear. Slope and aspect may be good predictors of species’ potential distributions on the Arctic Coastal Plain because floral diversity varies with topographic relief in arctic Alaska and south-facing slopes are well drained and warm (Matveyeva and Chernov, 2000). Wind speed may affect habitat selection in polar bears because wind stress controls snow and ice formation (Davis, 2000). Polar bears require stable ice for hunting and migration and need snow to construct a den (Schliebe, 2006; Fischbach et al., 2007). Finally, radiation influx may affect species’ distributions because radiation provides energy for biological and physical processes (Weller, 2000). The projected value of the climatic variables used in this study were available for download for both 2007 and 2040 from the World Data Center for Climate. Like other studies (Pyke and Fischer, 2005; Williams et al., 2005), this analysis assumes that the non-climatic environmental variables will not change by 2040.

2.4.3. Forecasting species’ future distributions

The Maxent models developed from the topographic variables and the July 2007 climate variables were then fitted to the climate scenarios for July 2040. This assumes that the species can fully disperse from habitat that is suitable in 2007 to habitat that may become suitable in 2040. This assumption is plausible for the nine bird species, which migrate thousands of kilometers annually (Troy, 1985, 2000). The assumption is also defensible for highly mobile quadrupeds such as the polar bears of the Southern Beaufort Sea, which disperse up to 6000 km annually (Amstrup et al., 2000), and caribou of the Porcupine Herd, which migrate more than 1000 km annually (Murphy and Lawhead, 2000). Nevertheless, the Discussion will note that these assumptions about successful dispersal may be overly optimistic and should be treated with caution. This analysis also assumes that climate constrains the species’ distributions. However, the primary determinants of the distributions of some of the species considered here may be prey availability, land-use, and vegetation (Pearson and Dawson, 2003; Araújo and Luoto, 2007). The response of vegetation to climate change may result in a migration lag due to inadequate seed dispersal or competition from the resident plants at a site (Davis, 1989).

2.5. Optimization model and computations

The optimization model used to select conservation areas on the Arctic Coastal Plain is a two-stage stochastic program (Birge and Louveaux, 1997; Fuller et al., 2008). In such a program, some of the data parameters are random variables whose values are determined by a random experiment. The first-stage decision is made before the values of the random variables are disclosed. The second-stage “recourse” decision constitutes a response to the random experiment. The program minimizes the costs associated with the first-stage decision and the expected value of a function of the stage one decision variables and the random variables.

Sets

$i \in I$	species
$j \in J$	sites
$\omega \in \Omega$	scenarios representing shifts in species’ potential distributions

Data parameters

c_j	cost of site j in stage one $c_j = 7.4 \times 10^8$ USD if j contains oil facilities, 9.47×10^4 USD otherwise
t_i	targeted number of hectares of habitat for species i
b_1	stage one budget $b_1 \in [5 \times 10^7, \dots, 10^{10}$ USD]
a	number of hectares per site

Random data

p^ω	probability of scenario ω . $p^\omega \in [0,1]$, $\sum_{\omega \in \Omega} p^\omega = 1$
b_{ij}^ω	1 if species i is in site j in scenario ω . 0 otherwise.
	$b^\omega \in \{0,1\}^{ I \times J }$

Decision variables

x_j	1 if site j is selected in stage one. 0 otherwise. $x \in \{0,1\}^{ J }$
y_i^ω	tally the shortfall in units of hectares for species i from its target in scenario ω . $y_i^\omega \in [0, t_i]$

Formulation

$$\min_x \sum_{\omega \in \Omega} p^\omega Q(x, b^\omega) \quad (1)$$

$$\text{s.t.} \quad \sum_{j \in J} c_j x_j \leq b_1 \quad (2)$$

$$x_j \in \{0, 1\}, \quad j \in J \quad (3)$$

where

$$Q(x, b^\omega) = \min_{y^\omega} \sum_{i \in I} y_i^\omega \quad (4)$$

$$\text{s.t.} \quad y_i^\omega \geq t_i - a \sum_{j \in J} b_{ij}^\omega x_j, \quad i \in I \quad (5)$$

