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A Bayesian Network Modeling Approach to Forecasting the 21st Century Worldwide Status of Polar Bears

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To inform the U.S. Fish and Wildlife Service decision, whether or not to list polar bears as threatened under the Endangered Species Act (ESA), we projected the status of the world's polar bears (*Ursus maritimus*) for decades centered on future years 2025, 2050, 2075, and 2095. We defined four ecoregions based on current and projected sea ice conditions: seasonal ice, Canadian Archipelago, polar basin divergent, and polar basin convergent ecoregions. We incorporated general circulation model projections of future sea ice into a Bayesian network (BN) model structured around the factors considered in ESA decisions. This first-generation BN model combined empirical data, interpretations of data, and professional judgments of one polar bear expert into a probabilistic framework that identifies causal links between environmental stressors and polar bear responses. We provide guidance regarding steps necessary to refine the model, including adding inputs from other experts. The BN model projected extirpation of polar bears from the seasonal ice and polar basin divergent ecoregions, where ≈2/3 of the world's polar bears currently occur, by mid century. Projections were less dire in other ecoregions. Decline in ice habitat was the overriding factor driving the model outcomes. Although this is a first-generation model, the dependence of polar bears on sea ice is universally accepted, and the observed sea ice decline is faster than models suggest. Therefore, incorporating judgments of multiple experts in a final model is not expected to fundamentally alter the outlook for polar bears described here.

1. INTRODUCTION

Polar bears depend upon sea ice for access to their prey and for other aspects of their life history [*Stirling and Øritsland*, 1995; *Stirling and Lunn*, 1997; *Amstrup*, 2003]. Observed declines in sea ice availability have been associated

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with reduced body condition, reproduction, survival, and population size for polar bears in parts of their range [*Stirling et al.*, 1999; *Obbard et al.*, 2006; *Stirling and Parkinson*, 2006; *Regehr et al.*, 2007b]. Observed [*Comiso*, 2006] and projected [*Holland et al.*, 2006] sea ice declines have led to the hypothesis that the future welfare of polar bears may be diminished worldwide and to the proposal by the U.S. Fish and Wildlife Service (FWS) to list the polar bear as a threatened species under the Endangered Species Act [*U.S. Fish and Wildlife Service*, 2007].

Classification as "threatened" requires determination that a species is likely to become "endangered" within the "foreseeable future" throughout all or a significant portion of its range. An "endangered" species is any species that is in danger of extinction throughout all or a significant portion of its range. For polar bears, the "foreseeable future" was defined as 45 years from now [*U.S. Fish and Wildlife Service*, 2007]. Here we describe a method for combining available information on polar bear life history and ecology with projections of the future state of Arctic sea ice to project the future worldwide status of polar bears. We present our forecast in a "compared to now" setting where projections for the decade of 2045–2054 are compared to the "present" period of 1996–2006. For added perspective, we looked to the nearer term as well as beyond the defined foreseeable future by comparing projections for the periods 2020–2029, 2070–2079, and 2090–2099 to the present. Also, we looked back to the period of 1985–1995. Hence we examined six time periods in total.

Our view of the present and past was based on sea ice conditions derived from satellite data. Our future forecasts were based on information derived from general circulation model (GCM) projections of the extent and spatiotemporal distribution of sea ice, our understanding of how polar bears have responded to ongoing changes in sea ice, and projections of how polar bears are likely to respond to future changes. This paper synthesizes information in nine Administrative Reports prepared by the U.S. Geological Survey and delivered to the FWS in 2007 (http://www.usgs.gov/newsroom/special/polar_bears/) plus other recent literature.

Polar bears occur throughout portions of the Northern Hemisphere where the sea is ice covered for all or much of the year. Polar bears are thought to have branched off of brown bear (*Ursus arctos*) stocks as long ago as 250,000 years, but they appear in the fossil record no earlier than 120,000 years ago [*Talbot and Shields*, 1996; *Hufthamer*, 2001; *Ingolfsson and Wiig*, 2007]. Since moving offshore, behavioral and physical adaptations have allowed polar bears to increasingly specialize at hunting seals from the surface of the ice [*Stirling*, 1974; *Smith*, 1980; *Stirling and Øritsland*, 1995].

Over much of their range, polar bears are nutritionally dependent on the ringed seal (*Phoca hispida*). Polar bears occasionally catch belugas (*Delphinapterus leucas*), narwhals (*Monodon monocerus*), walrus (*Odobenus rosmarus*), and harbor seals (*P. vitulina*) [*Smith*, 1985; *Calvert and Stirling*, 1990; *Smith and Sjare*, 1990; *Stirling and Øritsland*, 1995; *Derocher et al.*, 2002]. Walruses can be seasonally important in some parts of the polar bear range [*Parovshchikov*, 1964; *Ovsyanikov*, 1996]. Bearded seals (*Erignathus barbatus*) can be a large part of their diet where they are common and are probably the second most common prey of polar bears [*Derocher et al.*, 2002]. The most common prey of polar bears, however, is the ringed seal [*Smith and Stirling*, 1975; *Smith*, 1980]. The relationship between ringed seals and polar bears is so close that the abundance of ringed seals in some areas appears to regulate the density of polar bears, while polar bear predation, in turn, regulates density and reproductive success of ringed seals in other areas [*Hammill and Smith*, 1991; *Stirling and Øritsland*, 1995]. Across much of the polar bear range, their dependence on ringed seals is close enough that the abundances of ringed seals have been estimated by knowing the abundances of polar bears [*Stirling and Øritsland*, 1995; *Kingsley*, 1998]. Although polar bears occasionally catch seals on land or in open water [*Furnell and Oolooyuk*, 1980], they consistently catch seals and other marine mammals only at the air-ice-water interface.

Like all bears, polar bears are opportunistic and will take a broad variety of foods when available. When stranded on land for long periods polar bears will consume coastal marine and terrestrial plants and other terrestrial foods [*Derocher et al.*, 1993]. Polar bears have been observed hunting caribou [*Derocher et al.*, 2000; *Brook and Richardson*, 2002], and they rarely have been observed fishing [*Townsend*, 1911; *Dyck and Romber*, 2007]. They will eat eggs, catch flightless (molting) birds, take human refuse, and consume a variety of plant materials [*Russell*, 1975; *Lunn and Stirling*, 1985; *Derocher et al.*, 1993; *Smith and Hill*, 1996; *Stempniewicz*, 1993, 2006]. Although individual bears may gain short-term energetic rewards from alternate foods, available data suggest that polar bears gain little benefit at the population level from these sources [*Ramsay and Hobson*, 1991]. Maintenance of polar bear populations appears dependent upon marine prey, largely ringed seals.

Although polar bears occur in most ice-covered regions of the Northern Hemisphere [*Stefansson*, 1921], they are not evenly dispersed. They are observed most frequently in shallow water areas nearshore and in other areas, called polynyas, where currents and upwellings keep the winter ice cover from freezing solid. These shore leads and polynyas create a zone of active unconsolidated sea ice that is small in geographic area but contributes ~50% of the total productivity in Arctic waters [*Sakshaug*, 2004]. Polar bears have been shown to focus their annual activity areas over these regions [*Stirling et al.*, 1981; *Amstrup and DeMaster*, 1988; *Stirling*, 1990; *Stirling and Øritsland*, 1995; *Stirling and Lunn*, 1997; *Amstrup et al.*, 2000, 2004, 2005]. Ice over waters less than 300 m deep is the most preferred habitat of polar bears throughout the polar basin [*Durner et al.*, 2008].

Polar bears inhabit regions with very different sea ice characteristics. The southern reaches of their range includes areas where sea ice is seasonal. There, polar bears are forced onto land where they are food deprived for extended periods each year. Other polar bears live in the harshest and most northerly climes of the world where the ocean is ice covered year-round. Still others occupy the pelagic regions of the polar basin where there are strong seasonal changes in the character and especially distribution of the ice. The common denominator is that all polar bears regardless of where they live make seasonal movements to maximize their foraging time on sea ice that is suitable for hunting [*Amstrup*, 2003].

2. METHODS

2.1. Overview

We used a Bayesian network (BN) model [*Marcot et al.*, 2006] to forecast future population status of polar bears in each of four distinct ecoregions. The BN model incorporated projections of sea ice change as well as anticipated likelihoods of changes in several other potential population stressors. In the following sections, we provide detailed descriptions of the four polar bear ecoregions. We describe the process we used to make projections of the amount and distribution of future sea ice habitat. Finally, we provide details of the BN population stressor model we used to project the future status of polar bears.

2.2. Polar Bear Ecoregions

Polar bears are distributed throughout regions of the Arctic and subarctic where the sea is ice covered for large portions of the year. Telemetry studies have demonstrated spatial segregation among groups or stocks of polar bears in different regions of their circumpolar range [*Schweinsburg and Lee*, 1982; *Amstrup* 1986, 2000; *Garner et al.*, 1990, 1994; *Messier et al.*, 1992; *Amstrup and Gardner*, 1994; *Ferguson et al.*, 1999]. As a result of patterns in spatial segregation suggested by telemetry data, survey and reconnaissance, marking and tagging, and traditional knowledge, the Polar Bear Specialist Group (PBSG) of the International Union for the Conservation of Nature recognizes 19 partially discrete polar bear groups [*Aars et al.*, 2006]. Although there is considerable overlap in areas occupied by members of these groups [*Amstrup et al.*, 2004, 2005], they are thought to be ecologically meaningful [*Aars et al.*, 2006] and are managed as subpopulations (Plate 1).

We recognized that many of the 19 subpopulations share more similarities than differences and pooled them into four ecological regions (Plate 1). We defined "ecoregions" on the basis of observed temporal and spatial patterns of ice melt, freeze, and advection, observations of how polar bears respond to those patterns, and how general circulation models (GCMs) forecast future ice patterns in each ecoregion.

The seasonal ice ecoregion (SIE) includes the two subpopulations of bears which occur in Hudson Bay, as well as the bears of Foxe Basin, Baffin Bay, and Davis Strait. The sum of the members of these five subpopulations is thought to include about 7500 polar bears [*Aars et al.*, 2006]. All five share the characteristic that the sea ice, on which the polar bears hunt, melts entirely in summer and bears are forced ashore for extended periods of time during which they are food deprived.

The archipelago ecoregion (AE) includes the channels between the Canadian Arctic Islands. This ecoregion includes approximately 5000 polar bears representing six subpopulations recognized by the PBSG [*Aars et al.*, 2006]. These subpopulations are Kane Basin, Norwegian Bay, Viscount-Melville Sound, Lancaster Sound, M'Clintock Channel, and the Gulf of Boothia. Much of this region is characterized by heavy annual and multiyear (perennial) ice that historically has filled the interisland channels year-round. Polar bears remain on the sea ice, therefore, throughout the year.

In the polar basin as in the AE, polar bears mainly stay on the sea ice year-round. In our analyses, we split the polar basin into two ecoregions. This split was based upon the different patterns of sea ice formation and advection [*Rigor et al.*, 2002; *Rigor and Wallace* 2004; *Maslanik et al.*, 2007; *Meier et al.*, 2007; *Ogi and Wallace*, 2007]. The polar basin divergent ecoregion (PBDE) is characterized by extensive formation of annual sea ice that is typically advected toward the central polar basin, against the Canadian Arctic Islands and Greenland, or out of the polar basin through Fram Strait. The PBDE lies between ~127°W and 10°E and includes the southern Beaufort, Chukchi, East Siberian-Laptev, Kara, and Barents sea subpopulations. There are no population estimates for the Kara Sea region. Assuming that 1000 bears live in the Kara Sea, this ecoregion could be home to approximately 8500 polar bears [*Aars et al.*, 2006].

The polar basin convergent ecoregion (PBCE) is the remainder of the polar basin including the east Greenland Sea, the continental shelf areas adjacent to northern Greenland and the Queen Elizabeth Islands, and the northern Beaufort Sea (Plate 1). There are thought to be approximately

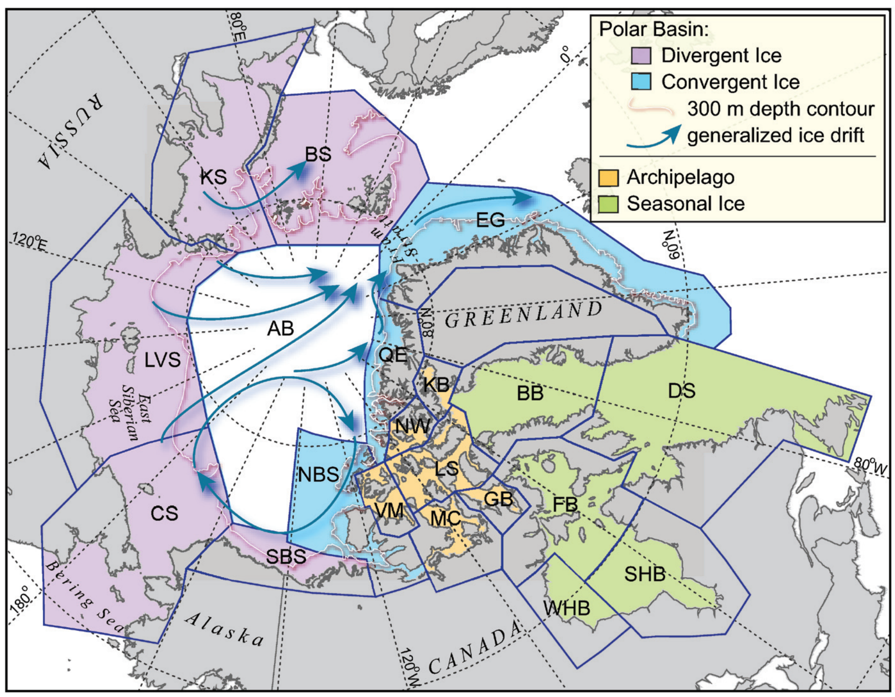

Plate 1. Map of four polar bear ecoregions defined by grouping recognized subpopulations which share seasonal patterns of ice motion and distribution. The polar basin divergent ecoregion (PBDE) (purple) includes Southern Beaufort Sea (SBS), Chukchi Sea (CS), Laptev Sea (LVS), Kara Sea (KS), and the Barents Sea (BS). The polar basin convergent ecoregion (PBCE) (blue) includes East Greenland (EG), Queen Elizabeth (QE), and Northern Beaufort Sea (NBS). The seasonal ice ecoregion (SIE) (green) includes southern Hudson Bay (SHB), western Hudson Bay (WHB), Foxe Basin (FB), Davis Strait (DS), and Baffin Bay (BB). The archipelago ecoregion (AE) (yellow) includes Gulf of Boothia (GB), M'Clintock Channel (MC), Lancaster Sound (LS), Viscount-Melville Sound (VM), Norwegian Bay (NW), and Kane Basin (KB).

1200 polar bears in the Northern Beaufort Sea subpopulation [*Aars et al.*, 2006], but numbers of bears in the rest of this ecoregion are poorly known. There are no estimates for the east Greenland subpopulation, but we assumed there currently may be up to 1000 bears there. We modified the PBSG recognized subpopulation boundaries of this ecoregion by redefining a Queen Elizabeth Islands subpopulation (QE). QE had formerly included the continental shelf region and interisland channels between Prince Patrick Island and the northeast corner of Ellesmere Island [*Aars et al.*, 2006]. We extended its boundary to northwest Greenland. This area is characterized by heavy multiyear ice, except for a recurring lead system that runs along the Queen Elizabeth Islands from the northeastern Beaufort Sea to northern Greenland [*Stirling*, 1980]. Over 200 polar bears could be resident here, and some bears from other regions have been recorded moving through the area [*Durner and Amstrup*, 1995; *Lunn et al.*, 1995]. Like the Northern Beaufort Sea subpopulation, QE occurs in a region of the polar basin that recruits ice as it is advected from the PBDE [*Comiso*, 2002; *Rigor and Wallace*, 2004; *Belchansky et al.*, 2005; *Holland et al.*, 2006; *Durner et al.*, 2008; *Ogi and Wallace*, 2007; *Serreze et al.*, 2007]. Assuming these rough estimates are close, up to 2400 bears might presently occupy the PBCE.

We did not incorporate the central Arctic Basin into our analyses. This area was defined to contain a separate subpopulation by the PBSG in 2001 [*Lunn et al.*, 2002] to recognize bears that may reside outside the territorial jurisdictions of the polar nations. The Arctic Basin region is characterized by very deep water which is known to be unproductive [*Pomeroy*, 1997]. Available data are conclusive that polar bears prefer sea ice over shallow water (<300 m deep) [*Amstrup et al.*, 2000, 2004; *Durner et al.*, 2008], and it is thought that this preference reflects increased hunting opportunities over more productive waters. Tracking studies indicate that few if any bears are year-round residents of the central Arctic Basin. For all of these reasons, we did not include the Arctic Basin in our analyses.

2.3. Sea Ice Habitat Variables

Our BN model incorporated changes in area and spatiotemporal distribution of sea ice habitat along with other "stressors" that might help predict the future of polar bears. We used monthly averaged ice concentration estimates derived from passive microwave satellite imagery for the observational period 1979–2006 [*Cavalieri et al.*, 1996]. Sea ice data for the future were derived from monthly sea ice concentration projections of 10 GCMs. The GCMs we used were included in the Intergovernmental Panel of Climate Change (IPCC) Fourth Assessment Report (AR4) (Table 1). These included hindcast ice estimates from the 20th Century Experiment (20C3M) and projection estimates for the 21st century forced with the "business as usual" Special Report on Emissions Scenarios (SRES) A1B emissions scenario [*Nakićenović et al.*, 2000]. We obtained GCM ice projection outputs of nine models from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set [*Meehl et al*., 2007a]. We obtained projections from the 10th model (Community Climate System Model, version 3 (CCSM3)) directly from the National Center for Atmospheric Research in its native CCSM grid format (D. Bailey and M. Holland, NCAR, personal communication, 2007). We obtained and analyzed one run (run 1) for each GCM, except CCSM3 for which we obtained eight runs. In our analyses we included the mean of the eight CCSM3 runs as a single member of our 10-model ensemble.

We selected the 10 GCMs from a larger group of 20 based on their ability to simulate (20C3M) the mean Northern Hemisphere ice extent for September 1953–1995 to within 20% of the observed September mean (Had1SST [*Rayner et al.*, 2003]). This selection method emulated that used by *Stroeve et al.* [2007], except we used a 50% ice concentration threshold [*DeWeaver*, 2007] to define ice extent (as opposed to 15%). We chose a 50% threshold because other studies have shown that polar bears prefer medium to high sea ice concentrations [*Arthur et al.*, 1996; *Ferguson et al.*, 2000; *Durner et al.*, 2006, 2008].

Sea ice grids among the 10 GCMs we analyzed had various model-specific spatial resolutions ranging from ~1×1 to 3×4 degrees of latitude × longitude. To facilitate integration with our analyses of observational data, we resampled the GCM grids to match the gridded 25 km resolution passive microwave sea ice concentration maps from the National Snow and Ice Data Center. Each native GCM grid of sea ice concentration was converted to an Arc/Info (version 9.2; ESRI, Redlands, California, United States) point coverage and projected to polar stereographic coordinates (central meridian 45°W, true scale 70°N). A triangular irregular network (TIN) (Arc/Info) was created from the point coverage using ice concentration as the z value, and a 25 km pixel resolution grid was generated by sampling the TIN surface. Effectively, this procedure oversampled the original GCM resolution using linear interpolation.

2.3.1. Total annual habitat area. For input to our models, we defined two area-based metrics of habitat availability to polar bears. The first was an expression of the yearly extent of "total available ice habitat," and the second, which was available in the polar basin only, was an expression of "total optimal habitat." We derived "total available ice habitat" from both observed and projected Arctic-wide sea ice con-

Table 1. Sea Ice Simulations and Projections Produced by Ten General Circulation Models[a]

GCM Model ID	Country	Grid Resolution (Latitude × Longitude)	Number of Runs
ncar_ccsm3_0	USA	1.0 × 1.0	8
cccma_cgcm3_1	Canada	3.8 × 3.8	1
cnrm_cm3	France	1.0 × 2.0	1
gfdl_cm2_0	USA	0.9 × 1.0	1
giss_aom	USA	3.0 × 4.0	1
ukmo_hadgem1	UK	0.8 × 1.0	1
ipsl_cm4	France	1.0 × 2.0	1
miroc3_2_medres	Japan	1.0 × 1.4	1
miub_echo_g	Germany/Korea	1.5 × 2.8	1
mpi_echam5	Germany	1.0 × 1.0	1

[a]GCMs were developed for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) [*Meehl et al.*, 2007b] to define ice covariates for polar bear RSF models and to project future sea ice distributions used in our BN model. Note that we used the ensemble mean of the 8 available runs to represent CCSM3 outputs. Sea ice estimates for the period of observational records were derived from the 20th Century Experiment (20C3M). All 21st century projections were forced with the "business as usual" SRES-A1B emissions scenario [*Nakićenović et al.*, 2000].

centration maps as the annual 12-month sum of sea ice extent over the continental shelves (<300 m depth) in each ecoregion. Ice extent was defined as the aerial cover (square kilometers) of all pixels with ≥50% ice concentration. Since deep water is uncommon in the AE and SIE, we considered those entire ecoregions to effectively reside over the continental shelf, meaning total ice habitat equated to the total annual amount of ice cover summed over all 12 months.

We quantified optimal polar bear habitat using the resource selection functions (RSFs) of *Durner et al.* [2008]. RSFs are quantitative expressions of the habitats animals choose to utilize, relative to the habitats that are available to them [*Manly et al.*, 2002]. Estimates of preferred habitat were derived only in the polar basin because only there were sufficient radio-tracking data available to build RSF models. The satellite imagery captured dynamics of the available sea ice habitats, while the satellite telemetry indicated the choices bears made. *Durner et al.* [2008] developed the RSFs with 1985–1995 location data from satellite radio-tagged female polar bears (n=12,171 locations from 333 bears), monthly passive microwave ice concentration maps [*Cavalieri et al.*, 1996], and digital bathymetry and coastline maps. Discrete-choice modeling distinguished between the available and chosen habitats based on six environmental covariates: ocean depth, distance to land, ice concentration, and distances to the 15%, 50%, and 75% ice edges. *Durner et al.* [2008] used 1985–1995 tracking data to establish a baseline of preferred polar bear habitat selection criteria, because during this early period of our study, year-round polar bear movements were less restricted and hence more likely to represent preferences than during the more recent years of reduced sea ice extent.

Optimal polar bear habitat was defined to be any mapped pixel with an RSF value in the upper 20% of the seasonally averaged (1985–1995) RSF scores [*Durner et al.*, 2008]. This approach created a foundation that allowed us to examine whether future ice projections indicated increases, decreases, or stability in the area, summed over all 12 months, of optimal polar bear habitat, relative to our earliest decade of empirical observations. Like "total ice habitat," optimal habitat had the disadvantage of not being able to resolve seasonal changes.

We note that expressing change on the basis of annual square kilometer months tends to minimize the potential effects of large seasonal swings in habitat availability. Whereas the yearly average sea ice extent has declined at a rate of 3.6% per decade during 1979–2006, the mean September sea ice extent has declined at a rate of 8.4% per decade [*Meier et al.*, 2007]. Further, because all GCMs project extensive winter sea ice through the 21st century in most ecoregions [*Durner et al.*, 2008], the severity of summer periods of food deprivation may be hidden by extensive sea ice in winter when data are pooled annually. Although polar bears are well adapted to a feast and famine diet [*Watts and Hansen*, 1987], there apparently are limits to their ability to sustain long periods of food deprivation [*Regehr et al.*, 2007b]. We recognized our measures of change in square kilometer months were largely insensitive to these seasonal effects. Two other sea ice variables included in our model, the distance and duration of ice retreat from the continental shelf, do, however, reflect projected seasonal fluctuations (see below).