$$y_i^\omega \geq 0, \quad i \in I \quad (6)$$

The optimization model (1)–(3) consists of a first-stage decision, followed by changes in the species' potential distributions, followed by a second-stage recourse decision. In the first stage, the x decision variables indicate which sites are selected as conservation areas. Whether oil facilities are present in the site determines site cost. The optimization model does not require discounting of future costs because it selects sites in 2007. Constraint (2) requires that the cost of the sites selected in stage one does not exceed the budget. This constraint models the limited funds available to conservation planners for buying and managing land. Constraint (3) states that each site must be selected or not selected in stage one. The selection of sites in 2007 is constrained only by the budget. There is no attempt to minimize the shortfall with respect to targets in 2007. Eleven different values for the budget were analyzed (see "Targets and budgets" in Supplementary Material).

The second-stage decision consists of tallying the amount by which the species' target exceeds the number of hectares selected in stage one that contain the species. After the stage-one decision, the species' potential distributions shift due to climate change by 2040. In the second stage, the optimization model checks whether the sites selected in 2007 cover the targeted number of ha of habitat for each species (targets are discussed in "Targets and budgets" in Supplementary Material). The objective function in (4) sums the shortfall under scenario ω , if any, of each species from its target. Eq. (4) is a minimization so that the shortfall is as small as possible in each scenario b^ω . The overall objective function in (1) then takes the expected value of the species' shortfalls over all b^ω scenarios. Together, constraints (5) and (6) capture $\max\{t_i - a \sum_{j \in J} b_{ij}^\omega x_j, 0\}$. This is the total shortfall (in hectares) of the habitat of species i from its target. $\sum_{j \in J} b_{ij}^\omega x_j$ is the number of selected sites in which species i is present in scenario ω . The conversion factor a translates this number into hectares.

The Maxent output consists of the probability of occurrence of each species in each site under the B1 and A2 climate scenarios in July 2040. However, the optimization model requires species' occurrence data with binary 0–1 values, with 1 indicating presence and 0 indicating absence. The Maxent output was converted to binary values using the following rounding procedure (Supplementary Material, Fig. A.1). Let p_{ij} be the probability of occurrence of species i in site j obtained from Maxent, let $X \sim U(0,1)$ be a uniformly distributed random variable, and let b_{ij}^ω be the output of iteration ω of the rounding procedure. If X is less than p_{ij} , then b_{ij}^ω is set to one.

Otherwise b_{ij}^ω is set to zero. So, the expected value of b_{ij}^ω generated via randomized rounding equals p_{ij} . A total of $|\Omega| = 100$ scenarios of species' relocation in 2040 were generated by rounding the Maxent predictions. Half of the relocation scenarios were constructed by running the rounding procedure on the Maxent models derived from the B1 climate scenario. The other half were constructed from the Maxent models based on the A2 climate scenario. Whereas the six cases of oil and gas development were deterministic, the species' responses to climate change were treated as uncertain and analyzed by examining 100 probabilistic scenarios.

The optimization problems were formulated as SMPS files and solved with the COIN-OR C++ library using CPLEX 9.0 to solve the mixed integer programs (Gassmann and Schweitzer, 2001; Lougee-Heimer, 2003). For a discussion of the solution of integer programs using branch-and-bound algorithms, see Önal (2004). Mixed integer programs were solved using a relative tolerance of 10^{-5} . Computations were performed on a Dell Precision 530 Workstation with dual 1.8 GHz Xeon processors and 1 GB of RAM running SuSE Linux version 9.3.

3. Results

3.1. Models of species' distributions

The null hypothesis that the Maxent model is no better than a model selected at random from the set of all models with the same proportional predicted area was rejected for all 11 species (Table 1, Supplementary Material, Table 6). Under the A2 climate scenario, the area of potential habitat is expected to decrease for eight of the 11 species, including the polar bear and Steller's Eider (Fig. 3). For each species, the decrease is very highly significant (Wilcoxon rank sum $W \geq 1.18 \times 10^8$, $p \leq 2.2 \times 10^{-16}$). Under the B1 climate scenario, the area of potential habitat is forecast to increase for ten species (Fig. 3). For each species, the increase is very highly significant ($W \geq 5.19 \times 10^6$, $p \leq 2.2 \times 10^{-16}$). "Climate scenarios and oil and gas development" in Supplementary Material details the predicted changes in precipitation and temperature on the Arctic Coastal Plain from 2007 to 2040.