2.3.2. Seasonal habitat availability. Recognizing the potential importance of the seasonal separation of sea ice cover from preferred continental shelf foraging areas, and duration of such separation, we determined the number of ice-free months over the continental shelf and the average shelf-to-ice distance in both the observed and GCM-projected ice concentration maps. An ice-free month occurred in an ecoregion when <50% of the shelf area was covered by sea ice of ≥50% concentration. Shelf ice distance was the mean distance from every shelf pixel in a polar basin ecoregion to the nearest ice-covered pixel (>50% concentration) during the month of minimum ice extent. This described how far polar bears occupying sea ice habitats would be from their preferred continental shelf foraging areas. The average shelf-to-ice distance was not calculated for the SIE and AE because we considered those ecoregions to be composed entirely of shelf waters.

2.4. Bayesian Network Population Stressor Model

A Bayesian network is a graphical model that represents a set of variables (nodes) linked by probabilities [*Neopolitan*, 2003; *McCann et al.*, 2006]. Nodes can represent correlates or causal variables that affect some outcome of interest, and links define which specific variables directly affect which other specific variables. BNs can combine expert knowledge and empirical data into the same modeling structure. Crafting a BN augments understanding of relationships and sensitivities among the elements of a causal web and provides insights into the workings of the system that otherwise would not have been evident. BNs have become an accepted and popular modeling tool in many fields [*Pourret et al.*, 2008] including ecological and environmental sciences [e.g., *Aalders*, 2008; *Uusitalo*, 2007]. Each node in a BN model typically has two or more mutually exclusive states, the probabilities of which sum to one. Prior probabilities are distributed as discontinuous Dirichlet functions in the form of $D(x) = \lim_{m\to\infty} \lim_{n\to\infty} \cos^{2n}(m!\pi x)$, which is a multivariate, n state generalization of the two-state Beta distribution with state probabilities being continuous within [0,1]. BN nodes can represent categorical, ordinal, or continuous variable states or constant (scalar) values and typically have an associated probability table that describes either prior (unconditional) probabilities of each state for input nodes or conditional probabilities of each state for nodes that directly depend on other nodes (see *Marcot et al.* [2006] for a description of the underlying statistics). States S of output nodes contain posterior probabilities that are calculated conditional upon nodes H that directly affect them, using Bayes theorem, as $P(S|H) = [P(H|S)P(S)/P(H)]$ (see *Jensen* [2001] and *Marcot* [2006] for further explanation of the statistical basis of BNs). BNs are "solved" by specifying the values of input nodes and having the model calculate posterior probabilities of the output node(s) through "Bayesian learning" [*Jensen*, 2001]. BNs are useful for modeling systems where empirical data are lacking, but variable interactions and their uncertainties can be depicted based on expert judgment [*Das*, 2000]. They are also particularly useful in efforts to synthesize large amounts of divergent quantitative and qualitative information to answer "what if" kinds of questions.

Developing a BN model entails depicting the "causal web" of interacting variables [*Marcot et al.*, 2006] in an influence diagram, assigning states to each node, and assigning probabilities to each node that define the conditions under which each state could occur. We used the modeling shell Netica® (Norsys, Inc.) and followed guidelines for developing BN models developed by *Jensen* [2001], *Cain* [2001], and *Marcot et al.* [2006].

Our BN stressor model was based on the knowledge of one polar bear expert (S. Amstrup), who established the model structure and probability tables according to expected influences among variables. B. Marcot served as a "knowledge engineer" and provided guidance to help structure the expert's knowledge into an appropriate BN format. Amstrup compiled an initial list of ecological correlates which were organized into an influence diagram (Plate 2). With discussion and questioning, Marcot guided Amstrup through several stages to a final model structure.

The BN model structure was divided into three kinds of nodes: (1) input nodes were anthropogenic stressors or environmental variables, states of input nodes were parameterized with unconditional probabilities; (2) summary nodes, sometimes called latent variables [e.g., *Bollen*, 1989], collect and summarize effects of multiple input nodes, states of these were parameterized with conditional probability tables; and (3) output nodes that represented numerical, distribution, and overall population responses to the suite of inputs. Probabilities of the various states of output nodes are derived through Bayesian learning. We developed the model structure in an iterative fashion adding variables for which we could hypothesize important roles. Published as well as unpublished information on how polar bears respond to changes in sea ice allowed us to parameterize the model to ensure it responded to particular input conditions in ways that paralleled responses of polar bear populations that have been observed or for which there are strong prevailing hypotheses among polar bear biologists worldwide.

To assure our outcomes were relevant to the question whether to list polar bears as a threatened species, we designed the summary nodes in the BN model to include four of the five major listing factors used to determine a species' status according to the Endangered Species Act [*U.S. Fish and Wildlife Service*, 2007]. We included summary nodes for factor A, habitat threats; factor B, overutilization; factor C, disease and predation; and factor E, other natural or manmade factors. We did not include factor D, inadequacy of existing regulatory mechanisms, because our model focused on ecosystem effects; however, regulatory aspects could be seamlessly added at a future time.

2.5. Parameterizing the Bayesian Network Model

We averaged the sea ice parameters for each GCM over decadal periods to generate metrics that were less sensitive to the intrinsic variability of GCM projections that occurs at annual timescales. The BN model was applied to each of the four ecoregions at six decadal time periods: 1985–1995, 1996–2006, 2020–2029, 2045–2054, 2070–2079, and 2090–2099. For convenience, we hereinafter refer to these six time periods, in relation to the present, as years −10, 0, 25, 50, 75, and 95. Analyses included observed habitat conditions from the satellite passive microwave data for years −10 and 0 and future habitat conditions projected by GCM ice projections for future years. To capture the full range of uncertainty in GCM outputs, we solved the BN model using sea ice parameters from the (1) GCM multimodel (ensemble) means, (2) GCM that projected the minimum ice extent, and (3) GCM that projected the maximum ice extent, for each ecoregion in each time period. Inputs other than sea ice features included various categories of anthropogenic stressors [*Barrett*, 1981] such as harvest, pollution, oil and gas development, shipping, and direct bear-human interactions. Inputs also included other environmental factors that could affect polar bear populations such as availability of primary and alternate prey and foraging areas and occurrence of parasites, disease, and predation [*Ramsay and Stirling*, 1984]. Whereas the ice habitat factors were entered into the BN model as ranges of values (e.g., ice retreat of 0–200 or 200–800 km beyond current measures), other potential stressors were included as ordinal or qualitative categories (Tables D1a and D1b).

Because we were interested in forecasting changes from current conditions, states of each node were expressed categorically as "compared to now." That is, an outcome state could represent a condition similar to present, better than present, or worse than present. Here, now or year "0" means the 1996–2006 period when referring to observations and 2000–2009 when referring to sea ice model projections. Before the BN model was run, we specified the states for each input node that seemed most plausible (Tables D1a and D1b).

States of environmental correlates were established under each combination of time step, ecoregion, and GCM model outputs. We ensured that input conditions matched the current understanding of polar bear ecology and parameterized the conditional probability tables to assure that node structures were specified in accordance with available polar bear data or expert understanding of data. We checked the validity of the model parameterization by testing whether the BN model responded to particular input conditions in ways that paralleled responses of polar bear populations to conditions that have been observed.

When the model is run, it calculates posterior probabilities of outcomes by applying standard Bayesian learning to the values assigned to each input variable. The relative influence of each input node, in terms of inherent model sensitivity structure, is determined by the values assigned in the conditional probability tables that underlie each summary or output node in the network. One input variable can be given greater influence than another if the result of a change in the first variable is thought to have a greater influence on the outcome states of the summary or output node than the second, and if the conditional probabilities are assigned accordingly. For example, it may be thought that the temporal absence of sea ice from the continental shelf is more important to the availability of foraging habitat than is the distance to which the ice retreats while it is absent. If data or projections suggest both measurements change in parallel, then temporal absence would have the greater final influence. If, however, data or projections show there is a greater change in distance than in time of absence, then distance may have the greatest contribution to posterior (outcome) probabilities even though its weight in the conditional probability table might be lower than temporal absence.

We used three different methods to arrive at final model structure: (1) sensitivity analyses of subparts of the model, (2) solving the model backward by specifying outcome states and evaluating if the most likely input states that were returned were plausible according to what we know about polar bears now, and (3) running the model (and subparts) forward to ascertain if the summary and output nodes responded as expected given the states of the input nodes. Our goals were to ensure that input conditions matched the current understanding of polar bear ecology and that the model responded to particular input conditions in ways that paralleled observed responses of polar bear populations.

As fully specified, the BN model consisted of 38 nodes, 44 links, and 1667 conditional probability values specified by the modelers (Plate 3 and Appendices A and B). The model was solved for each combination of four ecoregions, six time periods, and three future GCM scenarios (ensemble mean, maximum, and minimum).

The input data to run each combination were specified by summarizing the respective GCM-derived habitat variables

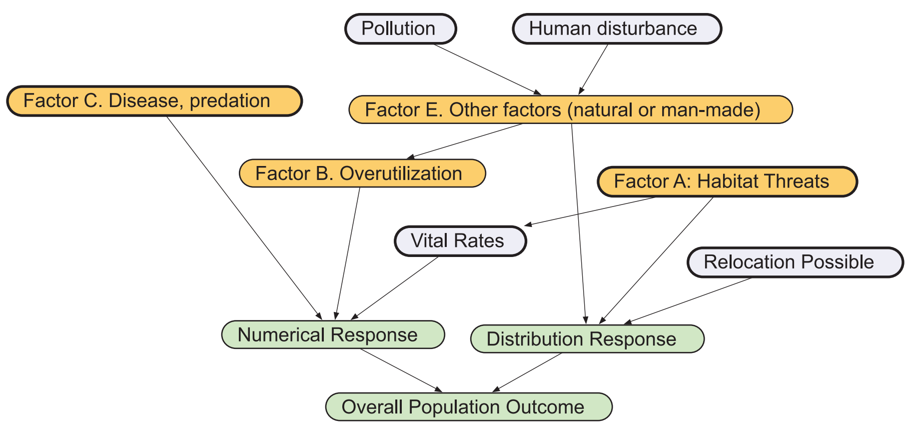

Plate 2. Basic influence diagram for the Bayesian network polar bear population stressor model showing the role of four listing factor categories (orange) used by U.S. Fish and Wildlife Service.

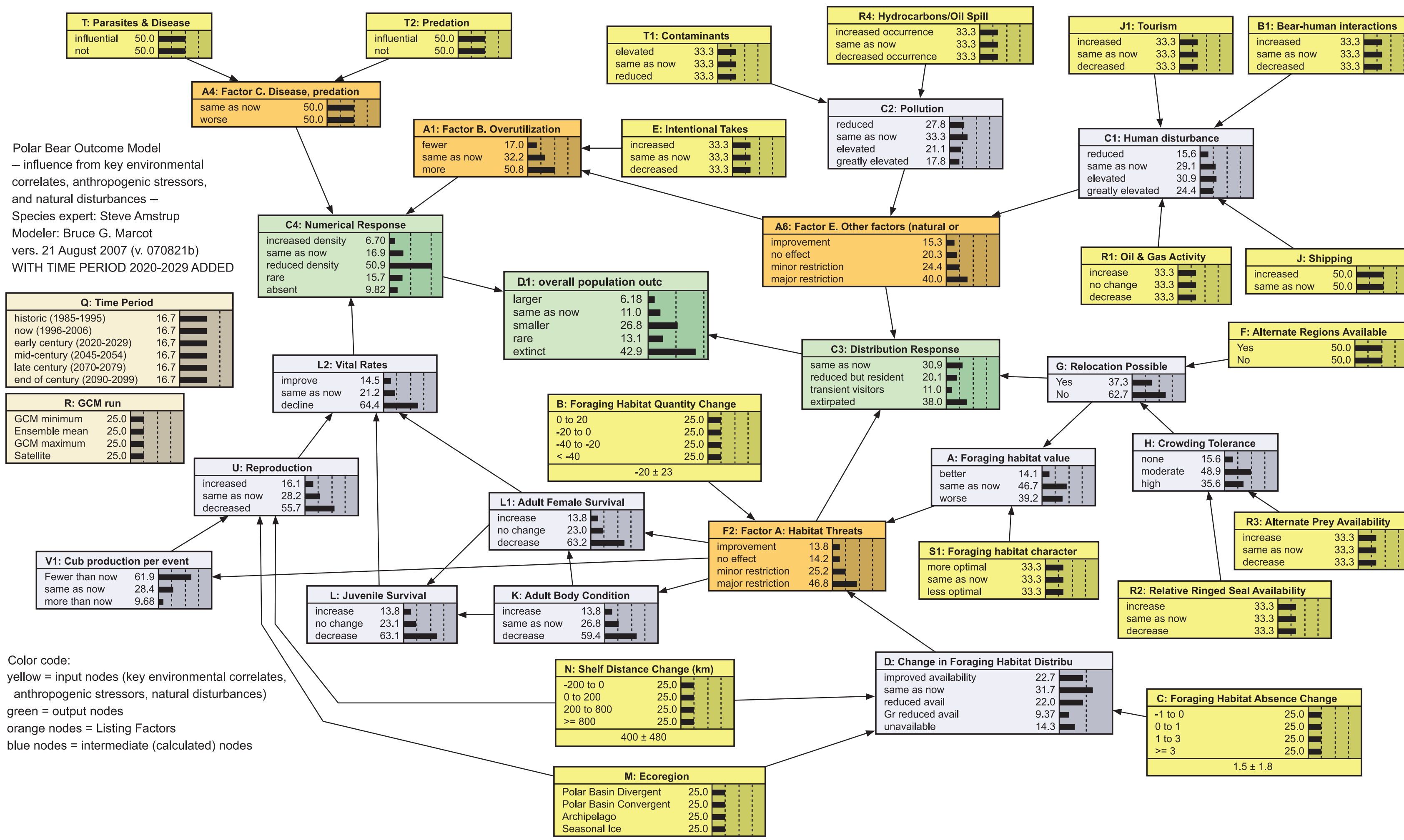
Polar Bear Outcome Model
-- influence from key environmental correlates, anthropogenic stressors, and natural disturbances --
Species expert: Steve Amstrup
Modeler: Bruce G. Marcot
vers. 21 August 2007 (v. 070821b)
WITH TIME PERIOD 2020-2029 ADDED
T: Parasites & Disease
influential 50.0
not 50.0
T2: Predation
influential 50.0
not 50.0
A4: Factor C. Disease, predation
same as now 50.0
worse 50.0
T1: Contaminants
elevated 33.3
same as now 33.3
reduced 33.3
R4: Hydrocarbons/Oil Spill
increased occurrence 33.3
same as now 33.3
decreased occurrence 33.3
J1: Tourism
increased 33.3
same as now 33.3
decreased 33.3
B1: Bear-human interactions
increased 33.3
same as now 33.3
decreased 33.3
A1: Factor B. Overutilization
fewer 17.0
same as now 32.2
more 50.8
E: Intentional Takes
increased 33.3
same as now 33.3
decreased 33.3
C2: Pollution
reduced 27.8
same as now 33.3
elevated 21.1
greatly elevated 17.8
C1: Human disturbance
reduced 15.6
same as now 29.1
elevated 30.9
greatly elevated 24.4
C4: Numerical Response
increased density 6.70
same as now 16.9
reduced density 50.9
rare 15.7
absent 9.82
A6: Factor E. Other factors (natural or
improvement 15.3
no effect 20.3
minor restriction 24.4
major restriction 40.0
R1: Oil & Gas Activity
increase 33.3
no change 33.3
decrease 33.3
J: Shipping
increased 50.0
same as now 50.0
D1: overall population outc
larger 6.18
same as now 11.0
smaller 26.8
rare 13.1
extinct 42.9
Q: Time Period
historic (1985-1995) 16.7
now (1996-2006) 16.7
early century (2020-2029) 16.7
mid-century (2045-2054) 16.7
late century (2070-2079) 16.7
end of century (2090-2099) 16.7
R: GCM run
GCM minimum 25.0
Ensemble mean 25.0
GCM maximum 25.0
Satellite 25.0
L2: Vital Rates
improve 14.5
same as now 21.2
decline 64.4
F: Alternate Regions Available
Yes 50.0
No 50.0
C3: Distribution Response
same as now 30.9
reduced but resident 20.1
transient visitors 11.0
extirpated 38.0
G: Relocation Possible
Yes 37.3
No 62.7
B: Foraging Habitat Quantity Change
0 to 20 25.0
-20 to 0 25.0
-40 to -20 25.0
< -40 25.0
-20 ± 23
H: Crowding Tolerance
none 15.6
moderate 48.9
high 35.6
A: Foraging habitat value
better 14.1
same as now 46.7
worse 39.2
U: Reproduction
increased 16.1
same as now 28.2
decreased 55.7
L1: Adult Female Survival
increase 13.8
no change 23.0
decrease 63.2
F2: Factor A: Habitat Threats
improvement 13.8
no effect 14.2
minor restriction 25.2
major restriction 46.8
R3: Alternate Prey Availability
increase 33.3
same as now 33.3
decrease 33.3
V1: Cub production per event
Fewer than now 61.9
same as now 28.4
more than now 9.68
S1: Foraging habitat character
more optimal 33.3
same as now 33.3
less optimal 33.3
L: Juvenile Survival
increase 13.8
no change 23.1
decrease 63.1
K: Adult Body Condition
increase 13.8
same as now 26.8
decrease 59.4
R2: Relative Ringed Seal Availability
increase 33.3
same as now 33.3
decrease 33.3
Color code:
yellow = input nodes (key environmental correlates, anthropogenic stressors, natural disturbances)
green = output nodes
orange nodes = Listing Factors
blue nodes = intermediate (calculated) nodes
N: Shelf Distance Change (km)
-200 to 0 25.0
0 to 200 25.0
200 to 800 25.0
>= 800 25.0
400 ± 480
D: Change in Foraging Habitat Distribu
improved availability 22.7
same as now 31.7
reduced avail 22.0
Gr reduced avail 9.37
unavailable 14.3
C: Foraging Habitat Absence Change
-1 to 0 25.0
0 to 1 25.0
1 to 3 25.0
>= 3 25.0
1.5 ± 1.8
M: Ecoregion
Polar Basin Divergent 25.0
Polar Basin Convergent 25.0
Archipelago 25.0
Seasonal Ice 25.0

Plate 3

and the professional judgment of polar bear expert S. Amstrup (Tables D1a and D1b). Because BN models combine expert judgment and interpretation with quantitative and qualitative empirical information, inputs from multiple experts are sometimes used to structure and parameterize a "final" model. Because the model presented was parameterized with the judgment of only one polar bear expert, it should be viewed as a first-generation version. Accordingly, it will be refined through formally developed processes (see section 4) at a future time.

2.6. Output States of the Bayesian Network Model

The final outcomes of BN model runs were statements of relative probabilities that the population in each ecoregion would be larger than now, same as now, smaller than now, rare, or extinct. Responses of polar bears to projected habitat changes and other potential stressors could affect polar bear distribution or polar bear numbers independently in some cases, or they could affect both distribution and numbers simultaneously. Principal results of the BN model are levels of relative probabilities for the potential states at output nodes. In the polar bear BN population stressor model, outcomes of greatest interest were (1) those related to listing factors used by the FWS, (2) the distribution responses, (3) numerical responses, and (4) the overall population response.

We defined our output nodes (shown in Plate 3) in such a way that their possible states could be assessed empirically through future field observations. Potential states at the three principal output nodes are described below.

2.6.1. Node C4: Numerical response. This node represents the anticipated numerical response of polar bears in an ecoregion based upon the sum total of the identified factors which are likely to have affected numbers of polar bears in each ecoregion:

- increased density, polar bear density detectable as significantly greater than that at year 0, where density can be expressed in terms of number of polar bears per unit area of optimal habitat (thus expressing "ecological density") or of total (optimal plus suboptimal) habitat (thus expressing "crude density");
- same as now, equivalent to the density at year 0;
- reduced density, polar bear density less than that at year 0 but greater than one half of the density at year 0;
- rare, polar bear density less than half of that at year 0;
- absent, polar bears are not demonstrably present.

2.6.2. Node C3: Distribution response. Distribution refers here to the functional response of polar bears (namely, movement and spatial redistribution of bears) to changing conditions:

- same as now, polar bear distribution equivalent to that at year 0;
- reduced but resident, bears would still occur in the area but their spatial distribution would be more limited than at year 0;
- transient visitors, changing conditions would seasonally limit distribution of polar bears;
- extirpated, complete or effective year-round dearth of polar bears in the area.

2.6.3. Node D1: Overall population outcome. Overall population outcome refers to the collective influence of both numerical response (node C4) and distribution response (node C3). It incorporates the full suite of effects from all anthropogenic stressors, natural disturbances, and environmental conditions on the expected occurrence and levels of polar bear populations in the ecoregion. Overall population outcome states were defined as follows:

- larger, polar bear populations have a numerical response greater than at present (year 0) and a distribution response at least the same as at present;
- same as now, polar bear populations numerically and distributionally indistinguishable from present;
- smaller, polar bears at a reduced density and distributed the same as at present or density same as at present but occur as transient visitors;
- rare, polar bears are numerically difficult to detect and have a distribution response same as at present, or occur as small numbers of transient visitors;
- extinct, polar bears are numerically absent or distributionally extirpated.

Here, the "extinct" state refers to conditions of (1) complete absence of the species (N=0) from an ecoregion; or (2) numbers and distributions below a "quasi-extinction" level, that refers to a nonzero population level at or below which the population is near extinction [*Ginzburg et al.*, 1982; *Otway et al.*, 2004]; or (3) functional extinction, that refers to being so scarce as to be near extinction and contributing negligibly to ecosystem processes [*Sekercioglu et al.*, 2004; *McConkey and Drake*, 2006].

Plate 3. (Opposite) Full Bayesian network population stressor model developed to forecast polar bear population outcomes in the 21st century. Values shown in the bottom of nodes B, N, and C represent expected values +/- 1 standard deviation which are automatically calculated and displayed by the Netica® modeling shell for continuous nodes with defined state values, based on Gaussian distributions.

Outcomes from the BN model are expressions of probability that each outcome state will occur (e.g., X% extinct, Y% rare, and Z% smaller). It is important here to understand that these probability values are provided without error bars and should not, in themselves, be interpreted as absolute measures of the certainty of any particular outcome. Rather, probabilities of outcome states of the model should be viewed in terms of their general direction and overall magnitudes. When predictions result in high probability of one outcome state and low or zero probabilities of all other states, there is low overall uncertainty of predicted results. When projected probabilities of various states are more equally distributed or when two or more states have large probability, there is greater uncertainty in the outcome. In these cases, careful consideration should be given to large probabilities representing particular states even if those probabilities are not the largest.

2.7. Sensitivity of the Bayesian Network Model

Knowledge of polar bears, their dependence on sea ice, the ways in which sea ice changes have been observed to affect polar bears, and professional judgment regarding how ecological and human factors may differ if sea ice changes occur as projected were used to populate the conditional probability tables in the BN model. Because our model incorporated the professional judgment of only one polar bear expert, it is reasonable to ask how robust the results might be to input probabilities which could vary among other experts. It also is appropriate to ask whether it is likely that future sea ice change, to which model outcomes are very sensitive, could fall into ranges that would result in qualitatively different outcomes than our BN model projects. Finally, it is appropriate to ask the extent to which model outcomes may be altered by active management of the states of nodes which represent variables humans could control.

We addressed questions about the ability of changes in human activities to alter the BN output states by fixing inputs humans could control and examining differences in the overall outcomes. We evaluated the extent to which sea ice projections would have to differ to make qualitative differences in outcomes by holding all non-ice variables at uniform priors and allowing ice variables only to vary at future time steps. Comparing those results to the range of ice conditions projected by our GCMs provided a sense of just how much the realized future ice conditions would have to vary from those projected to make a difference in population outcomes. Finally, although we cannot second guess how other polar bear experts may recommend parameterizing and structuring a BN model, comparison of model runs with preset values provides some sense of how much differently the model would have to be parameterized to provide qualitatively different outcome patterns than those we obtained.

We ran overall sensitivity analyses to determine the degree to which each input and summary variable influenced the outcome variables. For discrete and categorical variables, sensitivity was calculated in the modeling shell Netica® as the degree of entropy reduction (reduction in the disorder or variation) at one node relative to the information represented in other nodes of the model. That is, the sensitivity tests indicate how much of the variation in the node in question is explained by each of the other nodes considered. The degree of entropy reduction, I, is the expected reduction in mutual information of an output variable Q, with q states, due to a finding of an input variable F, with f states. For discrete variables, I is measured in terms of information bits and is calculated as

$$I = H(Q) - H(Q|F) = \sum_q \sum_f \frac{P(q,f)\log_2[P(q,f)]}{P(q)P(f)},$$

where $H(Q)$ is the entropy of Q before new findings are applied to input node F and $H(Q|F)$ is the entropy of Q after new findings are applied to F. In Netica®, entropy reduction is also termed mutual information.

For continuous variables, sensitivity is calculated as variance reduction VR, which is the expected reduction in variation, $V(Q)$, of the expected real value of the output variable Q due to the value of input variable F, and is calculated as

$$VR = V(Q) - V(Q|F),$$

where

$$V(Q) = \sum_q P(q)[X_q - E(Q)]^2,$$

$$V(Q|F) = \sum_q P(q|f)[X_q - E(Q|f)]^2,$$

$$E(Q) = \sum_q P(q)X_q,$$

and where X_q is the numeric real value corresponding to state q, $E(Q)$ is the expected real value of Q before new findings are applied, $E(Q|F)$ is the expected real value of Q after new findings f are applied to F, and $V(Q)$ is the variance in the real value of Q before any new findings [*Marcot et al.*, 2006].

3. RESULTS

3.1. Bayesian Network Model Outcomes

The most probable BN model outcome, for both the SIE and PBDE, was “extinct” (Table 2 and Plate 4). In all but

Table 2. Results of the Bayesian Network Population Stressor Model, Showing the Most Probable Outcome State, and Probabilities, in Percentiles, of Each State for Overall Population Outcome (Node D1) for Four Polar Bear Ecoregions[a]

Time Period	Basis	Node D1: Overall Population Outcome: Most Probable Outcome	Larger (%)	Same as Now (%)	Smaller (%)	Rare (%)	Extinct (%)
		Seasonal Ice Ecoregion					
Year −10	Satellite data	larger	93.92	5.75	0.30	0.02	0.00
Year 0	Satellite data	same_as_now	21.85	43.72	18.98	8.37	7.07
Year 25	GCM minimum	extinct	0.37	3.87	25.41	22.59	47.76
Year 50	GCM minimum	extinct	0.05	0.61	9.79	12.36	77.19
Year 75	GCM minimum	extinct	0.00	0.09	3.48	8.28	88.15
Year 95	GCM minimum	extinct	0.00	0.09	3.48	8.28	88.15
Year 25	Ensemble mean	extinct	0.37	3.87	25.41	22.59	47.76
Year 50	Ensemble mean	extinct	0.05	0.61	9.79	12.36	77.19
Year 75	Ensemble mean	extinct	0.00	0.09	3.48	8.28	88.15
Year 95	Ensemble mean	extinct	0.00	0.09	3.48	8.28	88.15
Year 25	GCM maximum	extinct	0.37	3.87	25.41	22.59	47.76
Year 50	GCM maximum	extinct	0.24	2.20	24.37	19.35	53.85
Year 75	GCM maximum	extinct	0.01	0.18	5.17	9.52	85.11
Year 95	GCM maximum	extinct	0.01	0.18	5.17	9.52	85.11
		Archipelago Ecoregion					
Year −10	Satellite data	same_as_now	22.51	34.73	31.48	8.72	2.56
Year 0	Satellite data	larger	69.48	29.26	1.06	0.19	0.00
Year 25	GCM minimum	same_as_now	14.23	36.36	32.10	6.58	10.73
Year 50	GCM minimum	smaller	4.57	12.93	51.34	20.60	10.56
Year 75	GCM minimum	extinct	0.89	3.16	32.07	19.34	44.54
Year 95	GCM minimum	extinct	1.38	4.65	33.38	19.51	41.07
Year 25	Ensemble mean	same_as_now	14.23	36.36	32.10	6.58	10.73
Year 50	Ensemble mean	smaller	4.57	12.93	51.34	20.60	10.56
Year 75	Ensemble mean	extinct	1.05	3.34	32.25	26.07	37.30
Year 95	Ensemble mean	extinct	1.38	4.65	33.38	19.51	41.07
Year 25	GCM maximum	same_as_now	14.23	36.36	32.10	6.58	10.73
Year 50	GCM maximum	smaller	5.83	15.93	52.35	18.01	7.88
Year 75	GCM maximum	smaller	4.42	12.40	49.36	22.96	10.85
Year 95	GCM maximum	extinct	1.38	4.65	33.38	19.51	41.07
		Polar Basin Divergent Ecoregion					
Year −10	Satellite data	larger	99.78	0.22	0.00	0.00	0.00
Year 0	Satellite data	same_as_now	24.16	56.60	13.36	4.73	1.14
Year 25	GCM minimum	extinct	0.00	0.97	18.98	23.00	57.05
Year 50	GCM minimum	extinct	0.00	0.00	2.86	10.58	86.55
Year 75	GCM minimum	extinct	0.00	0.00	3.07	10.91	86.02
Year 95	GCM minimum	extinct	0.00	0.00	3.88	12.23	83.89
Year 25	Ensemble mean	extinct	0.21	2.37	27.43	24.69	45.30
Year 50	Ensemble mean	extinct	0.00	0.18	6.16	13.34	80.33
Year 75	Ensemble mean	extinct	0.00	0.00	2.86	10.58	86.55
Year 95	Ensemble mean	extinct	0.00	0.00	3.88	12.23	83.89
Year 25	GCM maximum	extinct	0.25	2.43	27.88	27.58	41.86
Year 50	GCM maximum	extinct	0.00	0.18	6.16	13.34	80.33
Year 75	GCM maximum	extinct	0.00	0.07	4.46	12.00	83.47
Year 95	GCM maximum	extinct	0.00	0.09	5.73	13.84	80.33

Table 2. (continued)

Time Period	Basis	Most Probable Outcome	Larger (%)	Same as Now (%)	Smaller (%)	Rare (%)	Extinct (%)
			Node D1: Overall Population Outcome				
		Polar Basin Convergent Ecoregion					
Year −10	Satellite data	larger	98.39	1.61	0.00	0.00	0.00
Year 0	Satellite data	larger	71.69	27.49	0.63	0.19	0.00
Year 25	GCM minimum	larger	64.86	28.47	6.09	0.49	0.09
Year 50	GCM minimum	extinct	0.26	2.30	27.98	31.59	37.87
Year 75	GCM minimum	extinct	0.00	0.39	9.68	13.24	76.70
Year 95	GCM minimum	extinct	0.00	0.39	9.68	13.24	76.70
Year 25	Ensemble mean	same_as_now	18.23	41.81	26.37	5.16	8.43
Year 50	Ensemble mean	extinct	0.48	2.72	29.27	32.46	35.06
Year 75	Ensemble mean	extinct	0.00	0.27	8.40	15.10	76.23
Year 95	Ensemble mean	extinct	0.02	0.44	9.49	12.75	77.30
Year 25	GCM maximum	same_as_now	18.23	41.81	26.37	5.16	8.43
Year 50	GCM maximum	extinct	0.14	1.24	21.15	30.71	46.77
Year 75	GCM maximum	extinct	0.02	0.46	12.64	24.46	62.41
Year 95	GCM maximum	extinct	0.02	0.44	10.51	16.52	72.52

[a]See Plate 3.

the earliest time periods, we forecasted low probabilities for all other outcome states in these two ecoregions. The low probability afforded to outcome states other than extinct suggested a clear trend in these ecoregions toward probable extirpation by mid century. Forecasts were less severe in other ecoregions. At year 50, probability of the "extinct" state was only 8–10% in the AE. At all time steps in the AE, and at year 50 in the PBCE, considerable probability fell into outcome states other than extinct (Table 2 and Plate 4). The distribution of probabilities for the states of overall population outcome suggests polar bears could persist in all ecoregions through the early part of the century, through mid century in the PBCE and through the end of the century in the AE (Table 2 and Plate 4).

Future conditions affected node C3, polar bear distribution, more than they affected node C4, polar bear numbers. "Extirpated" was the most probable outcome at mid century for node C3 in the PBDE and SIE. The most probable outcome in these ecoregions for node C4, however, was reduced density [see *Amstrup et al.*, 2007]. This probably reflects the high relative certainty that areas where ice is absent for too long will not support many bears, and the relative uncertainty regarding how population dynamics features may change while the sea ice is retreating. Modeled future polar bear distributions were driven by the FWS listing factor "Habitat Threats" (node F2, Table 3), as well as by node D, habitat distribution. Distribution and availability of habitat, especially in the SIE and PBDE (Table 3) appear to be the most salient threats to polar bears. We also assumed that deteriorating sea ice would be accompanied by worsening conditions listed under FWS listing factors C, disease and predation, etc., and E, other natural or man-made factors (nodes A4 and A6) (Table 4). We included year 25 in our projections to help provide context for mid century projections and beyond and to help understand the transition from current to future conditions. It is important to emphasize, however, that polar bears have a long life span. Many individuals alive now could still be alive during the decade of 2020–2029. Hence, projecting changes between now and then incorporates the uncertainty of tradeoffs between functional and numerical responses, as well as the greater uncertainties in sea ice status in the nearer term.

3.2. *Sensitivity Structure of the Bayesian Network Model*

We conducted 10 tests on the BN population stressor model to determine its sensitivity structure (Appendix C). The BN model was well balanced in that sensitivity of overall population outcome (node D1, sensitivity test 1) was not dominated by a single or small group of input variables. Considering that "ecoregion" and "availability of alternate regions" are in essence habitat variables, 6 of the top 7 variables explaining overall outcome were sea ice related and together explained 87% of the variation in overall population outcome (node D1, Appendix C and Plate 5).

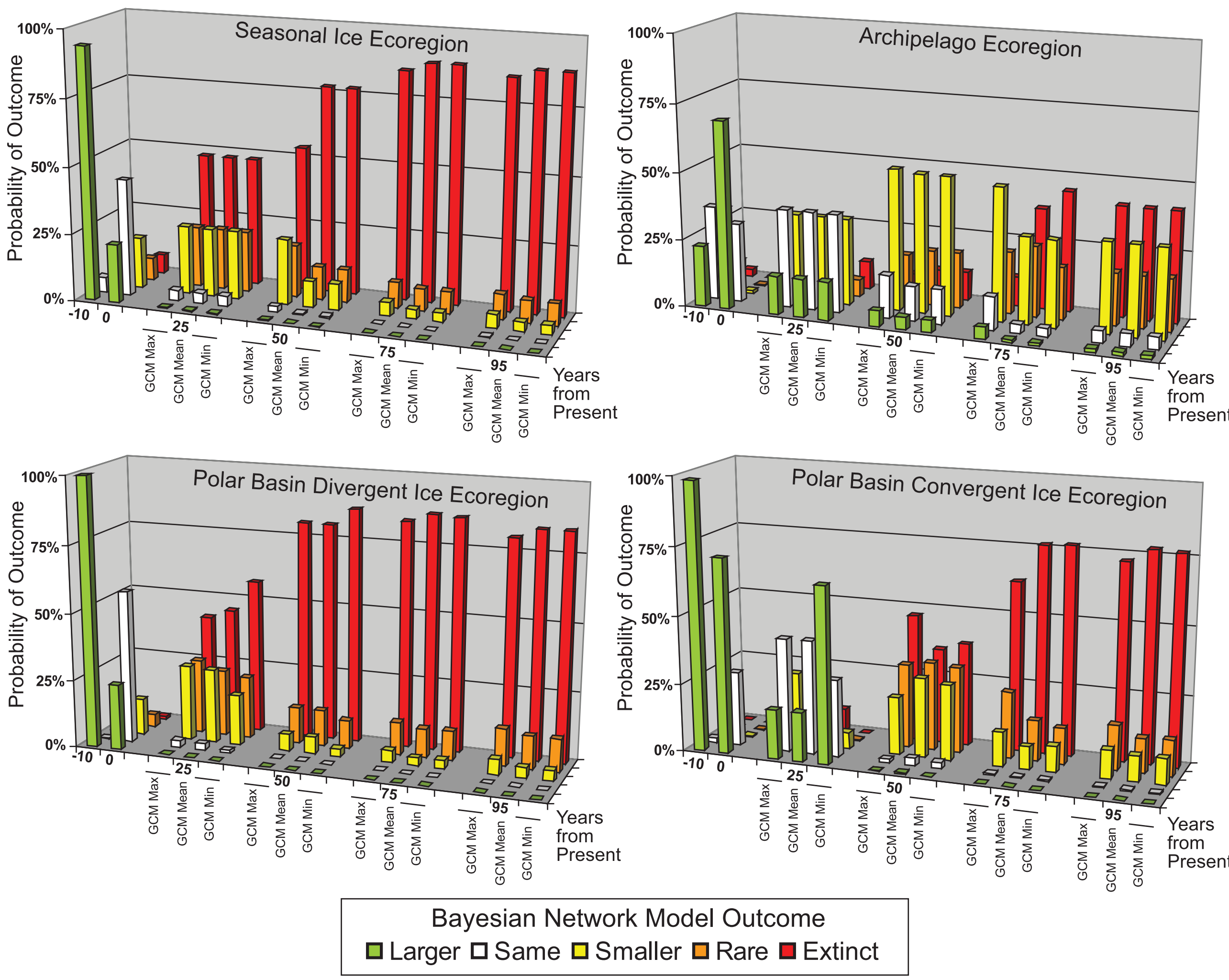

Plate 4. Projected polar bear population outcomes of Bayesian network model for four ecoregions at five time periods relative to present. Present and prior decade (years 0 and −10) sea ice conditions were from observed record. Future ice conditions were based on the ensemble mean of 10 GCMs and the two GCMs that forecasted maximum and minimum ice extent in each ecoregion at each time period. Note that strength of dominant outcomes (tallest bars) is inversely proportional to heights of competing outcomes. Outcome definitions are as follows: larger, more abundant than present (year 0) plus distribution at least the same as at present; same, numerical and distribution responses similar to present; smaller, reduced in numbers and distribution; rare, numerically rare but occupying similar distribution or reduced numerically but spatially represented as transient visitors; and extinct, numerically absent or distributionally extirpated.

Table 3. Results of the Bayesian Network Population Stressor Model, Showing the Most Probable Outcome States, and Probabilities of Each State, in Percentiles, for Habitat Threats and Direct Mortalities Summary Variables (Nodes F2 and A1) for Four Polar Bear Ecoregions[a]

		Node F2: Factor A—Habitat Threats					Node A1: Factor B—Overutilization			
Time Period	Basis	Most Probable Outcome	Improvement (%)	No Effect (%)	Minor Restriction (%)	Major Restriction (%)	Most Probable Outcome (%)	Fewer (%)	Same as Now (%)	More (%)
				Seasonal Ice Ecoregion						
Year −10	Satellite data	improvement	94.60	5.00	0.40	0.00	fewer	100.00	0.00	0.00
Year 0	Satellite data	no_effect	26.41	36.84	23.02	13.72	same_as_now	0.00	100.00	0.00
Year 25	GCM minimum	major_restriction	0.60	10.52	43.40	45.48	same_as_now	0.00	62.60	37.40
Year 50	GCM minimum	major_restriction	0.08	2.00	16.64	81.28	same_as_now	0.00	62.60	37.40
Year 75	GCM minimum	major_restriction	0.00	0.00	4.72	95.28	same_as_now	0.00	60.00	40.00
Year 95	GCM minimum	major_restriction	0.00	0.00	4.72	95.28	same_as_now	0.00	60.00	40.00
Year 25	Ensemble mean	major_restriction	0.60	10.52	43.40	45.48	same_as_now	0.00	62.60	37.40
Year 50	Ensemble mean	major_restriction	0.08	2.00	16.64	81.28	same_as_now	0.00	62.60	37.40
Year 75	Ensemble mean	major_restriction	0.00	0.00	4.72	95.28	same_as_now	0.00	60.00	40.00
Year 95	Ensemble mean	major_restriction	0.00	0.00	4.72	95.28	same_as_now	0.00	60.00	40.00
Year 25	GCM maximum	major_restriction	0.60	10.52	43.40	45.48	same_as_now	0.00	62.60	37.40
Year 50	GCM maximum	major_restriction	0.40	9.68	43.60	46.32	same_as_now	0.00	62.60	37.40
Year 75	GCM maximum	major_restriction	0.00	0.08	9.60	90.32	same_as_now	0.00	60.00	40.00
Year 95	GCM maximum	major_restriction	0.00	0.08	9.60	90.32	same_as_now	0.00	60.00	40.00
				Archipelago Ecoregion						
Year −10	Satellite data	no_effect	39.00	44.60	16.40	0.00	same_as_now	4.80	53.00	42.20
Year 0	Satellite data	improvement	88.56	10.43	1.01	0.00	same_as_now	0.00	100.00	0.00
Year 25	GCM minimum	no_effect	20.80	38.40	32.80	8.00	same_as_now	0.00	75.14	24.86
Year 50	GCM minimum	no_effect	32.48	41.28	22.30	3.94	more	0.00	0.00	100.00
Year 75	GCM minimum	minor_restriction	4.08	24.32	40.32	31.28	more	0.00	30.00	70.00
Year 95	GCM minimum	minor_restriction	4.08	24.32	40.32	31.28	same_as_now	0.00	60.00	40.00
Year 25	Ensemble mean	no_effect	20.80	38.40	32.80	8.00	same_as_now	0.00	75.14	24.86
Year 50	Ensemble mean	no_effect	32.48	41.28	22.30	3.94	more	0.00	0.00	100.00
Year 75	Ensemble mean	minor_restriction	4.96	25.44	39.84	29.76	more	0.00	30.00	70.00
Year 95	Ensemble mean	minor_restriction	4.08	24.32	40.32	31.28	same_as_now	0.00	60.00	40.00
Year 25	GCM maximum	no_effect	20.80	38.40	32.80	8.00	same_as_now	0.00	75.14	24.86
Year 50	GCM maximum	improvement	41.92	38.40	17.06	2.62	more	0.00	0.00	100.00
Year 75	GCM maximum	no_effect	32.48	41.28	22.30	3.94	more	0.00	0.00	100.00
Year 95	GCM maximum	minor_restriction	4.08	24.32	40.32	31.28	same_as_now	0.00	60.00	40.00
				Polar Basin Divergent Ecoregion						
Year −10	Satellite data	improvement	99.68	0.32	0.00	0.00	fewer	100.00	0.00	0.00
Year 0	Satellite data	no_effect	30.20	47.24	20.54	2.02	same_as_now	0.00	100.00	0.00
Year 25	GCM minimum	major_restriction	0.00	2.16	45.44	52.40	same_as_now	0.00	60.00	40.00
Year 50	GCM minimum	major_restriction	0.00	0.00	0.00	100.00	same_as_now	0.00	60.00	40.00
Year 75	GCM minimum	major_restriction	0.00	0.00	0.00	100.00	same_as_now	0.00	60.60	39.40
Year 95	GCM minimum	major_restriction	0.00	0.00	0.00	100.00	same_as_now	0.00	63.00	37.00
Year 25	Ensemble mean	minor_restriction	0.72	12.72	48.96	37.60	same_as_now	0.00	60.00	40.00
Year 50	Ensemble mean	major_restriction	0.00	0.36	9.80	89.84	same_as_now	0.00	60.00	40.00
Year 75	Ensemble mean	major_restriction	0.00	0.00	0.00	100.00	same_as_now	0.00	60.00	40.00
Year 95	Ensemble mean	major_restriction	0.00	0.00	0.00	100.00	same_as_now	0.00	63.00	37.00
Year 25	GCM maximum	minor_restriction	0.89	13.45	48.62	37.04	same_as_now	0.00	60.00	40.00
Year 50	GCM maximum	major_restriction	0.00	0.36	9.80	89.84	same_as_now	0.00	60.00	40.00
Year 75	GCM maximum	major_restriction	0.00	0.00	5.08	94.92	same_as_now	0.00	60.00	40.00
Year 95	GCM maximum	major_restriction	0.00	0.00	5.08	94.92	same_as_now	0.00	63.60	36.40

Table 3. (continued)

Time Period	Basis	Node F2: Factor A—Habitat Threats: Most Probable Outcome	Improvement (%)	No Effect (%)	Minor Restriction (%)	Major Restriction (%)	Node A1: Factor B—Overutilization: Most Probable Outcome (%)	Fewer (%)	Same as Now (%)	More (%)
		Polar Basin Convergent Ecoregion								
Year −10	Satellite data	improvement	97.48	2.52	0.00	0.00	fewer	100.00	0.00	0.00
Year 0	Satellite data	improvement	88.56	10.43	1.01	0.00	same_as_now	0.00	100.00	0.00
Year 25	GCM minimum	improvement	87.20	11.20	1.60	0.00	same_as_now	0.00	89.00	11.00
Year 50	GCM minimum	minor_restriction	1.10	14.38	48.19	36.32	same_as_now	0.00	60.00	40.00
Year 75	GCM minimum	major_restriction	0.00	0.00	23.60	76.40	same_as_now	0.00	60.00	40.00
Year 95	GCM minimum	major_restriction	0.00	0.00	23.60	76.40	same_as_now	0.00	60.00	40.00
Year 25	Ensemble mean	no_effect	20.80	38.40	32.80	8.00	same_as_now	0.00	89.00	11.00
Year 50	Ensemble mean	minor_restriction	1.25	15.49	49.10	34.16	same_as_now	0.00	60.00	40.00
Year 75	Ensemble mean	major_restriction	0.00	0.00	17.65	82.35	same_as_now	0.00	60.00	40.00
Year 95	Ensemble mean	major_restriction	0.00	0.24	22.16	77.60	same_as_now	0.00	60.00	40.00
Year 25	GCM maximum	no_effect	20.80	38.40	32.80	8.00	same_as_now	0.00	89.00	11.00
Year 50	GCM maximum	major_restriction	0.29	4.22	45.49	50.00	same_as_now	0.00	60.00	40.00
Year 75	GCM maximum	major_restriction	0.00	0.58	25.18	74.24	same_as_now	0.00	60.00	40.00
Year 95	GCM maximum	major_restriction	0.00	0.35	23.13	76.52	same_as_now	0.00	60.00	40.00

[a]See Plate 3.