Table 1 – Accuracy assessment of models of species' distributions

Species	AUC ^a	No. of significant tests ^b	TP ^c
<i>Branta bernicla nigricans</i>	0.834	11	0.87
<i>Calidris alba</i>	0.818	9	0.91
<i>Calidris alpina</i>	0.864	10	0.864
<i>Gavia adamsii</i>	0.863	11	0.82
<i>Numenius phaeopus</i>	0.957	11	0.788
<i>Pluvialis dominica</i>	0.832	10	0.886
<i>Phalaropus lobatus</i>	0.831	10	0.8
<i>Polysticta stelleri</i>	0.871	11	0.849
<i>Rangifer tarandus granti</i>	0.872	9	0.864
<i>Somateria fischeri</i>	0.893	11	0.925
<i>Ursus maritimus</i>	0.768	8	0.712

a Area under the receiver operating characteristic (ROC) curve.

b Number of hypothesis tests with a p -values ≤ 0.05 .

c True positive rate or sensitivity.

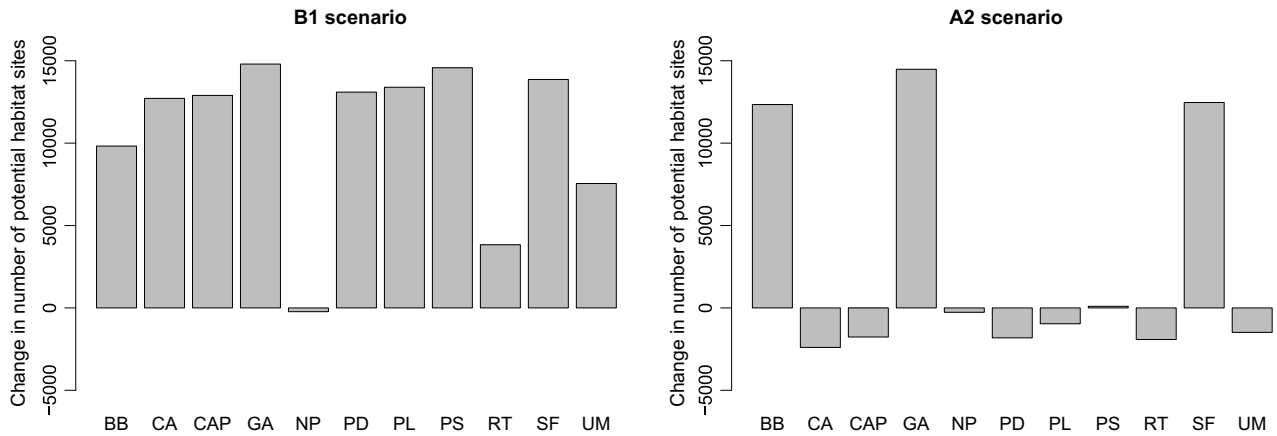


Fig. 3 – Change in the number of potential habitat sites for species of conservation concern on the Arctic Coastal Plain. In each case, the change in the number of sites potential habitat from 2007 to 2040 was significant at $\alpha = 0.05$ based on a Wilcoxon rank sum test. For each species, the height of the bar is based on the difference between the number of sites predicted to be potential habitat in 2007 with probability $> \frac{1}{2}$ and the number of sites predicted to be potential habitat in 2040 with probability $> \frac{1}{2}$. The probabilities of occurrence were obtained from Maxent. “BB”=*Branta bernicla nigricans*, “CA”=*Calidris alba*, “CAP”=*Calidris alpina*, “GA”=*Gavia adamsii*, “NP”=*Numenius phaeopus*, “PD”=*Pluvialis dominica*, “PL”=*Phalaropus lobatus*, “PS”=*Polysticta stelleri*, “RT” = *Rangifer tarandus*, “SF”=*Somateria fischeri*, “UM”=*Ursus maritimus*.