Table 4. Results of the Bayesian Network Population Stressor Model, Showing the Most Probable Outcome States, and Probabilities of Each State, for Disease/Predation and Other Disturbance Factors Variables (Nodes A4 and A6) for Four Polar Bear Ecoregions[a]

Time Period	Basis	Node A4: Factor C—Disease and Predation: Most Probable Outcome	Same as Now (%)	Worse (%)	Node A6: Factor E—Other Factors (Natural or Man-Made): Most Probable Outcome	Improvement (%)	No Effect (%)	Minor Restriction (%)	Major Restriction (%)
		Seasonal Ice Ecoregion							
Year −10	Satellite data	same_as_now	100.00	0.00	improvement	84.80	15.20	0.00	0.00
Year 0	Satellite data	same_as_now	100.00	0.00	no_effect	0.00	100.00	0.00	0.00
Year 25	GCM minimum	worse	30.00	70.00	major_restriction	0.00	0.00	13.00	87.00
Year 50	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	13.00	87.00
Year 75	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 25	Ensemble mean	worse	30.00	70.00	major_restriction	0.00	0.00	13.00	87.00
Year 50	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	13.00	87.00
Year 75	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 25	GCM maximum	worse	30.00	70.00	major_restriction	0.00	0.00	13.00	87.00
Year 50	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	13.00	87.00
Year 75	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM maximum	Worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
		Archipelago Ecoregion							
Year −10	Satellite data	same_as_now	100.00	0.00	major_restriction	4.80	20.00	34.80	40.40
Year 0	Satellite data	same_as_now	100.00	0.00	no_effect	0.00	100.00	0.00	0.00
Year 25	GCM minimum	same_as_now	100.00	0.00	no_effect	0.00	46.40	42.20	11.40
Year 50	GCM minimum	worse	30.00	70.00	major_restriction	0.00	0.00	28.00	72.00

Table 4. (continued)

		Node A4: Factor C—Disease and Predation			Node A6: Factor E—Other Factors (Natural or Man-Made)				
Time Period	Basis	Most Probable Outcome	Same as Now (%)	Worse (%)	Most Probable Outcome	Improvement (%)	No Effect (%)	Minor Restriction (%)	Major Restriction (%)
Year 75	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 25	Ensemble mean	same_as_now	100.00	0.00	no_effect	0.00	46.40	42.20	11.40
Year 50	Ensemble mean	worse	30.00	70.00	major_restriction	0.00	0.00	28.00	72.00
Year 75	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 25	GCM maximum	same_as_now	100.00	0.00	no_effect	0.00	46.40	42.20	11.40
Year 50	GCM maximum	worse	30.00	70.00	major_restriction	0.00	0.00	28.00	72.00
Year 75	GCM maximum	worse	30.00	70.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
				Polar Basin Divergent Ecoregion					
Year −10	Satellite data	same_as_now	100.00	0.00	improvement	100.00	0.00	0.00	0.00
Year 0	Satellite data	same_as_now	100.00	0.00	no_effect	0.00	100.00	0.00	0.00
Year 25	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 50	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 75	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	3.00	97.00
Year 95	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	15.00	85.00
Year 25	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 50	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 75	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	15.00	85.00
Year 25	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 50	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 75	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	18.00	82.00
				Polar Basin Convergent Ecoregion					
Year −10	Satellite data	same_as_now	100.00	0.00	improvement	100.00	0.00	0.00	0.00
Year 0	Satellite data	same_as_now	100.00	0.00	no_effect	0.00	100.00	0.00	0.00
Year 25	GCM minimum	same_as_now	100.00	0.00	no_effect	0.00	80.00	10.00	10.00
Year 50	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 75	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM minimum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 25	Ensemble mean	same_as_now	100.00	0.00	no_effect	0.00	80.00	10.00	10.00
Year 50	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 75	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	Ensemble mean	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 25	GCM maximum	same_as_now	100.00	0.00	no_effect	0.00	80.00	10.00	10.00
Year 50	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 75	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00
Year 95	GCM maximum	worse	0.00	100.00	major_restriction	0.00	0.00	0.00	100.00

[a]See Plate 3.

Relative to the FWS listing factors, overall population outcome was most influenced by stressors related to factor A (habitat threats). Influences from factor B (overutilization), factor E (other natural or man-made factors), and factor C (disease and predation) provided progressively less influence (Appendix C, sensitivity test 2).

Recognizing the sensitivity of model outcomes to changes in sea ice, we reran the BN population stressor model under two sets of fixed conditions to determine whether management of human activities on the ground might be able to alter sea ice–driven outcomes. In these "influence runs" we set the states for all nodes over which humans might be able to exert control (e.g., harvest, contaminants, oil, and gas development) first to "same as now," and then to "improved conditions." After doing so, projected probabilities of extinction were lower at every time step (Plate 6). At and beyond mid century, extinction was still the most probable outcome in the PBDE and SIE. However, extinction did not become the most probable outcome in the PBDE and SIE until mid century. And in the SIE, with model runs based on GCMs retaining the maximum sea ice, extinction, as the most probable outcome, was avoided until year 75. Recall that extinction was the most probable outcome in these ecoregions at year 25 in the original model runs. In contrast, results of these influence runs suggested that on the ground management of human activities could improve the fate of polar bears in the AE and PBCE through the latter part of the century (Plate 6). In summary, for our 50-year foreseeable future, it appeared that management of localized human activities could benefit polar bears in the PBCE and especially in the AE but was likely to have little qualitative effect on the future of polar bears in the PBDE and SIE if sea ice continues to decline as projected.

To examine how much different, than projected, future sea ice would need to be to cause a qualitative change in our overall outcomes, we composed another influence run in which we set the values for all non-ice inputs to uniform prior probabilities. That is, we assumed complete uncertainty with regard to future food availability, oil and gas activity, contaminants, disease, etc. Then, we ran the model to determine how changes in the sea ice states alone, specified by our ensemble of GCMs, would affect our outcomes. This exercise illustrated that in order to obtain any qualitative change in the probability of extinction in any of the ecoregions, sea ice projections would need to leave more sea ice, at all future time steps, than even the maximum-ice GCM projection we used (Plate 6).

4. DISCUSSION

4.1. Uncertainty

Analyses in this paper contain four main categories of uncertainty: (1) uncertainty in our understandings of the biological, ecological, and climatological systems; (2) uncertainty in the representation of those understandings in models and statistical descriptions; (3) uncertainty in predictions of species abundance and distribution, and (4) uncertainty in model credibility, acceptability, and appropriateness of model structure. All of these can influence model predictions. Uncertainty in our understanding of complex ecosystems is virtually inevitable. We have, however, dealt with this as well as possible by incorporating a broad sweep of available information regarding polar bears and their environment. How to best represent our understanding of the system in models, the second source of uncertainty, can be structured in various ways. Here, we captured and represented expert understanding of polar bear habitats and populations in a manner that can be reviewed, tested, verified, calibrated, and amended as appropriate. We have attempted to open the "black box" so to speak and to fully expose all formulas and probabilities. We also used sensitivity testing to understand the dynamics of BN model predictions [*Johnson and Gillingham*, 2004] (Appendix C). After BN models of this type are modified through peer review or revised by incorporating the knowledge from more than one expert into the model parameterization, any variation in resulting models can represent the divergence (or convergence) of expertise and judgment among multiple specialists.

Also included in the second category of uncertainty are those associated with statistical estimation of parameters, including measurement and random errors. The sea ice parameters we used in our polar bear models were derived from GCM outputs that possess their own wide margins of uncertainty [*DeWeaver*, 2007]. Hence, the magnitude and distribution of errors associated with our sea ice parameters were unknown. To compensate for these unknowns, we accommodated a broad range of sea ice uncertainties by analyzing the 10-member ensemble GCM mean, as well as the minimum and maximum GCM ice forecasts. In the case of polar bear population estimates, many are known so poorly that the best we have are educated guesses. Pooling subpopulations where numbers are merely guesses with those where precise estimates are available, to gain a range-wide perspective, prevents meaningful calculation and incorporation of specific error terms. We recognize that difficulty, but because our projections are expressed in the context of a comparison to present conditions, we largely avoid the issue. That is, whatever the population size is now, the future size is expressed relative to that and all errors are carried forward.

The third category, uncertainty in predictions of species abundance and distribution can be subject to errors because of spatial autocorrelation, dispersal and movement of organisms, and biotic and environmental interactions [*Guisan et al.*, 2006]. We addressed these error sources by deriving estimates of ice habitat area separately for each ecoregion from the GCM models because sea ice formation, melt, and advection occur differently in each ecoregion. The BN population stressor model accounted explicitly for potential movement of polar bears (e.g., availability of alternative regions) and for biotic and environmental interactions (as expressed in the conditional probability tables; see Appendix B). The spread of probabilities among the BN outcome states, reflect the combinations of uncertainties in states across all other variables, as reflected in each of their conditional probability tables (Appendix B). This spread carries important information for the decision maker who needs to weigh alternative outcomes in a risk assessment (see below).

Finally, uncertainty in model predictions entails addressing model credibility, acceptability, and appropriateness of the model structure. We made every effort to ensure that the model structure was appropriate and credible and that the inputs (Tables D1a and D1b) and conditional probability tables (Appendix B) were parameterized according to best available knowledge of polar bears and their environment. We explored the logic and structure of our BN model through sensitivity analyses, running the model backward from particular states to ensure it returned the appropriate starting point, and performing particular "what if" experiments (e.g., by fixing values in some nodes and watching how values at other nodes respond). We are as confident as we can be at this point of development that our BN model is performing in a plausible manner and providing outcomes that can be useful in qualitatively forecasting the potential future status of polar bears.

Although this manuscript and the model it describes have been peer reviewed by additional polar bear experts, the model structure and parameterizations were based upon the judgments of only one expert. Therefore, additional criteria of model validation must be addressed through subsequent peer review of the model parameters and structure [*Marcot et al.*, 1983; *Marcot*, 1990, 2006; *Marcot et al.*, 2006]. This requirement means the model presented here should be viewed as a first-generation alpha level model [*Marcot et al.*, 2006]. The next development steps have been described in detail by *Marcot et al.* [2006] and include peer review of the alpha model by other subject matter experts and consideration of their judgments regarding model parameterization; reconciliation of the peer reviews by the initial expert; updating the model to a beta level that incorporates the reviews; and testing the beta model for accuracy with existing data (e.g., determining if it matches historic or current known conditions). Additional updating of the model can include incorporation of new data or analyses if available. Throughout this process, sensitivity testing is used to verify model performance and structure. This framework has been used successfully for developing a number of BN models of rare species of plants and animals [*Marcot et al.*, 2001, 2006; *Raphael et al.*, 2001; *Marcot* , 2006]. Model variants that may have emerged in this process would represent the range of expert judgments and experiences (possibly verified with new data), and this range could be important information for decision making.

Because these additional steps in development have not yet been completed, it is important to view probabilities of outcome states of our first-generation model in terms of their general direction and overall magnitudes rather than focusing on the exact numerical probabilities of the outcomes. When predictions result in high probability of one population outcome state and low or zero probabilities of all other states, there is low overall uncertainty of predicted results. When projected probabilities of various states are more equally distributed, however, careful consideration should be given to large probabilities representing particular outcomes even if those probabilities are not the largest. Consistency of pattern among scenarios (e.g., different GCM runs) also is important to note. If the most probable outcome has a much higher probability than all of the other states and if the pattern across time frames and GCM models is consistent, confidence in that outcome pattern is high. If, on the other hand, probabilities are more uniformly spread among different states and if the pattern varies among scenarios, importance of the numerically most probable outcome should be tempered in view of the competing outcomes. This approach takes advantage of the information available from the model while recognizing that it is still in development. It also conforms to the concept of viewing the model as a tool describing relative probabilistic relationships among major levels of population response under multiple stressors.

4.2. Bayesian Network Model Outcomes

In the BN model, for each scenario run, the spread of population outcome probabilities (or at least nonzero possibilities) represented how individual uncertainties propagate and compound across multiple stressors. Beyond year 50, "extinct" was the most probable overall outcome state for all polar bear ecoregions, except the AE (Plate 4 and Table 2). For the decade of 2020–2029, outcomes were intermediate between the present (year 0) and the foreseeable future (year 50) time frames. We projected that polar bear numbers in the AE and PBCE could remain the same as now through the earlier decade, becoming smaller by mid century. In the SIE and PBDE, polar bears appeared to be headed toward extinction soon. However, probabilities they may persist in the PBDE and SIE were much higher at year 25 than at mid century (Plate 4). Although our BN model suggests polar bears are most likely to be absent from the PBDE and SIE by mid century, there is much uncertainty regarding when, between now and then, they might disappear from these ecoregions.

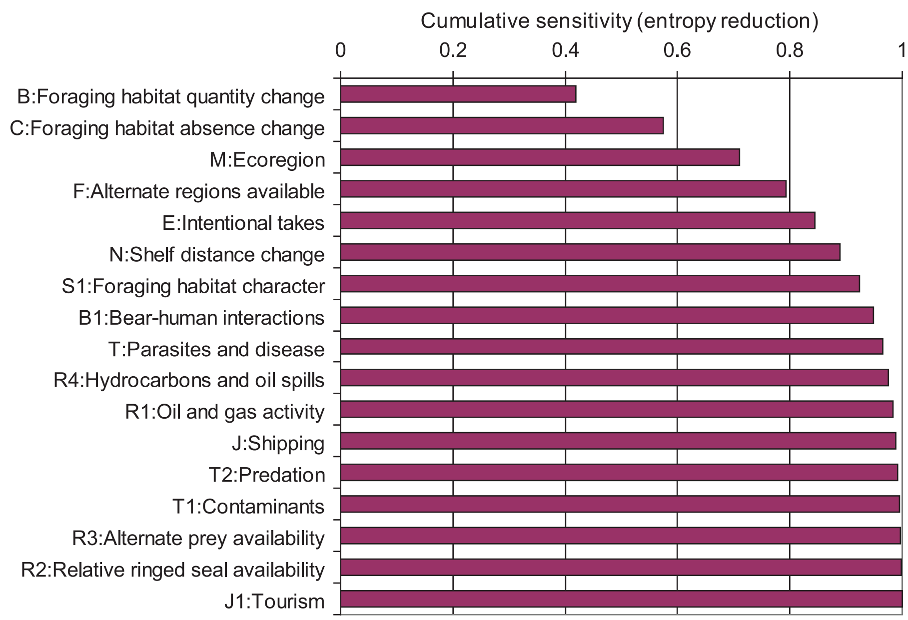

Plate 5. Cumulative sensitivity of overall population outcome (node D1, Plate 3) to all input variables (yellow boxes, Plate 3) in the Bayesian network population stressor model. The 17 input variables on the vertical axis are listed, top to bottom, in decreasing order of their individual influence on overall population outcome (see Appendix C, sensitivity test 1). The horizontal axis represents the cumulative proportion of total entropy reduction (mutual information) from the input variables. For example, the first two variables, foraging habitat quantity change and foraging habitat absence change, together explain 58% of the variation or uncertainty in the overall population outcome.

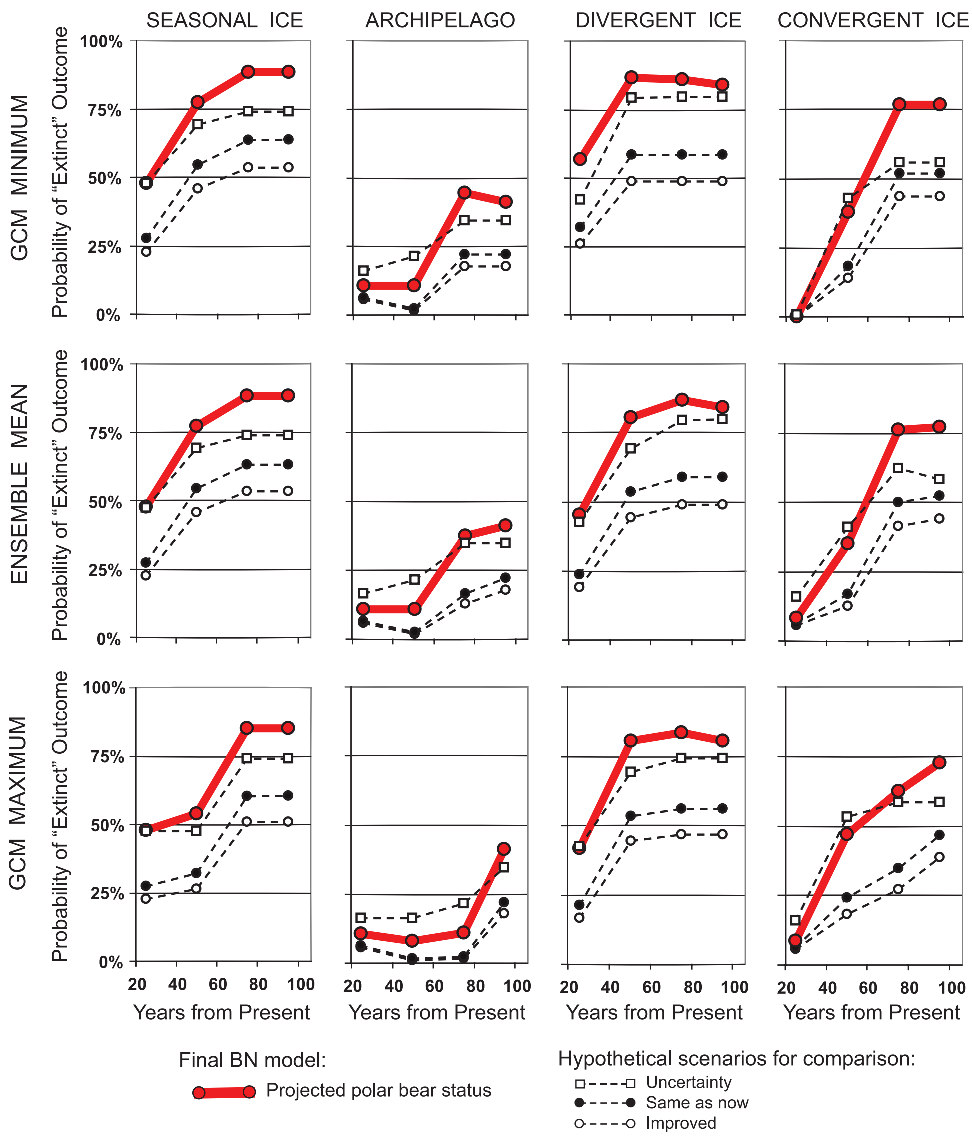

Plate 6. Probability of "extinct" outcome projected by Bayesian network (BN) model of worldwide polar bear populations. Shown are probabilities provided by the mean of a 10-member ensemble of general circulation models and the individual models which leave the maximum and minimum amount of sea ice at each time stop. Red line illustrates extinction probabilities from Table 2. Open circles illustrate results from setting all possible on the ground human influences to more favorable for bears than they are now. Solid circles illustrate holding all on the ground human influences as they are now. Squares illustrate results when all inputs, except ice nodes N, B and C, are held to uniform probabilities (i.e., total uncertainty). Only in the AE and PBCE does it appear that manipulating on the ground human activities can substantively influence overall outcomes at mid century and beyond.

Because polar bears are tied to the sea ice for obtaining food, major changes in the quantity and distribution of sea ice must result in similar changes in polar bear distribution. Therefore, the distributional effects of projected changes are most apparent. Whereas it is fairly certain that polar bears will not remain in areas where habitat absence is too prolonged to make seasonal use practical, it is less certain how many bears from areas of former habitat may be sustained in areas with remaining habitat. It is not surprising, therefore, that overall outcomes projected for polar bears appeared to be driven more by distributional effects than numerical effects. This is largely due to the parameterization in the model. Some input variables such as hunting or direct bear/human interactions might be expected to most immediately affect bear numbers rather than distribution. History has shown, however, that these things can be managed effectively to maintain sustainable populations when habitats are adequate. Our model incorporated the manageability of these human effects in the conditional probability tables. In contrast, polar bears cannot be maintained where their habitats are absent, and GCM projections suggest existing habitat areas will be progressively declining. Regardless of whether some concentration of numbers is possible in areas with remaining habitat, and there is great uncertainty regarding the relevance of this to the future, polar bears are not likely to survive in any numbers in areas where their current ice habitats no longer exist.

The most probable outcomes for factor A (Habitat Threats) of the proposal to list polar bears as a threatened species were "major restriction" (Table 3). Numerical responses of polar bears to future circumstances were forecast to be more modest than changes in distribution. In all regions, reduced density was the most probable outcome for numerical response. One way to interpret that outcome may be that where habitat remains, polar bears will remain even if in reduced numbers. This is consistent with our BN model results suggesting that polar bears may persist in the AE through the end of the 21st century. Declines in distribution and number are likely to be faster and more profound in the PBDE and the SIE than elsewhere. Sea ice availability in both the PBDE and SIE already is declining rapidly in these ecoregions [*Meier et al.*, 2007; *Stirling and Parkinson*, 2006]. The loss of sea ice habitats in the PBDE is projected to continue, and possibly to accelerate [*Holland et al.*, 2006; *Durner et al.*, 2008; *Stroeve et al.*, 2007].

Plate 7 illustrates how distribution changes driven by changes in the sea ice appeared to be the major factor leading to our dire predictions of the future for polar bears. For projection purposes, we binned the number of additional months during which the sea ice was projected to be absent from the continental shelf (node C) into four categories which included the range from 1 month less than current (−1) to ≥3 months longer than current. Similarly, we binned the maximum distance the ice edge could move away from the shelf (node N) into four categories including the range from 200 km less than current (−200) to ≥800 km additional distance. It is clear from node D (see Appendix B) that we parameterized the model such that more distant ice retreat and longer ice absence meant reduced availability of critical foraging habitats as documented by *Durner et al.* [2008]. Such reduced availability has been shown to have negative impacts on polar bears [*Regehr et al.*, 2007a]. In the PBDE as an example, the general circulation models that we used to project future ice conditions, indicated values for nodes C and N will range from 1.8 to 2.2 additional months of ice absence and 234 km to 1359 km additional ice distance by mid century. Similarly, foraging habitat quantity is projected to decline between 16 and 32% by mid century. As Plate 7 illustrates even the smaller of these values for temporal and spatial retreat of sea ice place factor A node F2 (see Appendix B) into the category of major habitat restriction. That, in turn, pushes the distribution response toward extirpated which pushes the most probable overall population outcome into the "extinct" category. The outcome percentages in this example differ from the overall outcomes presented in Table 2 because results shown in this example occurred without changing any other inputs included in the full model. Hence, this result provides an example of how the projected changes in sea ice alone influenced the dire projections of our BN model. Outcomes in the PBDE are even more dire when the GCMs that lose the most ice are used or when we look farther into the future. In contrast, as Table 2 and Plate 4 illustrate, outcomes are less alarming in the PBCE and AE because of the more modest changes projected for sea ice in those regions. Sensitivity analyses described below confirm this role of sea ice in driving the expected future for polar bears.

4.3. Sensitivity Analyses

Sensitivity analyses offer an opportunity to interpret model outcomes at every level. The overall population outcome was most sensitive to change in habitat quantity (node B) and temporal habitat availability (node C). The other major habitat variable, change in distance between ice and the continental shelf (node N) was the 6th most influential factor on the overall population outcome, despite its being relevant only to the polar basin ecoregions. Our BN model recognized that sea ice characteristics, and how polar bears respond to them, differed among the four ecoregions. In the SIE, for example, all members of the subpopulation are forced ashore when the ice melts entirely in summer. In the

PBDE, by comparison, some bears retreat to shore, while most follow the sea ice as it retreats far offshore in summer. The fact that ecoregion and the availability of alternate ecoregions together explained 22% of the variation in overall population outcome was further evidence of the importance of sea ice habitat and its regional differences.

Another habitat variable, "foraging habitat character" (node S1), was ranked 7th among variables having influence on the overall population outcome. This qualitative variable relating to sea ice character was included to allow for the fact that in addition to changes in quantity and distribution of sea ice, subtle changes in the composition of sea ice could affect polar bears. For example, longer open water periods and warmer winters have resulted in thinner ice in the polar basin region [*Lindsay and Zhang*, 2005; *Holland et al.*, 2006; *Belchansky et al.*, 2008]. *Fischbach et al.* [2007] concluded that increased prevalence of thinner and less stable ice in autumn has resulted in reduced sea ice denning among polar bears of the southern Beaufort Sea.

Observations during polar bear field work suggest that the thinning of the sea ice also has resulted in increased roughness and rafting among ice floes. Compared to the thicker ice that dominated the polar basin decades ago, thinner ice is more easily deformed, even late in the winter. Whether or not thinner ice is satisfactory for seals, the extensive areas of jagged pressure ridges that can result when ice is more easily deformed may not be well suited to polar bear foraging. These changes appear to reduce foraging effectiveness of polar bears, and it is suspected the changes in ice conditions may have contributed to recent cannibalism and other unusual foraging behaviors [*Stirling et al.*, 2008]. Also, thinner, rougher ice, interspersed with more open water, may be an impediment to the travels of young cubs. Physical difficulties in navigating this "new" ice environment could explain recent observed increases in mortality of first-year cubs [*Rode et al.*, 2007]. The fact that six of the seven variables most influential on overall outcome were sea ice related and explained 87% of the variation in that outcome corroborates the well established link between polar bears and sea ice.

The 5th ranked potential stressor to which overall population outcome was sensitive was intentional takes. Historically, the direct killing of polar bears by humans for subsistence or sport has been the biggest challenge to polar bear welfare [*Amstrup*, 2003]. Our model suggests that harvest of polar bears may remain an important factor in the population dynamics of polar bears in the AE and PBCE, as sea ice retreats.

It is important to remember that there is great uncertainty in the exact way the potential stressors we modeled may change in the future. Also, the degree of uncertainty differs among the variables we included in our model. There is relatively great certainty that the spatiotemporal distribution of sea ice will decline through the coming century. There is less certainty in just how much it will decline by a specified decade. The short, intermediate, and long-term effects of that decline on food availability for polar bears are largely unknown [*Bluhm and Gradinger*, 2008]. Here, we assumed that declining sea ice means declining food availability for polar bears, with the decline in food mirroring that of the sea ice. Spatiotemporal reductions in sea ice cover, however, could fundamentally alter the structure and function of the Arctic ecosystem. Such changes could result in different timing and level of productivity. It seems clear that continued declines in sea ice ultimately will mean reduced year-round food availability and declines in polar bear numbers and distribution. We cannot rule out, however, that increases in productivity could result in transitory increases in food availability for bears. Such changes would not alter the ultimate predictions made here, polar bears are clearly tied to the sea ice for access to their food. Such changes could, however, alter the temporal sensitivity of our outcomes to values at input nodes.

4.4. Strength of Evidence

Our BN population stressor model projects that sea ice and sea ice related factors will be the dominant driving force affecting future distributions and numbers of polar bears through the 21st century. Despite caveats regarding the early stage of development of our BN model, there are several reasons to believe that the directions and general magnitudes of its outcomes are reasonable.

First, they are consistent with hypothesized effects of global warming on polar bears [*Derocher et al.*, 2004] and with recent observations of how decreasing spatiotemporal distribution of sea ice has affected polar bears in some portions of their range [*Stirling and Derocher*, 1993; *Stirling and Parkinson*, 2006; *Stirling et al.*, 1999, 2007, 2008; *Ainley et al.*, 2003; *Ferguson et al.*, 2005; *Amstrup et al.*, 2006; *Hunter et al.*, 2007; *Regehr et al.*, 2007a, 2007b; *Rode et al.*, 2007]. The high sensitivity of our overall model outcomes to sea ice habitat changes is consistent with the recent PBSG decision, based mainly on projected changes in sea ice, that polar bears should be reclassified as vulnerable [*Aars et al.*, 2006].

Second, results of influence runs to assess the ability of on the ground activities to alter outcomes were not qualitatively different, during most time periods, from previous runs for the PBDE and SIE (Plate 6). Maintaining current conditions (other than sea ice) in the PBDE and SIE or improving conditions on the ground appeared to have some ability to reduce the risk of extinction being the most probable outcome during the first couple decades of this century. This effect

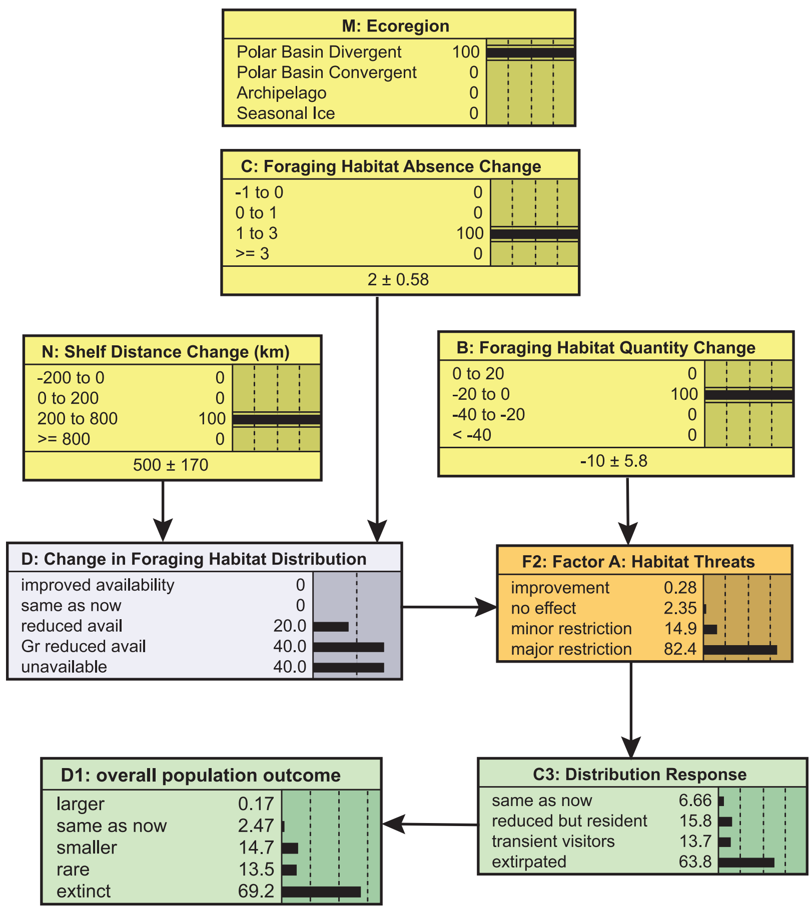

Plate 7. A subset of the Bayesian network model (Plate 3) illustrating why sea ice conditions projected for year 50 and beyond have such dire consequences for polar bears of the PBDE. Values of nodes N, C, and B are specified by the GCM outputs (see Tables D1a and D1b). Shown here are the input categories from the sea ice models projecting the smallest retreats of sea ice by mid century. Nodes D, F2, C3, and D1 are calculated by the Bayesian network model according to conditional probabilities specified in Appendix B. For illustration of the influence of sea ice on outcomes, we show future inputs only for the subset of nodes dealing with sea ice values here; therefore, outcomes shown here differ from those in Table 2. As illustrated in Table 2, results are more negative when other GCM outputs are used and when time frames farther into the future are examined.

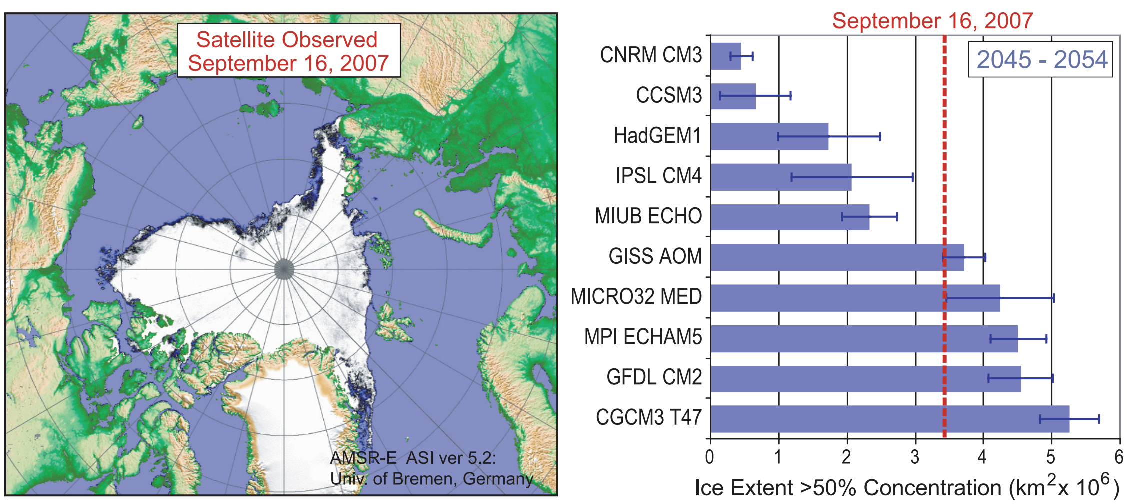

Plate 8. Area of sea ice extent (>50% ice concentration) on 16 September 2007, compared to 10 Intergovernmental Panel of Climate Change Fourth Assessment Report GCM mid century projections of ice extent for September 2045–2054 (mean ±1 standard deviation, n = 10 years). Ice extent for 16 September 2007 was calculated using near-real-time ice concentration estimates derived with the NASA Team algorithm and distributed by the National Snow and Ice Data Center (http://nsidc.org). Note that five of the models we used in our analyses project more perennial sea ice at mid century than was observed in 2007. This suggests our projections for the future status of polar bears may be conservative.

largely disappears by mid century, however, and management of localized human activities appears to have little qualitative effect on the future of polar bears in the PBDE and SIE if sea ice continues to decline as projected. The fact that sea ice has been declining more rapidly than even our minimum ice GCMs project (see below) suggests even possible transitory benefits of on the ground interventions may be illusory in these ecoregions. In contrast, our BN model suggested that managing human controlled stressors could qualitatively lower the probabilities of extinction in the PBCE and AE. Such management has played an important role in the past recovery of polar bears [*Amstrup*, 2003] and apparently could continue to be important in regions where sea ice habitat remains.

Third, influence runs in which we specified complete uncertainty in all inputs except sea ice illustrated that in order to obtain any qualitative change in the probability of extinction in any of the ecoregions, sea ice availability in future time periods must be greater than even the maximum-ice GCM projections we used (Plate 6). This eventuality may be unlikely in light of the fact that most GCMs simulate more ice than has actually been observed during 1979 to present [*Durner et al.*, 2008; *Stroeve et al.*, 2007]. It also seems unlikely in light of the most recent observations that September sea ice extent (15% concentration) in 2007 was 4.13×10^6 km^2. This is lower than the previous record set in 2005 by nearly 1.2×10^6 km^2 (National Snow and Ice Data Center, 1 October 2007 press release, available at http://nsidc.org/news/index.html). When ice extent based on a 50% concentration threshold, which is probably near the lower limit of ice cover useful to polar bears [*Durner et al.*, 2008], is calculated, the area in 2007 was down to approximately 3.5×10^6 km^2. Five of the GCM models in our 10-member ensemble forecast more September sea ice in 2050 than was observed in 2007 (Plate 8). Perhaps even more telling than the overall "faster-than-forecasted" ice decline, is the observation that much of the AE, the region where we forecasted polar bears to remain until late in the century, was ice free in September 2007 (Plate 8). Hence, the probability that more sea ice than projected will be available during the rest of this century seems low.

Finally, a polar bear BN population stressor model would have to be structured and parameterized very differently to project qualitatively different outcomes than we have here. Yet it seems unlikely that other polar bear experts would do that. Evidence for the polar bear's reliance on sea ice is replete. Although they are opportunistic and will take terrestrial foods, including human refuse when available, and may benefit from such activity [*Lunn and Stirling*, 1985; *Derocher et al.*, 1993], polar bears are largely dependent on the productivity of the marine environment. Refuse, for example, is of limited availability throughout the polar bear range, and could at best benefit relatively few individuals. Also, polar bears are inefficient in preying on terrestrial animals [*Brook and Richardson*, 2002; *Stempniewicz*, 2006]. Perhaps most importantly, polar bears have evolved a strategy designed to take advantage of the high fat content of marine mammals [*Best*, 1984]. Available terrestrial foods are, with few exceptions, not rich enough or cannot be gathered efficiently enough to support large bodied bears [*Welch et al.*, 1997; *Rode et al.*, 2001; *Robbins et al.*, 2004]. Because polar bears are the largest of the bears, it is unlikely that terrestrial arctic habitats which are depauperate from the standpoint of bear food could support them in anything like current numbers. Empirical evidence of this is provided by the fact that Arctic grizzly bears are the smallest grizzly bears found anywhere and they occur at the lowest densities [*Miller et al.*, 1997]. Habitats adjacent to present polar bear ranges just do not seem likely to support large numbers of the much larger-bodied polar bears. Although polar bears in Hudson Bay, which are forced onto land all summer, are known to consume a wide variety of foods; they gain little energetic benefit from those foods [*Ramsay and Hobson*, 1991]. The only foods, other than their ringed and bearded seal staples, that are known to be energetically important to polar bears in some regions are other marine mammals [*Iverson et al.*, 2006]. Polar bears, it appears, are obligately dependent on the surface of the sea ice for capture of the prey necessary to maintain their populations.

In short, although other polar bear experts might structure a model differently and populate the conditional probability tables differently than we have here, it seems unlikely that those differences would be great enough to make a qualitative difference in the outcomes projected by our BN population stressor model for mid century and beyond.

5. CONCLUSIONS

We used a first-generation BN population stressor model to forecast future populations of polar bears worldwide. Outcomes of this model suggested that declines in the spatiotemporal distribution of sea ice habitat along with other potential stressors will severely impact future polar bear populations. Polar bears in the PBDE and SIE, home to approximately two thirds of the current world population will likely disappear by mid century. Management of localized human activities is unlikely to mitigate those mid century losses. Polar bears in and around the AE appear likely to persist late into the 21st century, especially if on-the-ground human activities, particularly human harvests, are carefully managed.

A declining habitat base, corresponding with FWS listing factor A (habitat threats), is the overriding factor in projections of declining numbers and distribution of polar bears. Other factors which correspond with FWS listing factors B, C, and E, and which could result in additional population stress on polar bears, are likely to exacerbate effects of habitat loss. To qualitatively alter outcomes projected by our models, it appears future sea ice would have to be far more extensive than is projected by even the more conservative of the general circulation models we used. Because recently observed declines in sea ice extent continue to outpace most GCM projections [*Stroeve et al.*, 2007], more extensive sea ice in the future seems unlikely unless greenhouse gas emissions are reduced. This study and the others on which it was based establish that the future security of polar bears over much of their present range is threatened in an ecological context. In May 2008, Secretary of Interior Dirk Kempthorne, upon review of this and other available information, decided this ecological threat required policy actions and declared polar bears a threatened species under the definition of the Endangered Species Act [*U.S. Fish and Wildlife Service*, 2008].

APPENDIX A: DOCUMENTATION OF THE BAYESIAN NETWORK POLAR BEAR POPULATION STRESSOR MODEL

Appendix A documents the structure of the Bayesian network (BN) population stressor model. We used the BN modeling shell Netica® (Norsys, Inc.) to create a model that represents potential influences on distribution response, numerical response, and overall population response of polar bears under multiple stressors, which include anthropogenic stressors, natural disturbances, and other key environmental correlates to polar bear population amount and distribution.

The BN population stressor model was created to represent the knowledge and judgment of one polar bear biologist (S. Amstrup) with guidance from an ecologist modeler (B. Marcot). The general underlying influence diagram for the BN model is shown in Plate 2, and the full model is in Plate 3. A BN model consists of a series of variables represented as "nodes" (boxes in Plate 3) that interact through links (arrows in Plate 3). Nodes that have no incoming arrows are "input nodes" (the yellow boxes in Plate 3, e.g., node T Parasites and Disease). Nodes with both incoming and outgoing arrows are summary nodes (or latent variables, e.g., node L2 Vital Rates). In our model, we also specified four of the summary nodes as listing factors used by the U.S. Fish and Wildlife Service (S. Morey, personal communication, 2007). Nodes with incoming arrows but no outgoing arrows are output nodes (node D1 Overall Population Outcome). The model (Plate 3) was run by specifying conditions of all input nodes for each combination of ecoregion (node M), time period (node Q), and climate data source or GCM run (node R). In running the model, specifying ecoregion automatically adjusts two of its summary nodes (D and U). The input data set (Tables D1a and D1b) also specifies time period, GCM run, and all other inputs. Nodes Q and R appear in the model unconnected as visual placeholders for displaying the basis of each model run.

Each node in this model consists of a short node name (e.g., node D1), a longer node title (e.g., Overall Population Outcome), a set of states (e.g., larger, same as now, smaller, rare, and extinct), and an underlying probability table. The probability tables consist of unconditional (or prior) probabilities in the input nodes, or conditional probabilities in all other nodes, the latter representing probabilities of each state as a function of (conditional upon) the states of all nodes that directly influence it.

Table A1 presents a complete list of all nodes in the model with their short code letters, titles, description, possible states, and the group (Node Set, in Netica® parlance) to which it belongs (input nodes, output node, summary node, or summary listing factor node).

Table A1. Complete List of All Nodes in the Bayesian Network Population Stressor Model

Node Name	Node Title	Node Description	States
		Input Nodes	
T	Parasites and Disease	As the climate warms, regions of the Arctic are hospitable to parasites and disease agents which formerly did not survive there. Polar bears have always been free of most disease and parasite agents. *Trichinella* is one notable exception, but even rabies, common in the Arctic has had no significance to polar bears. Changes in other species disease vulnerability suggest that similar changes could occur in polar bears so that they could move from a position where parasites and disease are not influential on a population level to where they are influential.	influential not

Table A1. (continued)

Node Name	Node Title	Node Description	States
T2	Predation	Predation on polar bears by other species is very uncommon partly because bears spend almost all of their time on the ice. With more time on land, polar bears, especially young, will be subject to increased levels of predation from wolves, and perhaps grizzly bears. This will vary by region as some regions where polar bears occur have few other predators. Intraspecific predation is one behavior which is known to occur in bears. It has rarely been observed in polar bears and historically is not thought to have been influential. Recent observations of predation on other bears by large males, in regions where it has not been observed before, are consistent with the hypothesis that this sort of behavior may increase in frequency if polar bears are nutritionally stressed. At present, intraspecific predation is not thought to be influential at the population level anywhere in the polar bear range. It appears, however, that its frequency may be on the increase. At some point, it therefore could become influential. At very low population levels, even a minor increase in predation could be influential.	influential not
E	Intentional Takes	This node represents direct mortalities including hunting, and collection for zoos, and management actions. It also includes research deaths even though they are not intentional. These are mortality sources that are very much controllable by regulation.	increased same_as_now decreased
T1	Contaminants	Increased precipitation and glacial melt have recently resulted in greater influx of contaminants into the Arctic region from the interior of Eurasia via the large northward flowing rivers. Similarly, differing atmospheric circulation patterns have altered potential pathways for contaminants from lower latitudes. This node reflects the possible increase or decrease of contamination in the Arctic as a result of modified pathways. These contaminants can act to make habitat less suitable and directly affect things like survival and reproduction. The greatest likelihood seems to be that such contaminants will increase in Arctic regions (and indeed worldwide) as increasing numbers of chemicals are developed and as their persistence in the environment is belatedly determined. Some contaminants have been reduced and we have the ability to reduce others, but the record of reduction and the persistence of many of these chemicals in the environment suggests the greatest likelihood is for elevated levels in the short to medium term with some probability of stability or even declines far in the future.	elevated same_as_now reduced
R4	Hydrocarbons / Oil Spill	This refers to the release of oil or oil related products into polar bear habitat. Such action would result in direct mortality of bears, direct mortality of prey, and could result in displacement of bears from areas they formerly occupied. Hence, it has ramifications for both habitat quality and population dynamics directly. Hydrocarbon exploration and development are expanding and proposed to expand farther in the Arctic. Greater levels of such activity are most likely to increase the probability of oil spills. Also, increased shipping will result in higher levels of hydrocarbon release into Arctic waters.	increased_occurrence same_as_now decreased_occurrence
J1	Tourism	As sea ice extent declines spatially and temporally, access and opportunities for Arctic tourism also will increase. Increased tourism could lead to direct disturbances of polar bears as well as to increased levels of contamination. Here, we address only the physical presence of more tourism and the conveyances used by tourists (vessels, land vehicles, aircraft). The greatest likelihood seems to be that tourism will increase. It could decline, however, if governments take actions to reduce interactions with increasingly stressed polar bears. However, as tourism currently accounts for essentially no limitation to polar bears this effect only comes into play when it is noted to increase. I believe that tourism will increase in all areas of the Arctic until such time as fuel	increased same_as_now decreased

Table A1. (continued)

Node Name	Node Title	Node Description	States
		becomes too expensive for people to venture to such remote areas or in the polar basin divergent unit, when it is essentially devoid of ice, it may not attract many tourists and such activity may surge and then decline in that region. The arctic areas with more interesting coastlines etc., however, will probably see nothing but increases in tourism. Contamination that may accompany such activities, and biological effects from introduced organisms that may compete with residents of the food web or cause disease are covered under the nodes for contamination and parasites and disease.	
B1	Bear-human interactions	This includes nonlethal takes which may increase as a result of increased human-bear interactions because of food-stressed bears more frequently entering Arctic communities. Such takes can displace bears from their preferred locations and reduce habitat quality. This is separate from the similar interactions that may occur around oil and gas or other industrial sites which also can displace bears and lower habitat quality. These interactions also, however, can result in deaths as when problem bears are shot in defense of life and property. So, this node includes a component of both habitat quality and direct mortality. I believe that bear-human interactions will increase until such time as areas are devoid of bears or climate cools again and ice returns.	increased same_as_now decreased
R1	Oil and Gas Activity	This refers to the spatial effects of oil and gas activity. It refers to activities and infrastructure which may physically displace bears from habitat that was formally available to them. It also can result in direct killings of bears which become a persistent safety problem around industrial facilities. Oil companies etc. have great resources to prevent these events from leading to mortalities, but such mortalities cannot be totally avoided and are likely to increase as habitat base shrinks. I think oil and gas activity will increase in the polar basin region through mid century and then decline because resources will have been tapped. We may see some increase in exploration and development in the archipelago, however, as it becomes increasingly accessible.	increase no_change decrease
J	Shipping	As sea ice extent declines spatially and temporally it is predicted that shipping in Arctic regions will increase. Increased shipping could lead to direct disturbances of polar bears as well as to increased levels of contamination. Here, we address only the physical presence of more vessel traffic. Contamination (bilge oil, etc.), and biological effects from introduced organisms that may compete with residents of the food web or cause disease are covered under the nodes for contamination and parasites and disease. We allow only two states here: increased and same as now, because we can think of no reason why shipping will decrease in the foreseeable future. Even if international shipping does not increase, local shipping will, because barges and vessels are more efficient ways to move fuel and freight into remote Arctic locations than aircraft.	increased same_as_now
F	Alternate Regions Available	Are there geographic ecoregions to which bears from the subject region may effectively be able to relocate. This ability is contingent on other ecoregions with suitable habitats being contiguous with regions where habitat quantity or quality have degraded to the point they will not support polar bears on a seasonal or annual basis. For example, if the sea ice is deteriorating throughout the polar basin including the Beaufort Sea and the last vestiges of ice are along the Alaskan Coast, there may be no where else to go if the ice deteriorates to an unsatisfactory state. If, however, the ice retreats to the northeast as its extent reduces, bears remaining on the ice may have access to suitable habitats in the archipelago or in NE Greenland. I believe that bears in the seasonal ice region and in the polar basin will be able to collapse into the archipelago. Ice patterns suggest that the remaining ice in the Arctic is	yes no