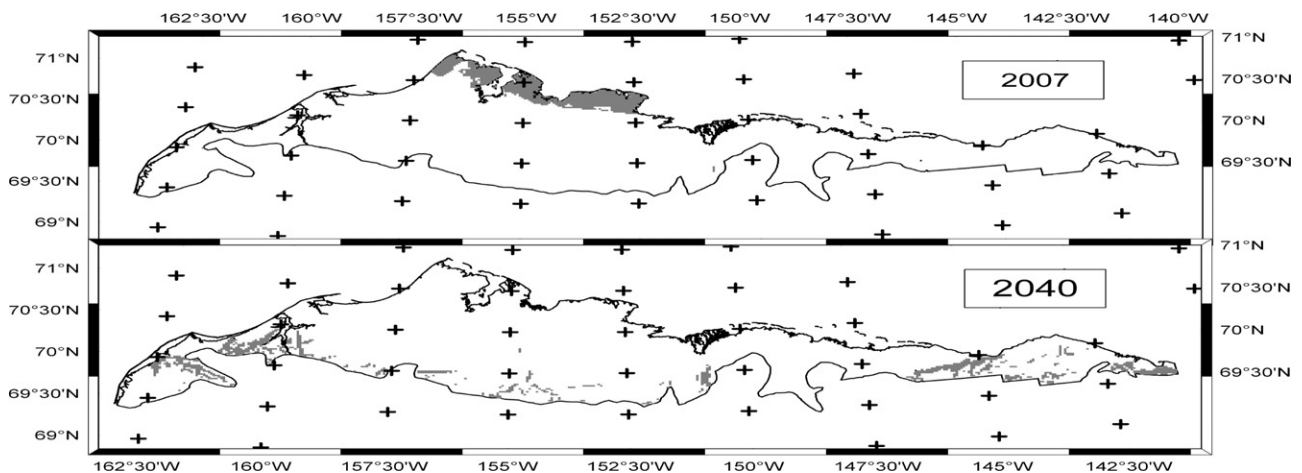


Fig. 4 – Effect of climate change on the distribution of birds on the Arctic Coastal Plain. Sites in gray are the potential distribution of Steller’s Eider *Polysticta stelleri*, a sea duck listed as “vulnerable” by the IUCN. The probability that each gray site is potential Eider habitat is $> \frac{1}{2}$ according to Maxent. Under the A2 climate scenario in 2040, the distribution of Steller’s Eider is predicted to shift south into sites in the 1002 Area. Crosses indicate 2.5° increments of longitude and 0.5° increments of latitude.

3.2. Optimization results

Results indicate that there is a trade-off between oil and gas development and the representation of biodiversity insofar as the shortfall from conservation targets increases with increasing development (Fig. 5). Each point in Fig. 5 represents the optimal solution to the optimization model for a given budget, target, and set of undeveloped sites. In Fig. 5 the target is 50% (Fig. A.2 of Supplementary Material provides the same information when the target is 20%). Points connected by a line represent the same case of oil and gas development. When the budget, target, and case of oil and gas development

are fixed, the shortfall plotted in Fig. 5 is optimal, that is, there is no stage-one site selection decision that can achieve a lower expected shortfall while satisfying the budget constraint for that target. However, different cases of oil and gas development result in different shortfalls from the conservation target. A shortfall greater than zero indicates that even if an optimal algorithm is used to design the conservation area network, then it is not possible to protect the targeted amount of habitat for each species using the amount of land that can be afforded at the current budget level.

For a fixed budget and target, the shortfall from conservation targets is a non-decreasing function of the amount of