Table A1. (continued)

Node Name	Node Title	Node Description	States
		likely to converge on the archipelago rather than form disjunct chunks of ice (although some GCMs do predict the latter, this is contrary to the historical record and the paleo-record). Yes = other suitable areas are contiguous No = other suitable regions are not contiguous	
R2	Relative Ringed Seal Availability	This node expresses changes in prey availability that are likely to occur as sea ice cover declines and its character changes. This node specifically includes only the possibility that ringed seals, the mainstay of polar bears over most of their range, might change in abundance and availability. This is specific to the amount of remaining ice. That is, as sea ice declines in coverage (which is the only way it seems possible for it to go) will the remaining habitat be more productive? Availability here refers to the combined effects of abundance and accessibility, recognizing that seals may occupy areas that make them less available to polar bears even if the seals are still relatively abundant. Examples of this are the recent observations of failed bear attempts to dig through solid ice (a result of the thinner ice that deforms and rafts more easily) that predominates now, and the fact that seals may simply stay in open water all summer and not be available to bears even if the seal numbers are stable. My judgment is that only in the northern part of the ice convergent zone of the polar basin and in portions of the archipelago are conditions likely to improve for ringed seal availability. And, there, such improvements are likely to be transient perhaps through mid century. increase = greater abundance or availability of ringed seals compared to now decrease = less abundance or availability	increase same_as_now decrease
R3	Alternate Prey Availability	This node expresses changes in prey availability that are likely to occur as sea ice cover declines and its character changes. This is largely expert opinion because there is little to go on to suggest prey base change possibilities in the future. With very different ice and other ecological differences that may accompany global warming things could occur which are totally unforeseen. Today's experience, however, suggests that little in the way of significant alternate prey is likely to emerge to allow bears to replace traditional prey that may be greatly reduced in the future. Where alternate prey could become important is in the seasonal ice regions and the archipelago. Now, harp (*Phoca groenlandicus*) and hooded (*Cystophora cristata*) seals have become important to polar bears as they have moved farther north than historically. As the ice retreats into the archipelago it is reasonable to expect that these animals may penetrate deeper into the archipelago and provide at least a transient improvement in alternate prey. It is unclear, however, that such changes could persist as bears prey on these seals which are forced onto smaller and smaller areas of ice. So, I project only transient improvements followed by decline. This node specifically addresses the possibility that alternate prey, either marine or terrestrial, might change in a way that would allow polar bears to take advantage of it. increase = greater availability of alternate prey decrease = less opportunity for access to prey items other than ringed seals	increase same_as_now decrease
S1	Foraging Habitat Character	This node expresses a subjective assessment of the quality of sea ice for foraging by polar bears. Recent observations of the changes in sea ice character in the southern Beaufort Sea suggest that the later freeze-up, warmer winters, and earlier ice retreat in summer have resulted in thinner ice that more easily deforms and more frequently rafts over itself. These changes have reduced the quality of ice as a denning substrate, and may have reduced its quality as a foraging substrate since the extensive ice deformation can result in ice covered refugia for ringed seals which are less likely for polar bears to get into. Also, it can result in very rough sharp pressure ridges that are hugely	more_optimal same_as_now less_optimal

Table A1. (continued)

Node Name	Node Title	Node Description	States
		expansive compared to earlier years. This rough ice may also provide refuge for seals, and it also is surely difficult for polar bear COYs to negotiate as they attempt to move out onto the ice after den emergence in spring. More optimal ice is somewhat heavier and not as rough, with pressure ridges composed of larger ice blocks. However, it can go the other way. Very heavy stable ice in the Beaufort Sea in the past may have been limiting polar bears. This is also probably currently true in portions of the AE and in the northern part of the PBCE. So, in those areas, I expect that ice quality will at first improve with global warming and then decline. Because my only sense of this ice quality is in the polar basin, I am leaving all priors uniform for the other ice regions.	
C	Foraging Habitat Absence Change	This node expresses the length, in months, of ice absence from the continental shelf regions currently preferred by polar bears. It corresponds to the value "proportional ice-free months" from D. Douglas' calculations based on GCMs. This is the number of months during which the continental shelf was ice free where ice free is defined as fewer than 50% of the pixels over the shelf having less than 50% ice cover. We express this as a change from now. So the figures in this node represent the difference in months between the forecasted number of ice-free months for four future time periods and the number of ice-free months for the present which is defined as the GCM model outputs for the period 2000–2009. The bears in some regions already experience protracted ice-free periods. In other regions they do not. The impact of the length of the ice-free period is dependent mainly upon the productivity of the environment, and has a different impact in the Beaufort Sea, for example, than it does in the currently seasonal ice environments which are, for the most part, very productive. For example, a difference in the amount of time ice was absent of GT 3 months means a mean absence of 7 or 8 months in the PBDE, and 8, 9 or 10 months in the seasonal ice zone, but only 3+ months in portions of the AE or the PBCE where ice is now present year-round.	−1 to 0 0 to 1 1 to 3 >=3
B	Foraging Habitat Quantity Change	This node expresses the proportional change in the area of polar bear habitat over time. Polar bear habitat is expressed as the number of square km months of optimal RSF habitat in the two polar basin geographic units, and as square km months of ice over continental shelf in the other regions. Because the other regions are almost entirely shallow water areas, the habitat in those areas boils down to essentially the ice extent months over each region. We further express this as the percent change in quantity of these ice habitats, from the baseline now which is defined as the period 1996–2006. Interpreting the percent difference must take into account that a given percent change in the archipelago or the PB convergent region is a very different thing than it might be in the other two units. The absolute change in the archipelago, for example, may be very small, but because it is measured from essentially 0, it may look like a great% . These measurements are derived from the satellite record for the observational period and from the GCM outputs of sea ice for future periods.	0 to 20 −20 to 0 −40 to −20 < −40
N	Shelf Distance Change (km)	This node expresses the distance that the ice retreats from traditional autumn/winter foraging areas which are over the continental shelves and other shallow water areas within the polar basin. It is calculated by extracting the largest contiguous chunk of ice whose pixels have >50% concentration and determining the mean of the measured distances between all cells in the subpopulation unit and the nearest point within that chunk of ice. It is expressed as the difference between this mean distance calculated for the period 1996–2006 and the same mean distance calculated for the other time periods of interest. These distances are derived from the satellite record for the observational period and from the GCM outputs of sea ice for future periods.	−200 to 0 0 to 200 200 to 800 >= 800

Table A1. (continued)

Node Name	Node Title	Node Description	States
		Expressing this value as a change from the current time allows the model to show that conditions improve in a hind cast back to the period of 1985–1995. This measurement is available only from the polar basin ecoregions because all other management units occur in areas that are essentially all shelf. Hence, the measurement of distance to shelf means nothing.	
M	Ecoregion	Geographic region used for combining populations of polar bears.	Polar_Basin_ Divergence Polar_Basin_ Convergence Archipelago Seasonal_Ice
		Output Nodes[a]	
D1	Overall Population Outcome	Composite influence of numerical response and distribution response.	larger same_as_now smaller rare extinct
C4	Numerical Response	This node represents the anticipated numerical response of polar bears based upon the sum total of the identified factors which are likely to have affected numbers of polar bears in any particular area.	increased_density same_as_now reduced_density rare absent
C3	Distribution Response	This is the sum total of ecological and human factors that predict the future distribution of polar bears. Reduced but Resident: habitat has changed in a way that would likely lead to a reduced spatial distribution (e.g., because of avoidance of a human development or because sea ice is still present in the area but in more limited quantity). Bears would still occur in the area, but their distribution would be more limited. Transient = habitat is seasonally limited or human activities have resulted in a situation where available ice is precluded from use on a seasonal basis.	same_as_now reduced_but_resident transient_visitors extirpated
		Summary Nodes	
C2	Pollution	This is the sum of pollution effects from hydrocarbon discharges directly into arctic waters and from other pollutants brought to the Arctic from other parts of the world. The FWS listing proposal included pollution as one of the “other factors” along with direct human bear interactions that may displace bears or otherwise make habitats less satisfactory. I viewed the main effect of pollution as a potential effect on population dynamics. Clearly, severe pollution as in an oil spill, for example, could make habitats unsatisfactory and result in direct displacement. The main effect, however, is likely to be how pollution affects immune systems, reproductive performance, and survival. Hence, I have included input from this node as well as from the human disturbance node into both the habitat and the abundance side of the network by including input from factor E into both population effects and habitat effects.	reduced same_as_now elevated greatly_elevated
C1	Human Disturbance	This node expresses the combination of the changes in “other” direct human disturbances to polar bears. This does not include changes in sea ice habitat. Nor does it include the contamination possibilities from hydrocarbon exploration. Those are covered elsewhere. It does cover the direct bear-human interactions that can occur in association with industrial development.	reduced same_as_now elevated greatly_elevated
H	Crowding Tolerance	The degree to which polar bears may tolerate increased densities that may result from migration of bears from presently occupied regions that become unsuitable to other regions already occupied by polar bears.	none moderate high

Table A1. (continued)

Node Name	Node Title	Node Description	States
		In essence, this is the tolerance of bears to live in more crowded conditions than those at which they presently live. And, it is a function of food availability. I believe that bears have a reasonable tolerance of crowding if food is abundant or if they are in good condition while waiting for sea ice to return etc. Examples of these situations include (1) portions of the high Arctic-like near Resolute, where bear densities on the sea ice in spring are apparently much higher than they are in most of the polar basin, and (2) the high densities at which polar bears occur on land in Hudson Bay in summer when they are loafing and waiting for the sea ice to return. I assumed that crowding tolerance has little or no effect on outcome likelihoods until habitat quantity was reduced substantially requiring bears from one area to either perish or find some place else to go on at least a seasonal basis. Thereafter, if relocations of members of some subpopulations meant invading the areas occupied by other bears, crowding tolerance entered an assessment of whether or not relocation was a practical solution.	
G	Relocation Possible	Is it likely that polar bears displaced from one region could either seasonally or permanently relocate to another region in order to persist. This is a function of foraging effects (e.g., prey availability) in the alternative area (here I am specifically focusing on prey availability in the alternative area rather than the area from which the bears may have been displaced) crowding tolerance, and contiguity of habitats.	yes no
A	Foraging Habitat Value	This node expresses the sum total of things which may work to alter the quality of habitats available to polar bears in the future. The idea here is that sea ice is retreating spatially and temporally, but is the ice that remains of comparable, better or worse quality as polar bear habitat. Our RSF values are projected into the future with the assumption that a piece of ice in 2090 that looks the same as piece of ice in 1985 has the same value to a polar bear. Perhaps because of responses we cannot foresee, it may be better seal habitat, or it may be habitat for an alternate prey. Conversely, it may be worse because of atmospheric and oceanic processes (e.g., the epontic community is less vibrant because of thinner ice which is not around for as long each year). Or it may be worse habitat because of oil and gas development, tourism, shipping etc.	better same_as_now worse
D	Change in Foraging Habitat Distribution	This node expresses the combination of the quantitative ways the retreat of sea ice may affect use of continental shelf habitats. Our analyses indicate, in addition to reductions of total ice (and RSF Optimum ice) extent (expressed under habitat quantity), we will see seasonal retreats of the sea ice away from coastal areas now preferred by polar bears, and these retreats are projected to progressively become longer. These changes will affect polar bears by reducing the total availability of ice substrate for bears. They also will make ice unavailable for extended periods in some regions where bears now occur year-round. This will result in the opportunity for seasonal occupancy but not year-round occupancy as they have had in the past. Note that in the PBCE because it includes the North Beaufort and Queen Elizabeth and East Greenland each of which has different starting points, the values in the CPT express kind of an average. Similarly, in the Seasonal region, there is a huge difference between Hudson Bay and Foxe Basin or Baffin Bay. So, again the CPT values are a sort of an average, trying to reflect these differences.	improved_availability same_as_now reduced_availability Gr_reduced_availability Unavailable
L2	Vital Rates	This expresses the combined effect of changes in survival of adult females and of young and reproductive patterns. The probabilities assigned each of the states reflects the relative importance to polar bear population dynamics of each of these vital rates to the growth of the population. This node does not reflect human influences on population growth such as hunting, or mortalities resulting from bear-human interactions. Those things, along with effects of parasites, contaminants, etc. are brought in as modifiers at the level of the next node.	improve same_as_now decline

Table A1. (continued)

Node Name	Node Title	Node Description	States
U	Reproduction	The sum of trends in numbers of cubs produced and the effect of retreating sea ice on the ability of females to reach traditional denning areas.	increased same_as_now decreased
V1	Cub production per event	This node describes the number of cubs produced per denning attempt.	fewer_than_now same_as_now more_than_now
L	Juvenile Survival	Annual natural survival rate of cubs and yearlings. Note that this is conditional on survival of the mother. This is the survival rate for juveniles that would occur in absence of hunting or other anthropogenic factors. Those anthropogenic factors that would influence survival are included in node F.	increase no_change decrease
L1	Adult Female Survival	Annual natural survival rate of sexually mature females. This is the survival rate for adult females that would occur in absence of hunting or other anthropogenic factors. Those anthropogenic factors that would influence survival are included in node F.	increase no_change decrease
K	Adult Body Condition	Body mass index or other indicator of ability of bears to secure resources. Our analysis suggests body stature has been declining in the SBS and is inversely correlated with ice extent. Also recent analyses indicate that body condition may soon be an important predictor of survival of polar bears in SHB.	increase same_as_now decrease
		Summary Nodes – USFWS Listing Factors [b]	
F2	Factor A. Habitat Threats	This node summarizes the combined information about changes in habitat quantity and quality. It approximately reflects factor A of the proposal to list polar bears as threatened.	improvement no_effect minor_restriction major_restriction
A1	Factor B. Overutilization	This node approximates the FWS listing factor B. It includes the combination of hunting (harvest), take for scientific purposes, and take for zoos. It also includes mortalities from bear-human interactions etc. brought in from factor E. These all are factors which serve to modify the population changes that would be brought about without the direct local interference of humans.	fewer same_as_now more
A4	Factor C. Disease, predation	This node expresses probability of changing vulnerability of polar bears to diseases and parasites, and to potential increases of intraspecific predation/cannibalism.	same_as_now worse
A6	Factor E. Other factors (natural or man-made)	This node approximately corresponds to factor E of the listing proposal. It includes factors (other than the changes in sea ice quality and quantity) which may affect habitat suitability for polar bears. Also, its effects can be directly on population dynamics features. Hence, it applies directly to both the habitat and population sides of our network. Included here are effects of a variety of contaminants, including: petroleum hydrocarbons, persistent organic pollutants, and metals. Although we do not know much quantitatively about effects of these contaminants at the population level, we know qualitatively that effects on immune systems and steroid levels etc. will ultimately have such effects. We also know that oil spills will have immediate and dire effects. It also includes effects of human activities and developments which may directly affect habitat quality, including: shipping and transportation activities, habitat change, noise, spills, ballast discharge, and ecotourism. This includes disturbance but not direct killing of bears by humans as a result of DLP cases (direct killing is included under node A1). I viewed human disturbances as the most predictable in their negative effects until pollution levels reached their greatly elevated stage at which time, their import to future populations was judged to be great.	improvement no_effect minor_restriction major_restriction
		Descriptive (Disconnected) Nodes [c]	
Q	Time Period	The states for this node correspond to years −10 (historic), 0 (now), 25 (early century), 50 (mid century), 75 (late century), and 95 (end of century).	historic (1985–1995) now (1996–2006) early century

Table A1. (continued)

Node Name	Node Title	Node Description	States
			(2020–2029) mid century (2045–2055) late century (2070–2080) end of century (2090–2099)
R	GCM run	The states for this node correspond to the data source (either "satellite" for year −10 and 0 runs) and GCM modeling scenario (minimum, ensemble mean, or maximum) basis for a given condition.	GCM_minimum ensemble_mean GCM_maximum satellite

[a]Output nodes here include the Numerical Response and Distribution Response nodes that provide summary output conditions.
[b]U.S. Fish and Wildlife Service (USFWS) lists five listing factors. Listing factor D pertains to inadequacy of existing regulatory mechanisms, and was not included in the BN population stressor model because it does not correspond to any specific environmental stressor.
[c]These two nodes are included in the model to help denote the basis for a given model run. They are not included as environmental stressors per se.

APPENDIX B: PROBABILITY TABLES FOR EACH NODE IN THE BAYESIAN NETWORK MODEL

Tables B1–B19 are probability tables for each node in the BN model. (These were generated in the Netica® software.) Not included here are all input nodes (yellow coded nodes in Plate 3) because each of their prior probability tables was set to uniform distributions.

Table B1. Node A: Foraging Habitat Value

Node S1: Foraging Habitat Character	Node G: Relocation Possible	Value of Foraging Habitat: Better	Same as Now	Worse
More optimal	yes	0.7	0.3	0.0
More optimal	no	0.2	0.6	0.2
Same as now	yes	0.1	0.8	0.1
Same as now	no	0.0	0.8	0.2
Less optimal	yes	0.0	0.3	0.7
Less optimal	no	0.0	0.0	1.0

Table B2. Node A1: Factor B Overutilization

Node E: Intentional Takes	Node A6: Factor E—Other Factors (Natural or Man-Made)	Level of Overutilization: Fewer	Same as Now	More
Increased	improvement	0.0	0.4	0.6
Increased	no effect	0.0	0.0	1.0
Increased	minor restriction	0.0	0.0	1.0
Increased	major restriction	0.0	0.0	1.0
Same as now	improvement	1.0	0.0	0.0
Same as now	no effect	0.0	1.0	0.0
Same as now	minor restriction	0.0	0.6	0.4
Same as now	major restriction	0.0	0.3	0.7
Decreased	improvement	1.0	0.0	0.0
Decreased	no effect	1.0	0.0	0.0
Decreased	minor restriction	0.0	0.8	0.2
Decreased	major restriction	0.0	0.6	0.4

Table B3. Node A4: Factor C Disease and Predation

Node T : Parasites and Disease	Node T2: Predation	Level of Disease and Predation	
		Same as Now	Worse
Influential	influential	0.0	1.0
Influential	not	0.3	0.7
Not	influential	0.7	0.3
Not	not	1.0	0.0

Table B4. Node A6: Factor E Other Factors Natural or Man-Made

Node C1: Human Disturbance	Node C2: Pollution	Level of Other Factors			
		Improvement	No Effect	Minor Restriction	Major Restriction
Reduced	reduced	1.0	0.0	0.0	0.0
Reduced	same as now	1.0	0.0	0.0	0.0
Reduced	elevated	0.3	0.4	0.3	0.0
Reduced	greatly elevated	0.0	0.3	0.3	0.4
Same as now	reduced	0.6	0.4	0.0	0.0
Same as now	same as now	0.0	1.0	0.0	0.0
Same as now	elevated	0.0	0.4	0.6	0.0
Same as now	greatly elevated	0.0	0.2	0.2	0.6
Elevated	reduced	0.0	0.2	0.5	0.3
Elevated	same as now	0.0	0.0	0.5	0.5
Elevated	elevated	0.0	0.0	0.4	0.6
Elevated	greatly elevated	0.0	0.0	0.3	0.7
Greatly elevated	reduced	0.0	0.0	0.3	0.7
Greatly elevated	same as now	0.0	0.0	0.2	0.8
Greatly elevated	elevated	0.0	0.0	0.1	0.9
Greatly elevated	greatly elevated	0.0	0.0	0.0	1.0

Table B5. Node C1: Human Disturbance

Node B1: Bear-Human Interactions	Node J: Shipping	Node R1: Oil and Gas Activity	Node J1: Tourism	Level of Human Disturbance			
				Reduced	Same as Now	Elevated	Greatly Elevated
Increased	increased	increase	increased	0.0	0.0	0.0	1.0
Increased	increased	increase	same as now	0.0	0.0	0.0	1.0
Increased	increased	increase	decreased	0.0	0.0	0.1	0.9
Increased	increased	no change	increased	0.0	0.0	0.0	1.0
Increased	increased	no change	same as now	0.0	0.0	0.1	0.9
Increased	increased	no change	decreased	0.0	0.0	0.2	0.8
Increased	increased	decrease	increased	0.0	0.0	0.3	0.7
Increased	increased	decrease	same as now	0.0	0.0	0.6	0.4
Increased	increased	decrease	decreased	0.0	0.0	0.5	0.5

Table B5. (continued)

Node B1: Bear-Human Interactions	Node J: Shipping	Node R1: Oil and Gas Activity	Node J1: Tourism	Level of Human Disturbance			
				Reduced	Same as Now	Elevated	Greatly Elevated
Increased	same as now	increase	increased	0.0	0.0	0.0	1.0
Increased	same as now	increase	same as now	0.0	0.0	0.2	0.8
Increased	same as now	increase	decreased	0.0	0.0	0.3	0.7
Increased	same as now	no change	increased	0.0	0.0	0.5	0.5
Increased	same as now	no change	same as now	0.0	0.0	0.7	0.3
Increased	same as now	no change	decreased	0.0	0.2	0.6	0.2
Increased	same as now	decrease	increased	0.0	0.0	0.7	0.3
Increased	same as now	decrease	same as now	0.0	0.2	0.7	0.1
Increased	same as now	decrease	decreased	0.0	0.4	0.6	0.0
Same as now	increased	increase	increased	0.0	0.0	0.2	0.8
Same as now	increased	increase	same as now	0.0	0.0	0.5	0.5
Same as now	increased	increase	decreased	0.0	0.2	0.6	0.2
Same as now	increased	no change	increased	0.0	0.2	0.8	0.0
Same as now	increased	no change	same as now	0.0	0.3	0.7	0.0
Same as now	increased	no change	decreased	0.0	0.5	0.5	0.0
Same as now	increased	decrease	increased	0.0	0.3	0.7	0.0
Same as now	increased	decrease	same as now	0.0	0.5	0.5	0.0
Same as now	increased	decrease	decreased	0.0	0.6	0.4	0.0
Same as now	same as now	increase	increased	0.0	0.2	0.8	0.0
Same as now	same as now	increase	same as now	0.0	0.4	0.6	0.0
Same as now	same as now	increase	decreased	0.0	0.5	0.5	0.0
Same as now	same as now	no change	increased	0.0	0.8	0.2	0.0
Same as now	same as now	no change	same as now	0.0	1.0	0.0	0.0
Same as now	same as now	no change	decreased	0.1	0.9	0.0	0.0
Same as now	same as now	decrease	increased	0.3	0.7	0.0	0.0
Same as now	same as now	decrease	same as now	0.5	0.5	0.0	0.0
Same as now	same as now	decrease	decreased	0.6	0.4	0.0	0.0
Decreased	increased	increase	increased	0.0	0.0	0.6	0.4
Decreased	increased	increase	same as now	0.0	0.2	0.6	0.2
Decreased	increased	increase	decreased	0.0	0.3	0.7	0.0
Decreased	increased	no change	increased	0.1	0.6	0.3	0.0
Decreased	increased	no change	same as now	0.2	0.6	0.2	0.0
Decreased	increased	no change	decreased	0.3	0.5	0.2	0.0
Decreased	increased	decrease	increased	0.2	0.6	0.2	0.0
Decreased	increased	decrease	same as now	0.3	0.7	0.0	0.0
Decreased	increased	decrease	decreased	0.4	0.6	0.0	0.0
Decreased	same as now	increase	increased	0.0	0.5	0.5	0.0
Decreased	same as now	increase	same as now	0.2	0.6	0.2	0.0
Decreased	same as now	increase	decreased	0.3	0.6	0.1	0.0
Decreased	same as now	no change	increased	0.5	0.5	0.0	0.0
Decreased	same as now	no change	same as now	0.7	0.3	0.0	0.0
Decreased	same as now	no change	decreased	0.8	0.2	0.0	0.0
Decreased	same as now	decrease	increased	0.9	0.1	0.0	0.0
Decreased	same as now	decrease	same as now	1.0	0.0	0.0	0.0
Decreased	same as now	decrease	decreased	1.0	0.0	0.0	0.0

Table B6. Node C2: Pollution

Node R4: Hydrocarbons/ Oil Spill	Node T1: Contaminants	Level of Pollution			
		Reduced	Same as Now	Elevated	Greatly Elevated
Increased occur	elevated	0.0	0.0	0.0	1.0
Increased occur	same as now	0.0	0.0	0.6	0.4
Increased occur	reduced	0.0	0.4	0.4	0.2
Same as now	elevated	0.0	0.3	0.7	0.0
Same as now	same as now	0.0	1.0	0.0	0.0
Same as now	reduced	0.4	0.6	0.0	0.0
Decreased occur	elevated	0.3	0.5	0.2	0.0
Decreased occur	same as now	0.8	0.2	0.0	0.0
Decreased occur	reduced	1.0	0.0	0.0	0.0

Table B7. Node C3: Distribution Response

Node F2: Factor A—Habitat Threats	Node A6: Factor E—Other Factors (Natural or Man-Made)	Node G: Relocation Possible	Distribution Response			
			Same as Now	Reduced but Resident	Transient Visitor	Extirpated
Improvement	improvement	yes	1.0	0.0	0.0	0.0
Improvement	improvement	no	1.0	0.0	0.0	0.0
Improvement	no effect	yes	1.0	0.0	0.0	0.0
Improvement	no effect	no	1.0	0.0	0.0	0.0
Improvement	minor restriction	yes	0.9	0.1	0.0	0.0
Improvement	minor restriction	no	0.9	0.1	0.0	0.0
Improvement	major restriction	yes	0.8	0.1	0.1	0.0
Improvement	major restriction	no	0.8	0.2	0.0	0.0
No effect	improvement	yes	1.0	0.0	0.0	0.0
No effect	improvement	no	1.0	0.0	0.0	0.0
No effect	no effect	yes	1.0	0.0	0.0	0.0
No effect	no effect	no	1.0	0.0	0.0	0.0
No effect	minor restriction	yes	0.8	0.1	0.1	0.0
No effect	minor restriction	no	0.8	0.2	0.0	0.0
No effect	major restriction	yes	0.5	0.2	0.3	0.0
No effect	major restriction	no	0.5	0.5	0.0	0.0
Minor restriction	improvement	yes	0.5	0.25	0.25	0.0
Minor restriction	improvement	no	0.5	0.5	0.0	0.0
Minor restriction	no effect	yes	0.4	0.3	0.3	0.0
Minor restriction	no effect	no	0.4	0.6	0.0	0.0
Minor restriction	minor restriction	yes	0.3	0.3	0.4	0.0
Minor restriction	minor restriction	no	0.3	0.6	0.0	0.1
Minor restriction	major restriction	yes	0.2	0.2	0.6	0.0
Minor restriction	major restriction	no	0.2	0.5	0.0	0.3
Major restriction	improvement	yes	0.0	0.3	0.35	0.35
Major restriction	improvement	no	0.0	0.3	0.0	0.7
Major restriction	no effect	yes	0.0	0.2	0.4	0.4
Major restriction	no effect	no	0.0	0.2	0.0	0.8
Major restriction	minor restriction	yes	0.0	0.1	0.45	0.45
Major restriction	minor restriction	no	0.0	0.1	0.0	0.9
Major restriction	major restriction	yes	0.0	0.0	0.3	0.7
Major restriction	major restriction	no	0.0	0.0	0.0	1.0

Table B8. Node C4: Numerical Response

Node L2: Vital Rates	Node A1: Factor B—Overutilization	Node A4: Factor C—Disease and Predation	Numerical Response: Increased Density	Same as Now	Reduced Density	Rare	Absent
Improve	fewer	same as now	1.0	0.0	0.0	0.0	0.0
Improve	fewer	worse	0.5	0.25	0.25	0.0	0.0
Improve	same as now	same as now	0.8	0.2	0.0	0.0	0.0
Improve	same as now	worse	0.5	0.25	0.25	0.0	0.0
Improve	more	same as now	0.3	0.35	0.35	0.0	0.0
Improve	more	worse	0.1	0.4	0.5	0.0	0.0
Same as now	fewer	same as now	0.2	0.8	0.0	0.0	0.0
Same as now	fewer	worse	0.0	0.8	0.2	0.0	0.0
Same as now	same as now	same as now	0.0	1.0	0.0	0.0	0.0
Same as now	same as now	worse	0.0	0.3	0.7	0.0	0.0
Same as now	more	same as now	0.0	0.2	0.8	0.0	0.0
Same as now	more	worse	0.0	0.0	1.0	0.0	0.0
Decline	fewer	same as now	0.0	0.5	0.5	0.0	0.0
Decline	fewer	worse	0.0	0.3	0.7	0.0	0.0
Decline	same as now	same as now	0.0	0.0	1.0	0.0	0.0
Decline	same as now	worse	0.0	0.0	0.75	0.25	0.0
Decline	more	same as now	0.0	0.0	0.4	0.4	0.2
Decline	more	worse	0.0	0.0	0.2	0.4	0.4

Table B9. Node D: Change in Foraging Habitat Distribution

Node M: Ecoregion	Node C: Foraging Habitat Absence Change	Node N: Shelf Distance Change	Distribution of Foraging Habitat: Improved Availability	Same as Now	Reduced Availability	Greatly Reduced Availability	Unavailable
Polar basin divergent	–1 to 0	–200 to 0	1.0	0.0	0.0	0.0	0.0
Polar basin divergent	–1 to 0	0 to 200	0.8	0.2	0.0	0.0	0.0
Polar basin divergent	–1 to 0	200 to 800	0.2	0.6	0.2	0.0	0.0
Polar basin divergent	–1 to 0	>= 800	0.0	0.4	0.6	0.0	0.0
Polar basin divergent	0 to 1	–200 to 0	0.5	0.5	0.0	0.0	0.0
Polar basin divergent	0 to 1	0 to 200	0.0	0.2	0.8	0.0	0.0
Polar basin divergent	0 to 1	200 to 800	0.0	0.0	0.5	0.5	0.0
Polar basin divergent	0 to 1	>= 800	0.0	0.0	0.25	0.5	0.25
Polar basin divergent	1 to 3	–200 to 0	0.2	0.4	0.4	0.0	0.0
Polar basin divergent	1 to 3	0 to 200	0.0	0.0	0.5	0.3	0.2
Polar basin divergent	1 to 3	200 to 800	0.0	0.0	0.2	0.4	0.4
Polar basin divergent	1 to 3	>= 800	0.0	0.0	0.0	0.2	0.8
Polar basin divergent	>= 3	–200 to 0	0.0	0.3	0.5	0.2	0.0
Polar basin divergent	>= 3	0 to 200	0.0	0.0	0.2	0.4	0.4
Polar basin divergent	>= 3	200 to 800	0.0	0.0	0.0	0.1	0.9
Polar basin divergent	>= 3	>= 800	0.0	0.0	0.0	0.0	1.0
Polar basin convergent	–1 to 0	–200 to 0	1.0	0.0	0.0	0.0	0.0
Polar basin convergent	–1 to 0	0 to 200	0.8	0.2	0.0	0.0	0.0
Polar basin convergent	–1 to 0	200 to 800	0.6	0.4	0.0	0.0	0.0
Polar basin convergent	–1 to 0	>= 800	0.4	0.6	0.0	0.0	0.0
Polar basin convergent	0 to 1	–200 to 0	1.0	0.0	0.0	0.0	0.0
Polar basin convergent	0 to 1	0 to 200	0.6	0.4	0.0	0.0	0.0
Polar basin convergent	0 to 1	200 to 800	0.2	0.4	0.4	0.0	0.0
Polar basin convergent	0 to 1	>= 800	0.0	0.2	0.8	0.0	0.0
Polar basin convergent	1 to 3	–200 to 0	0.6	0.4	0.0	0.0	0.0

Table B9. (continued)

Node M: Ecoregion	Node C: Foraging Habitat Absence Change	Node N: Shelf Distance Change	Distribution of Foraging Habitat: Improved Availability	Same as Now	Reduced Availability	Greatly Reduced Availability	Unavailable
Polar basin convergent	1 to 3	0 to 200	0.1	0.5	0.4	0.0	0.0
Polar basin convergent	1 to 3	200 to 800	0.0	0.3	0.7	0.0	0.0
Polar basin convergent	1 to 3	>= 800	0.0	0.0	1.0	0.0	0.0
Polar basin convergent	>= 3	–200 to 0	0.4	0.6	0.0	0.0	0.0
Polar basin convergent	>= 3	0 to 200	0.1	0.3	0.5	0.1	0.0
Polar basin convergent	>= 3	200 to 800	0.0	0.2	0.6	0.2	0.0
Polar basin convergent	>= 3	>= 800	0.0	0.0	0.7	0.3	0.0
Archipelago	–1 to 0	–200 to 0	0.0	1.0	0.0	0.0	0.0
Archipelago	–1 to 0	0 to 200	0.0	1.0	0.0	0.0	0.0
Archipelago	–1 to 0	200 to 800	0.0	1.0	0.0	0.0	0.0
Archipelago	–1 to 0	>= 800	0.0	1.0	0.0	0.0	0.0
Archipelago	0 to 1	–200 to 0	0.6	0.4	0.0	0.0	0.0
Archipelago	0 to 1	0 to 200	0.6	0.4	0.0	0.0	0.0
Archipelago	0 to 1	200 to 800	0.6	0.4	0.0	0.0	0.0
Archipelago	0 to 1	>= 800	0.6	0.4	0.0	0.0	0.0
Archipelago	1 to 3	–200 to 0	0.4	0.6	0.0	0.0	0.0
Archipelago	1 to 3	0 to 200	0.4	0.6	0.0	0.0	0.0
Archipelago	1 to 3	200 to 800	0.4	0.6	0.0	0.0	0.0
Archipelago	1 to 3	>= 800	0.4	0.6	0.0	0.0	0.0
Archipelago	>= 3	–200 to 0	0.0	0.6	0.4	0.0	0.0
Archipelago	>= 3	0 to 200	0.0	0.6	0.4	0.0	0.0
Archipelago	>= 3	200 to 800	0.0	0.6	0.4	0.0	0.0
Archipelago	>= 3	>= 800	0.0	0.6	0.4	0.0	0.0
Seasonal ice	–1 to 0	–200 to 0	0.5	0.5	0.0	0.0	0.0
Seasonal ice	–1 to 0	0 to 200	0.5	0.5	0.0	0.0	0.0
Seasonal ice	–1 to 0	200 to 800	0.5	0.5	0.0	0.0	0.0
Seasonal ice	–1 to 0	>= 800	0.5	0.5	0.0	0.0	0.0
Seasonal ice	0 to 1	–200 to 0	0.0	0.2	0.6	0.2	0.0
Seasonal ice	0 to 1	0 to 200	0.0	0.2	0.6	0.2	0.0
Seasonal ice	0 to 1	200 to 800	0.0	0.2	0.6	0.2	0.0
Seasonal ice	0 to 1	>= 800	0.0	0.2	0.6	0.2	0.0
Seasonal ice	1 to 3	–200 to 0	0.0	0.0	0.2	0.4	0.4
Seasonal ice	1 to 3	0 to 200	0.0	0.0	0.2	0.4	0.4
Seasonal ice	1 to 3	200 to 800	0.0	0.0	0.2	0.4	0.4
Seasonal ice	1 to 3	>= 800	0.0	0.0	0.2	0.4	0.4
Seasonal ice	>= 3	–200 to 0	0.0	0.0	0.0	0.1	0.9
Seasonal ice	>= 3	0 to 200	0.0	0.0	0.0	0.1	0.9
Seasonal ice	>= 3	200 to 800	0.0	0.0	0.0	0.1	0.9
Seasonal ice	>= 3	>= 800	0.0	0.0	0.0	0.1	0.9

Table B10. Node D1: Overall Population Outcome

Node C4: Numerical Response	Node C3: Distribution Response	Overall Population Outcome: Larger	Same as Now	Smaller	Rare	Extinct
Increased density	same as now	1.0	0.0	0.0	0.0	0.0
Increased density	reduced but resident	0.3	0.5	0.2	0.0	0.0
Increased density	transient visitor	0.1	0.3	0.3	0.3	0.0
Increased density	extirpated	0.0	0.0	0.0	0.0	1.0

Table B10. (continued)

Node C4: Numerical Response	Node C3: Distribution Response	Overall Population Outcome				
		Larger	Same as Now	Smaller	Rare	Extinct
Same as now	same as now	0.0	1.0	0.0	0.0	0.0
Same as now	reduced but resident	0.0	0.3	0.7	0.0	0.0
Same as now	transient visitor	0.0	0.0	0.6	0.4	0.0
Same as now	extirpated	0.0	0.0	0.0	0.0	1.0
Reduced density	same as now	0.0	0.0	1.0	0.0	0.0
Reduced density	reduced but resident	0.0	0.0	0.7	0.3	0.0
Reduced density	transient visitor	0.0	0.0	0.3	0.7	0.0
Reduced density	extirpated	0.0	0.0	0.0	0.0	1.0
Rare	same as now	0.0	0.0	0.0	1.0	0.0
Rare	reduced but resident	0.0	0.0	0.0	0.8	0.2
Rare	transient visitor	0.0	0.0	0.0	0.7	0.3
Rare	extirpated	0.0	0.0	0.0	0.0	1.0
Absent	same as now	0.0	0.0	0.0	0.0	1.0
Absent	reduced but resident	0.0	0.0	0.0	0.0	1.0
Absent	transient visitor	0.0	0.0	0.0	0.0	1.0
Absent	extirpated	0.0	0.0	0.0	0.0	1.0

Table B11. Node F2: Factor A Habitat Threats

Node B: Foraging Habitat Quantity Change	Node D: Change in Foraging Habitat Distribution	Node A: Foraging Habitat Value	Level of Habitat Threat			
			Improvement	No Effect	Minor Restriction	Major Restriction
0 to 20	improved availability	better	1.0	0.0	0.0	0.0
0 to 20	improved availability	same as now	1.0	0.0	0.0	0.0
0 to 20	improved availability	worse	0.8	0.2	0.0	0.0
0 to 20	same as now	better	1.0	0.0	0.0	0.0
0 to 20	same as now	same as now	0.8	0.2	0.0	0.0
0 to 20	same as now	worse	0.3	0.5	0.2	0.0
0 to 20	reduced availability	better	0.4	0.4	0.2	0.0
0 to 20	reduced availability	same as now	0.2	0.6	0.2	0.0
0 to 20	reduced availability	worse	0.0	0.2	0.6	0.2
0 to 20	greatly reduced availability	better	0.0	0.2	0.4	0.4
0 to 20	greatly reduced availability	same as now	0.0	0.0	0.4	0.6
0 to 20	greatly reduced availability	worse	0.0	0.0	0.2	0.8
0 to 20	unavailable	better	0.0	0.0	0.0	1.0
0 to 20	unavailable	same as now	0.0	0.0	0.0	1.0
0 to 20	unavailable	worse	0.0	0.0	0.0	1.0
–20 to 0	improved availab	better	0.8	0.2	0.0	0.0
–20 to 0	improved availab	same as now	0.2	0.6	0.2	0.0
–20 to 0	improved availab	worse	0.2	0.4	0.4	0.0
–20 to 0	same as now	better	0.2	0.6	0.2	0.0
–20 to 0	same as now	same as now	0.0	0.2	0.6	0.2
–20 to 0	same as now	worse	0.0	0.0	0.6	0.4
–20 to 0	reduced availability	better	0.1	0.5	0.2	0.2
–20 to 0	reduced availability	same as now	0.0	0.1	0.5	0.4
–20 to 0	reduced availability	worse	0.0	0.0	0.4	0.6
–20 to 0	greatly reduced availability	better	0.0	0.0	0.5	0.5
–20 to 0	greatly reduced availability	same as now	0.0	0.0	0.2	0.8
–20 to 0	greatly reduced availability	worse	0.0	0.0	0.0	1.0

Table B11. (continued)

Node B: Foraging Habitat Quantity Change	Node D: Change in Foraging Habitat Distribution	Node A: Foraging Habitat Value	Level of Habitat Threat			
			Improvement	No Effect	Minor Restriction	Major Restriction
–20 to 0	unavailable	better	0.0	0.0	0.0	1.0
–20 to 0	unavailable	same as now	0.0	0.0	0.0	1.0
–20 to 0	unavailable	worse	0.0	0.0	0.0	1.0
–40 to –20	improved availability	better	0.4	0.4	0.2	0.0
–40 to –20	improved availability	same as now	0.1	0.5	0.4	0.0
–40 to –20	improved availability	worse	0.0	0.3	0.5	0.2
–40 to –20	same as now	better	0.1	0.4	0.4	0.1
–40 to –20	same as now	same as now	0.0	0.1	0.4	0.5
–40 to –20	same as now	worse	0.0	0.0	0.4	0.6
–40 to –20	reduced availability	better	0.0	0.1	0.6	0.3
–40 to –20	reduced availability	same as now	0.0	0.0	0.5	0.5
–40 to –20	reduced availability	worse	0.0	0.0	0.2	0.8
–40 to –20	greatly reduced availability	better	0.0	0.0	0.3	0.7
–40 to –20	greatly reduced availability	same as now	0.0	0.0	0.0	1.0
–40 to –20	greatly reduced availability	worse	0.0	0.0	0.0	1.0
–40 to –20	unavailable	better	0.0	0.0	0.0	1.0
–40 to –20	unavailable	same as now	0.0	0.0	0.0	1.0
–40 to –20	unavailable	worse	0.0	0.0	0.0	1.0
< –40	improved availability	better	0.2	0.6	0.2	0.0
< –40	improved availability	same as now	0.0	0.2	0.6	0.2
< –40	improved availability	worse	0.0	0.0	0.5	0.5
< –40	same as now	better	0.0	0.1	0.6	0.3
< –40	same as now	same as now	0.0	0.0	0.3	0.7
< –40	same as now	worse	0.0	0.0	0.2	0.8
< –40	reduced availability	better	0.0	0.1	0.2	0.7
< –40	reduced availability	same as now	0.0	0.0	0.1	0.9
< –40	reduced availability	worse	0.0	0.0	0.0	1.0
< –40	greatly reduced availability	better	0.0	0.0	0.0	1.0
< –40	greatly reduced availability	same as now	0.0	0.0	0.0	1.0
< –40	greatly reduced availability	worse	0.0	0.0	0.0	1.0
< –40	unavailable	better	0.0	0.0	0.0	1.0
< –40	unavailable	same as now	0.0	0.0	0.0	1.0
< –40	unavailable	worse	0.0	0.0	0.0	1.0

Table B12. Node G: Relocation Possible

Node F: Alternative Regions Available	Node H: Crowding Tolerance	Possibility of Relocation	
		Yes	No
Yes	none	0.0	1.0
Yes	moderate	0.8	0.2
Yes	high	1.0	0.0
No	none	0.0	1.0
No	moderate	0.0	1.0
No	high	0.0	1.0

Table B13. Node H: Crowding Tolerance

Node R2: Alternative Prey Availability	Node R3: Relative Ringed Seal Availability	Level of Crowding Tolerance		
		None	Moderate	High
Increase	increase	0.0	0.2	0.8
Increase	same as now	0.0	0.4	0.6
Increase	decrease	0.1	0.5	0.4
Same as now	increase	0.0	0.4	0.6
Same as now	same as now	0.1	0.8	0.1
Same as now	decrease	0.3	0.6	0.1
Decrease	increase	0.1	0.5	0.4
Decrease	same as now	0.3	0.5	0.2
Decrease	decrease	0.5	0.5	0.0

Table B14. Node K: Adult Body Condition

Node F2: Factor A—Habitat Threats	Quality of Adult Body Condition		
	Increase	Same as Now	Decrease
Improvement	1.0	0.0	0.0
No effect	0.0	1.0	0.0
Minor restriction	0.0	0.5	0.5
Major restriction	0.0	0.0	1.0

Table B15. Node L: Juvenile Survival

Node K: Adult Body Condition	Node L1: Adult Female Survival	Juvenile Survival		
		Increase	No Change	Decrease
Increase	increase	1.0	0.0	0.0
Increase	no change	0.7	0.3	0.0
Increase	decrease	0.0	0.4	0.6
Same as now	increase	0.8	0.2	0.0
Same as now	no change	0.0	1.0	0.0
Same as now	decrease	0.0	0.2	0.8
Decrease	increase	0.0	0.6	0.4
Decrease	no change	0.0	0.3	0.7
Decrease	decrease	0.0	0.0	1.0

Table B16. Node L1: Adult Female Survival

Node K: Adult Body Condition	Node F2: Factor A—Habitat Threats	Adult Female Survival		
		Increase	No Change	Decrease
Increase	improvement	1.0	0.0	0.0
Increase	no effect	0.8	0.2	0.0
Increase	minor restriction	0.1	0.6	0.3
Increase	major restriction	0.0	0.5	0.5
Same as now	improvement	0.5	0.5	0.0
Same as now	no effect	0.0	1.0	0.0
Same as now	minor restriction	0.0	0.6	0.4
Same as now	major restriction	0.0	0.3	0.7
Decrease	improvement	0.0	0.4	0.6
Decrease	no effect	0.0	0.2	0.8
Decrease	minor restriction	0.0	0.1	0.9
Decrease	major restriction	0.0	0.0	1.0

Table B17. Node L2:Vital Rates

Node L1: Adult Female Survival	Node L: Juvenile Survival	Node U: Reproduction	Vital Rates		
			Improve	Same as Now	Decline
Increase	increase	increased	1.0	0.0	0.0
Increase	increase	same as now	1.0	0.0	0.0
Increase	increase	decreased	0.6	0.4	0.0
Increase	no change	increased	0.9	0.1	0.0
Increase	no change	same as now	0.8	0.2	0.0
Increase	no change	decreased	0.7	0.2	0.1
Increase	decrease	increased	0.3	0.5	0.2
Increase	decrease	same as now	0.2	0.5	0.3
Increase	decrease	decreased	0.0	0.4	0.6
No change	increase	increased	0.7	0.3	0.0
No change	increase	same as now	0.6	0.4	0.0
No change	increase	decreased	0.2	0.5	0.3
No change	no change	increased	0.2	0.8	0.0
No change	no change	same as now	0.0	1.0	0.0
No change	no change	decreased	0.0	0.8	0.2
No change	decrease	increased	0.0	0.6	0.4
No change	decrease	same as now	0.0	0.5	0.5
No change	decrease	decreased	0.0	0.3	0.7
Decrease	increase	increased	0.2	0.4	0.4
Decrease	increase	same as now	0.0	0.6	0.4
Decrease	increase	decreased	0.0	0.5	0.5
Decrease	no change	increased	0.1	0.5	0.4
Decrease	no change	same as now	0.0	0.4	0.6
Decrease	no change	decreased	0.0	0.3	0.7
Decrease	decrease	increased	0.0	0.2	0.8
Decrease	decrease	same as now	0.0	0.0	1.0
Decrease	decrease	decreased	0.0	0.0	1.0