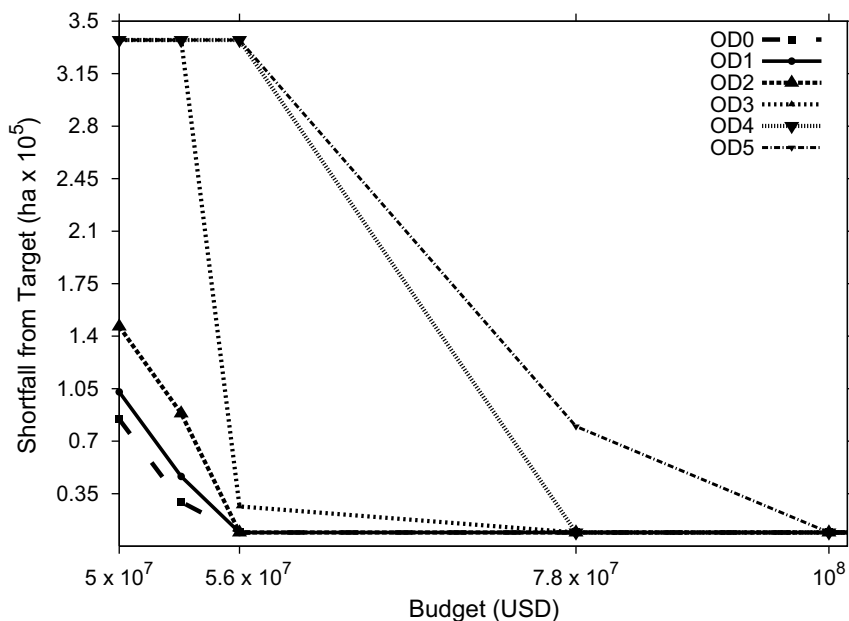


Fig. 5 – Effect of budget on the shortfall from the conservation target. Target: 50% of the potential distribution of each species. The x-axis is plotted on a log scale but budgets are labeled in units of USD to facilitate interpretation. The shortfall measures the extent to which the conservation areas selected in 2007 represent the species' potential distributions after climate change. The effectiveness of the conservation area network decreases as the shortfall increases.

development in the 1002 Area. For example, when the budget is 50 million USD, the shortfall is 85 592 ha if no development occurs (Fig. 5). However, under OD5, the shortfall is 337,400 ha, an increase of 299%. When the amount of development is fixed, the shortfall is a non-increasing function of the budget. For example, under OD4, in which there is extensive natural gas production east of Prudhoe Bay, if the budget is 50 million USD, then the shortfall is 337,400 ha. However, if planners could afford to spend 78 million USD to establish conservation areas, then the shortfall decreases to 9152 ha, a 97% decrease. As the shortfall decreases, the extent to which the conservation areas represent the species' potential distributions increases. Thus, a 97% increase in target satisfaction requires only a 56% increase in spending. For a fixed target and budget, the shortfall is up to 35 times greater when the entire 1002 Area is developed than when no development occurs. Fig. 5 only plots the results for budgets from 50 million USD to 100 million USD because for larger budgets, the shortfall does not decrease.

3.3. Computational performance

The running time for the optimization model was at most 72.27 s (Supplementary Material, Tables 4 and 5). The only optimization problem that required the use of any branch-and-bound nodes in the integer programming solution algorithm was that with the 50% target with a budget of 7.8×10^7 USD under OD4, which required 79 nodes. For a fixed target and budget, the running time decreased with increasing oil and gas development because fewer sites are available for selection. The computational difficulty of the optimization problem increases with the number of sites. In particular, the running time of the optimization model decreases up to 89%

when there is extensive oil and gas development such that 11% fewer sites are available for selection as conservation areas (see the rightmost column of Supplementary Material, Table 4).

4. Discussion

Several recent studies have incorporated predictions about climate change into the selection of conservation areas. The protocol developed here, including the stochastic optimization model, has several advantages over these studies. Like Pyke and Fischer (2005), this study selects optimal conservation areas to minimize the shortfall from conservation targets after climate change. (Long before Pyke and Fischer (2005), a model for minimizing the expected shortfall from species' targets was introduced by Cocks and Baird (1989).) However, the analysis presented here differs from Pyke and Fischer (2005) by incorporating uncertainty about species' distributions, by using real data on site cost, by modeling shifts in species' potential distributions due to climate change with a machine-learning algorithm, and by using IPCC scenarios to model future climate. The decision-making structure of the model presented here also differs from that of Pyke and Fischer, which selects conservation areas at present to represent species' habitat, present-day environmental classes, and future environmental classes. This requires assigning weights to species and bioclimatic parameters. Such weights are open to the charge of arbitrariness.

Williams et al. (2005) used heuristics to select dispersal and persistence areas for sessile species in an urbanized landscape under a single IPCC climate scenario. In contrast, this study implements an optimal algorithm to select conservation areas in a remote, largely untransformed landscape

and analyzes two IPCC scenarios that represent the extreme scenarios for northern Alaska with respect to the predicted increase in temperature. The optimization model used does not select dispersal chains to link the conservation areas because each species considered here is a long-distance migrant. For this reason, it is plausible that the species can relocate to new conservation areas if its current habitat becomes unsuitable due to climate change. Hannah et al. (2007) applied the approach of Williams et al. (2005) to the Cape Floristic Region of South Africa, Mexico, and Western Europe, again using a deterministic heuristic algorithm and a single IPCC climate scenario. The approach of Hannah et al. (2007) is similar to the model presented here to the extent that both analyses involve two stages. The model presented here selects sites in 2007 but also takes a recourse decision in 2040 to respond to shifts in species' potential distributions under climate change. The recourse decision computes the shortfall of the species from the conservation targets established in 2007. The model selects conservation areas in 2007 that are optimal to the extent that they minimize the expected value of this shortfall. Hannah et al. (2007) selected sites to satisfy species' conservation targets in 2007 and then selected the additional sites, if any, required to satisfy the targets in 2050. Thus, the approach of Hannah et al. (2007) can be characterized as finding a heuristic solution to a single-stage planning model two times – once in 2007 and once in 2050. In contrast, the present analysis finds the optimal solution to a two-stage planning model.

Araújo et al. (2004) and Rounsevell et al. (2006) used heuristics and metaheuristics to select conservation areas now and then examined the predicted performance of the areas in 2050. van Rensburg et al. (2004) conducted similar analyses for an optimal algorithm. McClean et al. (2006) compared conservation area networks designed using complementarity-based heuristics based on species' distributions in 2005 to networks designed to represent species' modeled distributions in 2025, 2055, and 2085. This study differs from Araújo et al. (2004), McClean et al. (2006) and Rounsevell et al. (2006) to the extent that the area selection algorithm used here is optimal. Unlike the optimal algorithm of van Rensburg et al. (2004), which selects sites based on species' current distributions, the optimization model presented here has two stages and uses species' predicted distributions in 2040. Pyke et al. (2005) prioritized areas using site scores based on the difference between the mean annual precipitation across a species' range in 2000 and the predicted precipitation in protected areas under the HADCM2n general circulation model in 2050. This study differs from Pyke et al. (2005) by implementing an optimal algorithm, by examining two general circulation models, and by incorporating uncertainty about species' potential distributions into the area prioritization.

Other recent models have generalized conservation area selection to stochastic contexts to include the establishment of conservation area networks in multiple stages and random destruction of species' habitat (Costello and Polasky, 2004; Snyder et al., 2004; O'Hanley et al., 2007). However, these models have been applied only to relatively small planning problems of up to 146 sites. In addition, these models have assumed that protecting a single population of each species is adequate. The model presented here can accommodate

varying targets of representation from one population up to all populations of a species and is computationally tractable up to at least 1.547×10^4 sites.

For the majority of species examined here, the area of potential habitat on the Arctic Coastal Plain is predicted to expand by 2040 (Fig. 3). Two of the bird species whose potential distributions are predicted to increase under both climate scenarios, the Spectacled Eider and Yellow-billed Loon, breed on the Arctic Coastal Plain in the summer and winter elsewhere in Alaska (North, 1994; Petersen et al., 2000). If northern Alaska experiences sufficient warming, these species might become winter residents on the Plain. However, increases in the area of their potential distributions do not ensure that Alaskan fauna will experience significant increases in geographic distribution or abundance as a result of climate change. Though increases in temperature and precipitation associated with a changing climate may make additional sites on the Plain part of a species' "fundamental niche", which is defined using the complement of ecological factors required by the species, the geographic distribution of the species may not increase due to behavioral and topographic barriers that block the colonization of new habitat (Soberón and Peterson, 2005). Migratory bird species such as those analyzed here typically have higher mortality on the periphery of their ranges (Brown and Gibson, 1983; Kertell, 1991). This may make it difficult to establish new populations in habitat that becomes suitable due to climatic warming. Topographic barriers to the colonization of more southerly sites on the Plain by shorebirds include the fact that the salt marsh and meltwater pond habitats preferred by these birds are rare further inland (Spindler et al., 1984; Troy, 1985, 2000). As indicated in Section 2.4.3, the species modeled here are probably good dispersers; nevertheless, these possible dispersal restrictions should be recognized so that there is no overly optimistic interpretation of the niche models.