Table B18. Node U: Reproduction

Node M: Ecoregion	Node V1: Cub Production per Event	Node N: Shelf Distance Change (km)	Rate of Reproduction		
			Increased	Same as Now	Decreased
Polar basin divergent	fewer than now	–200 to 0	0.0	0.3	0.7
Polar basin divergent	fewer than now	0 to 200	0.0	0.2	0.8
Polar basin divergent	fewer than now	200 to 800	0.0	0.0	1.0
Polar basin divergent	fewer than now	>= 800	0.0	0.0	1.0
Polar basin divergent	same as now	–200 to 0	0.7	0.3	0.0
Polar basin divergent	same as now	0 to 200	0.0	1.0	0.0
Polar basin divergent	same as now	200 to 800	0.0	0.3	0.7
Polar basin divergent	same as now	>= 800	0.0	0.0	1.0
Polar basin divergent	more than now	–200 to 0	1.0	0.0	0.0
Polar basin divergent	more than now	0 to 200	0.5	0.5	0.0
Polar basin divergent	more than now	200 to 800	0.0	0.5	0.5
Polar basin divergent	more than now	>= 800	0.0	0.0	1.0
Polar basin convergent	fewer than now	–200 to 0	0.0	0.5	0.5
Polar basin convergent	fewer than now	0 to 200	0.0	0.4	0.6
Polar basin convergent	fewer than now	200 to 800	0.0	0.3	0.7
Polar basin convergent	fewer than now	>= 800	0.0	0.2	0.8
Polar basin convergent	same as now	–200 to 0	1.0	0.0	0.0
Polar basin convergent	same as now	0 to 200	0.5	0.5	0.0
Polar basin convergent	same as now	200 to 800	0.2	0.6	0.2
Polar basin convergent	same as now	>= 800	0.0	0.5	0.5
Polar basin convergent	more than now	–200 to 0	1.0	0.0	0.0
Polar basin convergent	more than now	0 to 200	0.8	0.2	0.0
Polar basin convergent	more than now	200 to 800	0.4	0.4	0.2
Polar basin convergent	more than now	>= 800	0.2	0.4	0.4
Archipelago	fewer than now	–200 to 0	0.0	0.2	0.8
Archipelago	fewer than now	0 to 200	0.0	0.2	0.8
Archipelago	fewer than now	200 to 800	0.0	0.2	0.8
Archipelago	fewer than now	>= 800	0.0	0.2	0.8
Archipelago	same as now	–200 to 0	0.2	0.6	0.2
Archipelago	same as now	0 to 200	0.2	0.6	0.2
Archipelago	same as now	200 to 800	0.2	0.6	0.2
Archipelago	same as now	>= 800	0.2	0.6	0.2
Archipelago	more than now	–200 to 0	0.8	0.2	0.0
Archipelago	more than now	0 to 200	0.8	0.2	0.0
Archipelago	more than now	200 to 800	0.8	0.2	0.0
Archipelago	more than now	>= 800	0.8	0.2	0.0
Seasonal ice	fewer than now	–200 to 0	0.0	0.2	0.8
Seasonal ice	fewer than now	0 to 200	0.0	0.2	0.8
Seasonal ice	fewer than now	200 to 800	0.0	0.2	0.8
Seasonal ice	fewer than now	>= 800	0.0	0.2	0.8
Seasonal ice	same as now	–200 to 0	0.2	0.6	0.2
Seasonal ice	same as now	0 to 200	0.2	0.6	0.2
Seasonal ice	same as now	200 to 800	0.2	0.6	0.2
Seasonal ice	same as now	>= 800	0.2	0.6	0.2
Seasonal ice	more than now	–200 to 0	0.8	0.2	0.0
Seasonal ice	more than now	0 to 200	0.8	0.2	0.0
Seasonal ice	more than now	200 to 800	0.8	0.2	0.0
Seasonal ice	more than now	>= 800	0.8	0.2	0.0

Table B19. Node V1: Cub Production per Event

Node F2: Factor A—Habitat Threats	Cub Production per Event		
	Fewer Than Now	Same as Now	More Than Now
Improvement	0.0	0.3	0.7
No effect	0.0	1.0	0.0
Minor restriction	0.6	0.4	0.0
Major restriction	1.0	0.0	0.0

APPENDIX C: RESULTS OF SENSITIVITY ANALYSES OF THE BAYESIAN NETWORK POPULATION STRESSOR MODEL

Tables C1 and C2 present the results of conducting a series of sensitivity analyses of the Bayesian network population stressor model discussed in the text (also see Plate 3). Sensitivity analysis reveals the degree to which selected input or summary variables influence the calculated values of a specified output variable. Tables C1 and C2 present results of 10 sensitivity tests on various summary and output nodes in the model (see text for explanation of calculations). Note that mutual information is also called entropy reduction. All tests were conducted using the Bayesian network modeling software package Netica® (Norsys, Inc.).

Table C1. Sensitivity Group 1: Sensitivity of Overall Population Outcome

Node	Mutual Information	Node Title
Test 1: Sensitivity of Node D1—Overall Population Outcome to All Input Nodes		
B	0.12974	Foraging Habitat Quantity Change
C	0.04876	foraging habitat absence change
M	0.04166	ecoregion
F	0.02590	alternate regions available
E	0.01607	intentional takes
N	0.01393	shelf distance change (km)
S1	0.01037	foraging habitat character
B1	0.00821	bear-human interactions
T	0.00506	parasites and disease
R4	0.00271	hydrocarbons/oil spill
R1	0.00254	oil and gas activity
J	0.00198	shipping
T2	0.00092	predation
T1	0.00073	contaminants
R3	0.00069	alternate prey availability
R2	0.00065	relative ringed seal availability
J1	0.00040	tourism
Test 2. Sensitivity of Node D1—Overall Population Outcome to Listing Factor Nodes		
F2	0.66422	factor a: habitat threats
A1	0.05253	factor b: direct mortalities
A6	0.03150	factor e: other factors (natural or man-made)
A4	0.01039	factor c: disease, predation
Test 3: Sensitivity of Node D1—Overall Population Outcome to Intermediate Nodes[a]		
L2	0.56624	vital rates
L	0.54067	juvenile survival
L1	0.54057	adult female survival
K	0.53353	adult body condition
V1	0.44705	cub production per event

Table C1. (continued)

Node	Mutual Information	Node Title
U	0.24141	reproduction
D	0.19993	change in foraging habitat distribution
G	0.04235	relocation possible
A	0.02866	foraging habitat value
C1	0.01856	human disturbance
H	0.00537	crowding tolerance
C2	0.00432	pollution
Test 4: Sensitivity of Node D1—Overall Population Outcome to Selected Intermediate Nodes[b]		
F2	0.66422	factor a: habitat threats
L2	0.56624	vital rates
A1	0.05253	factor b: direct mortalities
G	0.04235	relocation possible
A6	0.03150	factor e: other factors (natural or man-made)
A4	0.01039	factor c: disease and predation

[a]This does not include the listing factor nodes included in test 2 above.
[b]This includes all (6) nodes that are two links distant from the output node.

Table C2. Sensitivity Group 2: Sensitivity of Submodels

Node	Mutual Information	Node Title
Test 5: Sensitivity of Node A4—Factor C Disease and Predation		
T	0.39016	parasites and disease
T2	0.06593	predation
Test 6: Sensitivity of Node C2—Pollution		
R4	0.69005	hydrocarbons/oil spill
T1	0.13542	contaminants
Test 7: Sensitivity of Node C1—Human Disturbance		
B1	0.45796	bear-human interactions
R1	0.12450	oil and gas activity
J	0.08941	shipping
J1	0.01729	tourism
Test 8: Sensitivity of Node A—Foraging Habitat Value		
S1	0.51589	foraging habitat character
F	0.04028	alternate regions available
R3	0.00105	alternate prey availability
R2	0.00100	relative ringed seal availability
Test 9: Sensitivity of Node D—Change in Foraging Habitat Distribution		
M	0.33239	ecoregion
C	0.32674	foraging habitat absence change
N	0.06131	shelf distance change (km)

Table C2. (continued)

Node	Mutual Information	Node Title
Test 10: Sensitivity of Node L2—Vital Rates		
L1	1.04302	adult female survival
L	1.04048	juvenile survival
F2	0.93484	factor a: habitat threats
K	0.92047	adult body condition
V1	0.64819	cub production per event
U	0.34420	reproduction
M	0.04217	ecoregion
N	0.01843	shelf distance change (km)

APPENDIX D: INPUT VALUES USED IN THE BAYESIAN NETWORK POLAR BEAR POPULATION STRESSOR MODEL FOR EACH OF FOUR POLAR BEAR ECOREGIONS

Tables D1a and D1b present input data values used in the Bayesian network polar bear population stressor model for each of four polar bear ecoregions. Separate input values were provided for each time period projected and for the ensemble mean of general circulation model outputs as well as for individual GCMs that projected the maximum and minimum sea ice remaining in each time period.

Table D1a. Input Data Values for Nodes B, C, N, S1, R3, R2, and F Used in the Bayesian Network Polar Bear Population Stressor Model for Each of Four Polar Bear Ecoregions

		Node and Variable Name[b]						
Time Period[a]	Sea Ice Data Source	B: Foraging Habitat Quantity Change (%)	C: Foraging Habitat Absence Change	N: Shelf Distance Change[c] (km)	S1: Foraging Habitat Character	R3: Alternative Prey Availability	R2: Relative Ringed Seal Availability	F: Alternative Regions Available
Seasonal Ice Ecoregion								
Year –10	Satellite data	17.14	–0.7	NA	more_optimal	decrease	increase	yes
Year 0	Satellite data	0.00	0.0	NA	same_as_now	same_as_now	same_as_now	yes
Year 25	GCM minimum	–4.17	0.1	NA	same_as_now	same_as_now	decrease	yes
Year 50	GCM minimum	–10.36	1.0	NA	same_as_now	decrease	decrease	yes
Year 75	GCM minimum	–31.89	2.5	NA	less_optimal	decrease	decrease	yes
Year 95	GCM minimum	–32.11	2.7	NA	less_optimal	decrease	decrease	yes
Year 25	Ensemble mean	–4.65	0.3	NA	same_as_now	same_as_now	decrease	yes
Year 50	Ensemble mean	–14.62	1.0	NA	same_as_now	decrease	decrease	yes
Year 75	Ensemble mean	–25.75	1.6	NA	less_optimal	decrease	decrease	yes
Year 95	Ensemble mean	–27.83	1.8	NA	less_optimal	decrease	decrease	yes
Year 25	GCM maximum	–0.05	0.1	NA	same_as_now	same_as_now	decrease	yes
Year 50	GCM maximum	–6.71	0.7	NA	same_as_now	decrease	decrease	yes
Year 75	GCM maximum	–21.16	1.3	NA	same_as_now	decrease	decrease	yes
Year 95	GCM maximum	–21.69	1.7	NA	same_as_now	decrease	decrease	yes
Archipelago Ecoregion								
Year –10	Satellite data	3.21	–0.5	NA	less_optimal	same_as_now	decrease	no
Year 0	Satellite data	0.00	0.0	NA	same_as_now	same_as_now	same_as_now	no
Year 25	GCM minimum	–6.16	0.6	NA	more_optimal	same_as_now	increase	no
Year 50	GCM minimum	–13.79	1.1	NA	more_optimal	increase	increase	no
Year 75	GCM minimum	–20.71	2.0	NA	same_as_now	decrease	decrease	no

Table D1a. (continued)

		Node and Variable Name[b]						
Time Period[a]	Sea Ice Data Source	B: Foraging Habitat Quantity Change (%)	C: Foraging Habitat Absence Change	N: Shelf Distance Change[c] (km)	S1: Foraging Habitat Character	R3: Alternative Prey Availability	R2: Relative Ringed Seal Availability	F: Alternative Regions Available
Year 95	GCM minimum	−24.30	2.3	NA	same_as_now	decrease	decrease	no
Year 25	Ensemble mean	−2.35	0.2	NA	more_optimal	same_as_now	increase	no
Year 50	Ensemble mean	−11.93	1.5	NA	more_optimal	increase	increase	no
Year 75	Ensemble mean	−20.06	2.4	NA	same_as_now	increase	decrease	no
Year 95	Ensemble mean	−22.16	2.5	NA	same_as_now	decrease	decrease	no
Year 25	GCM maximum	−0.08	0.0	NA	more_optimal	same_as_now	increase	no
Year 50	GCM maximum	−3.43	0.0	NA	more_optimal	increase	increase	no
Year 75	GCM maximum	−18.02	2.7	NA	more_optimal	increase	increase	no
Year 95	GCM maximum	−20.85	2.3	NA	same_as_now	decrease	decrease	no
				Polar Basin Divergent Ecoregion				
Year −10	Satellite data	5.33	−0.3	−83	more_optimal	same_as_now	increase	yes
Year 0	Satellite data	0.00	0.0	0	same_as_now	same_as_now	same_as_now	yes
Year 25	GCM minimum	−9.76	0.9	183	less_optimal	same_as_now	decrease	yes
Year 50	GCM minimum	−32.16	2.1	1359	less_optimal	same_as_now	decrease	yes
Year 75	GCM minimum	−41.28	2.9	2006	less_optimal	same_as_now	decrease	yes
Year 95	GCM minimum	−46.30	3.2	2177	less_optimal	same_as_now	decrease	yes
Year 25	Ensemble mean	−5.25	0.7	114	same_as_now	same_as_now	decrease	yes
Year 50	Ensemble mean	−19.31	1.8	631	less_optimal	same_as_now	decrease	yes
Year 75	Ensemble mean	−31.68	2.6	1034	less_optimal	same_as_now	decrease	yes
Year 95	Ensemble mean	−35.77	3.0	1275	less_optimal	same_as_now	decrease	yes
Year 25	GCM maximum	−5.12	0.7	42	same_as_now	same_as_now	same_as_now	yes
Year 50	GCM maximum	−15.68	2.2	234	less_optimal	same_as_now	decrease	yes
Year 75	GCM maximum	−24.23	2.4	233	less_optimal	same_as_now	decrease	yes
Year 95	GCM maximum	−21.33	2.7	315	less_optimal	same_as_now	decrease	yes
				Polar Basin Convergent Ecoregion				
Year −10	Satellite data	4.34	−0.5	−41	same_as_now	same_as_now	same_as_now	no
Year 0	Satellite data	0.00	0.0	0	same_as_now	same_as_now	same_as_now	no
Year 25	GCM minimum	2.65	0.3	26	more_optimal	same_as_now	increase	no
Year 50	GCM minimum	−4.60	0.9	831	same_as_now	increase	same_as_now	no
Year 75	GCM minimum	−23.19	1.9	1542	less_optimal	decrease	decrease	no
Year 95	GCM minimum	−30.33	2.5	1478	less_optimal	decrease	decrease	no
Year 25	Ensemble mean	−2.76	0.7	83	more_optimal	increase	increase	no
Year 50	Ensemble mean	−13.85	2.0	464	same_as_now	increase	increase	no
Year 75	Ensemble mean	−22.65	3.0	847	less_optimal	decrease	same_as_now	no
Year 95	Ensemble mean	−25.02	3.3	795	less_optimal	decrease	decrease	no
Year 25	GCM maximum	−6.68	0.9	109	more_optimal	increase	increase	no
Year 50	GCM maximum	−26.76	2.9	334	same_as_now	increase	increase	no
Year 75	GCM maximum	−34.08	3.5	434	less_optimal	increase	increase	no
Year 95	GCM maximum	−34.88	3.7	510	less_optimal	decrease	same_as_now	no

[a]Time period is expressed as the central year in each decade for which projections were made.
[b]Units of measure at each node are B, percentile change from present in the annual sum of habitat quantity; C, difference between present and future number of ice-free months; N, difference between present and future distance between the edge of the continental shelf and the edge of the pack ice; and discrete states for all other nodes. See Figure 3 for allowable states at each node.
[c]NA stands for not applicable; shelf distance change only applies to the polar basin ecoregions.

Table D1b. Input Data Values for Nodes J1, B1, R1, J, R4, T1, E, T, and T2 Used in the Bayesian Network Polar Bear Population Stressor Model for Each of Four Polar Bear Ecoregions[a]

		BN Node and Variable Name[b]			
Time Period[a]	Sea Ice Data Source	J1: Tourism	B1: Bear-Human Interactions	R1: Oil and Gas Activity	J: Shipping
		Seasonal Ice Ecoregion			
Year −10	Satellite data	decreased	decreased	no_change	same_as_now
Year 0	Satellite data	same_as_now	same_as_now	no_change	same_as_now
Year 25	GCM minimum	increased	increased	no_change	increased
Year 50	GCM minimum	increased	increased	no_change	increased
Year 75	GCM minimum	increased	increased	no_change	increased
Year 95	GCM minimum	increased	increased	no_change	increased
Year 25	Ensemble mean	increased	increased	no_change	increased
Year 50	Ensemble mean	increased	increased	no_change	increased
Year 75	Ensemble mean	increased	increased	no_change	increased
Year 95	Ensemble mean	increased	increased	no_change	increased
Year 25	GCM maximum	increased	increased	no_change	increased
Year 50	GCM maximum	increased	increased	no_change	increased
Year 75	GCM maximum	increased	increased	no_change	increased
Year 95	GCM maximum	increased	increased	no_change	increased
		Archipelago Ecoregion			
Year –10	Satellite data	decreased	increased	no_change	same_as_now
Year 0	Satellite data	same_as_now	same_as_now	no_change	same_as_now
Year 25	GCM minimum	increased	same_as_now	no_change	same_as_now
Year 50	GCM minimum	increased	increased	no_change	same_as_now
Year 75	GCM minimum	increased	increased	increase	increased
Year 95	GCM minimum	increased	increased	increase	increased
Year 25	Ensemble mean	increased	same_as_now	no_change	same_as_now
Year 50	Ensemble mean	increased	increased	no_change	same_as_now
Year 75	Ensemble mean	increased	increased	increase	same_as_now
Year 95	Ensemble mean	increased	increased	increase	increased
Year 25	GCM maximum	increased	same_as_now	no_change	same_as_now
Year 50	GCM maximum	increased	increased	no_change	same_as_now
Year 75	GCM maximum	increased	increased	increase	same_as_now
Year 95	GCM maximum	increased	increased	increase	same_as_now
		Polar Basin Divergent Ecoregion			
Year –10	Satellite data	decreased	decreased	decrease	same_as_now
Year 0	Satellite data	same_as_now	same_as_now	no_change	same_as_now
Year 25	GCM minimum	increased	increased	increase	increased
Year 50	GCM minimum	increased	increased	increase	increased
Year 75	GCM minimum	decreased	increased	increase	increased
Year 95	GCM minimum	decreased	increased	decrease	increased
Year 25	Ensemble mean	increased	increased	increase	increased
Year 50	Ensemble mean	increased	increased	increase	increased
Year 75	Ensemble mean	same_as_now	increased	increase	increased
Year 95	Ensemble mean	decreased	increased	decrease	increased
Year 25	GCM maximum	increased	increased	increase	increased
Year 50	GCM maximum	increased	increased	increase	increased
Year 75	GCM maximum	same_as_now	increased	increase	increased
Year 95	GCM maximum	same_as_now	increased	decrease	increased

Table D1b. (continued)

Time Period[a]	Sea Ice Data Source	BN Node and Variable Name[b] J1: Tourism	B1: Bear-Human Interactions	R1: Oil and Gas Activity	J: Shipping
		Polar Basin Convergent Ecoregion			
Year –10	Satellite data	decreased	decreased	decrease	same_as_now
Year 0	Satellite data	same_as_now	same_as_now	no_change	same_as_now
Year 25	GCM minimum	increased	same_as_now	no_change	same_as_now
Year 50	GCM minimum	increased	increased	increase	increased
Year 75	GCM minimum	increased	increased	increase	increased
Year 95	GCM minimum	increased	increased	increase	increased
Year 25	Ensemble mean	increased	same_as_now	same_as_now	same_as_now
Year 50	Ensemble mean	increased	increased	increase	increased
Year 75	Ensemble mean	increased	increased	increase	increased
Year 95	Ensemble mean	increased	increased	increase	increased
Year 25	GCM maximum	increased	same_as_now	same_as_now	same_as_now
Year 50	GCM maximum	increased	increased	increase	increased
Year 75	GCM maximum	increased	increased	increase	increased
Year 95	GCM maximum	increased	increased	increase	increased

Time Period[a]	BN Node and Variable Name[b] R4: Hydrocarbons/ Oil Spill	T1: Contaminants	E: Intentional Takes	T: Parasites and Disease	T2: Predation
		Seasonal Ice Ecoregion			
Year –10	same_as_now	reduced	decreased	not	not
Year 0	same_as_now	same_as_now	same_as_now	not	not
Year 25	same_as_now	elevated	decreased	influential	not
Year 50	same_as_now	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	same_as_now	elevated	decreased	influential	not
Year 50	same_as_now	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	same_as_now	elevated	decreased	influential	not
Year 50	same_as_now	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
		Archipelago Ecoregion			
Year –10	same_as_now	reduced	same_as_now	not	not
Year 0	same_as_now	same_as_now	same_as_now	not	not
Year 25	same_as_now	elevated	same_as_now	not	not
Year 50	same_as_now	elevated	increased	influential	not
Year 75	increased_occurrence	elevated	same_as_now	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	same_as_now	elevated	same_as_now	not	not
Year 50	same_as_now	elevated	increased	influential	not
Year 75	increased_occurrence	elevated	same_as_now	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	same_as_now	elevated	same_as_now	not	not
Year 50	same_as_now	elevated	increased	influential	not

Table D1b. (continued)

Time Period[a]	BN Node and Variable Name[b]				
	R4: Hydrocarbons/ Oil Spill	T1: Contaminants	E: Intentional Takes	T: Parasites and Disease	T2: Predation
Year 75	increased_occurrence	elevated	increased	influential	not
Year 95	increased_occurrence	elevated	decreased	influential	influential
			Polar Basin Divergent Ecoregion		
Year –10	same_as_now	reduced	decreased	not	not
Year 0	same_as_now	same_as_now	same_as_now	not	not
Year 25	increased_occurrence	elevated	decreased	influential	influential
Year 50	increased_occurrence	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	increased_occurrence	elevated	decreased	influential	influential
Year 50	increased_occurrence	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	increased_occurrence	elevated	decreased	influential	influential
Year 50	increased_occurrence	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
			Polar Basin Convergent Ecoregion		
Year –10	same_as_now	reduced	same_as_now	not	not
Year 0	same_as_now	same_as_now	same_as_now	not	not
Year 25	same_as_now	same_as_now	same_as_now	not	not
Year 50	increased_occurrence	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	same_as_now	same_as_now	same_as_now	not	not
Year 50	increased_occurrence	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential
Year 25	same_as_now	same_as_now	same_as_now	not	not
Year 50	increased_occurrence	elevated	decreased	influential	influential
Year 75	increased_occurrence	elevated	decreased	influential	influential
Year 95	increased_occurrence	elevated	decreased	influential	influential

[a]Time period is expressed as the central year in each decade for which projections were made.
[b]Units of measure are discrete states at each node. See Figure 3 for allowable states at each node.

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