This analysis assumes that the elevation of sites on the Arctic Coastal Plain will not change by 2040. It is possible that elevation serves as surrogate for some climate variables and masks the effect of climate change on species' future distributions. To assess this masking effect, the percent contribution of each explanatory variable to the Maxent model was determined (Phillips et al., 2006). Of the 11 species considered here, elevation was the most important variable for only three and its contribution to the Maxent model was at most 33%. The contribution was computed by calculating, at each iteration of the Maxent algorithm, the increase in the likelihood of the samples due to elevation (Phillips, 2006). Thus, the evidence that the effect of climate change may be masked by elevation is not compelling. Another assumption of this analysis is that species will be able to disperse to new habitat that will become suitable in the future. For the species analyzed here, this assumption seems justified (see Section 2.4.3). However, the possibility that dispersal is more restricted is a limitation of this analysis that should be explicitly recognized. What this means is that the more positive results about successful conservation measures in the presence of development should be regarded as the most optimistic predictions for Alaskan fauna in the presence of climate change.

The preceding discussion assumes that no oil and gas development accompanies climate change. However, the

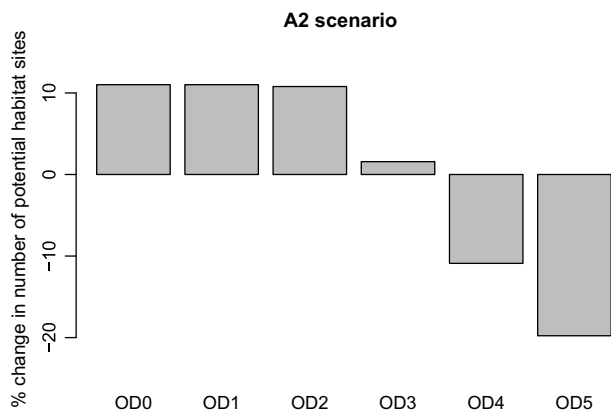


Fig. 6 – Climate × development interactions for Steller's Eider. When there is no development of the 1002 Area, the potential distribution of Steller's Eider increases 11.01% under the A2 climate scenario in 2040. When the entire 1002 Area is developed, the potential distribution decreases by 19.78%.

simulations presented here document a synergy between climate and oil and gas development such that, even if the geographical area of a species' fundamental niche increases by 2040 due to climatic change, climate-change × development interaction might reduce the number of suitable sites in the niche. For example, the area of potential Steller's Eider habitat on the Plain is forecast to increase 11.01% from 2007 to 2040 under the A2 climate scenario if the 1002 Area is intact. However, if development of the entire 1002 Area occurs alongside climate change, then the area of potential Steller's Eider habitat decreases 19.78% (Fig. 6).

Another interesting aspect of the predicted distributional shift for Steller's Eider is that climatic warming is forecast to shift the distribution southward under the A2 scenario. The habitat model presented here seems plausible insofar as the maximum distance from the Beaufort Sea to any site forecast to become potential breeding habitat by 2040 is ~100 km and Steller's Eiders are known to nest at least this far inland (Fredrickson, 2001). In addition, according to the model, the majority of suitable habitat is in the western half of the Arctic Coastal Plain. This is corroborated by Steller's Eider survey data (Spindler et al., 1984; Kertell, 1991). Several previous studies have reported northward shifts in the geographic distributions of species in the Northern Hemisphere in response to climate change, including migratory waterfowl (Parmesan et al., 1999; Žalakevičius and Švažas, 2005; Huntley et al., 2006; Žydelis et al., 2006). Thus, the niche model for Steller's Eider presented here is noteworthy because it forecasts a southward range shift, most likely because the Southern Beaufort Sea blocks dispersal any further north.

According to the ecological niche models, the majority of sites classified as potential polar bear habitat with probability $> \frac{1}{2}$ in 2007 occur along the eastern coast of the Plain. This is consistent with previous findings based on VHF radio-tracking and satellite telemetry indicating that the polar bears of the Beaufort Sea population preferentially occupy sites in the vicinity of the 1002 Area (Amstrup and Gardner, 1994; Fischbach et al., 2007). Polar bears in the Barents Sea show a sim-

ilar preference for habitat along the continental coastline (Belchansky, 2004). The ecological explanation for the polar bear's use of habitat near the 1002 Area is that this region provides suitable areas for maternity denning (Durner et al., 2006) and that birth lairs of young-of-the-year ring seal *Phoca hispida* pups, the bears' principal prey, are more abundant and accessible in this area (Stirling, 1990; Stirling and Lunn, 1997; National Research Council, 2003). The proportion of suitable habitat for the polar bear is predicted to be higher in the central Arctic Coastal Plain under the B1 climate scenario in 2040. Under the A2 scenario, no site on the Plain is predicted to be potential habitat for the polar bear with probability $> \frac{1}{2}$. This contrasts with model predictions for Steller's Eider, which is forecast to shift its breeding range south under the A2 climate scenario but not the B1 scenario. The climate scenarios differ in that increases in CO₂ and anthropogenic radiative forcing are more rapid in A2 than in B1 (IPCC, 2007). Due to its smaller body size, Steller's Eider may be sensitive to the rate of warming between the scenarios not perceived by much larger polar bear, which weighs 300–600 kg (Stirling, 1990; Fredrickson, 2001). The smallest of all eiders (Blood, 1977), Steller's Eider has a sensitive thermoregulatory system and is known to vary its feeding behavior in response to temperature changes (Systad and Bustnes, 2001). The management implications of this analysis for Steller's Eider are that additional conservation areas should be established in the Brooks Range foothills, which are forecast to become habitable for Steller's Eider due to climatic warming (Fig. 4).

This analysis predicts that, in combination with climate change, the development of the 1002 Area will result in a significant shortfall from conservation targets for 11 at-risk species. This finding may potentially inform debate in the 110th United States Congress about proscribing oil and gas development permanently in the 1002 Area by designating it a “wilderness” area, as proposed in HR 39, which was submitted to the House Subcommittee on National Parks, Forests, and Public Lands on 7 February 2007. These results document the 1002 Area's importance for the persistence of faunal biodiversity to the extent that shortfall from conservation targets is up to 35 times greater if the 1002 Area is developed than if the 1002 Area is intact. These results are not incompatible with oil and gas development on the Arctic Coastal Plain, provided that assessments of ecological impact precede such development, as required by the United States National Environmental Policy Act. For example, if an optimal algorithm is used to design the conservation area network, then it is possible to achieve zero shortfall from 20% conservation target even under OD3, which includes the construction of an oil and gas pipeline across the 1002 Area (Supplementary Material, Fig. A.2). If the budget for the establishment of conservation areas is liberal, then the representation of biodiversity that can be achieved in the presence of extensive oil and gas development is the same as the representation possible with a reduced budget and more limited oil and gas development. For example, planners can achieve zero shortfall from the 20% conservation target when the entire 1002 Area is developed if they have a budget of 78 million USD to establish conservation areas elsewhere on the Arctic Coastal Plain. Alternatively, zero shortfall can be achieved for a budget of only 50 million USD if the development of the 1002 Area is re-

stricted to the Canning River Delta. There is thus a trade-off between the extent of oil and gas development and the cost of achieving an adequate conservation area network.

Although this study focuses on the Arctic Coastal Plain, the framework presented here could be applied to any region subject to data availability. The data required to use this optimization model for the first stage are conservation targets for each species, land costs, and the budget for purchasing land. The stage-two parameters of the model are the species' expected distribution shifts due to various scenarios. A limitation of the present analysis is that it treats all of the scenarios as equiprobable. Future research should investigate more sophisticated methods for attributing probabilities to the scenarios. In the case of climate change, an analogous problem is the attribution of a probability to the proposition that temperature will increase by a prescribed amount due to greenhouse gas emissions (reviewed in IPCC, 2007, Chapter 11). Determining the extent to which methods developed in that context provide accurate probabilities for species' relocation scenarios remains an important task for future research.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2008.03.021.

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