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Incremental evolution of modeling a prognosis for polar bears in a rapidly changing Arctic

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ABSTRACT

Updating predictions of the response of high-profile, at-risk species to climate change and anthropogenic stressors is vital for informing effective conservation action. Here, we review two prior generations of Bayesian network probability models predicting changes in global polar bear (*Ursus maritimus*) population status, and provide a contemporary update based on recent research findings and sea-ice projections by newer climate models. We compare predictions of polar bear population response from all 3 models among four circumpolar Arctic ecoregions, using sea ice projections based on three IPCC greenhouse gas emissions scenarios (SSP2.6, 4.5, 8.5). Consistent with the previous two model generations, polar bears will continue to experience increasing probability of declining or greatly declining populations throughout the 21st century, varying by emission scenario. Populations within the Polar Basin Divergent Ice Ecoregion have the highest predicted probability of declines, but predictions were slightly less dire relative to the previous model generation. Most of the influence, denoted by model sensitivity analysis, is from expected degradation and loss of sea ice and reduced access to marine prey. The lack of terrestrial prey adequate to substitute for loss of access to marine prey, as well as human-caused bear morality associated with hunting and defense of life and property encountered when polar bears are increasingly forced ashore also contributed to predicted declines. Although some tidewater glacial fjords and other localized onshore resources may provide local refugia, their benefit is transient. Our findings continue to inform priorities for inventory, monitoring, and research needs, and suggest that similar updates to models of other at-risk species can capitalize on the comparison framework we present here.

1. Introduction

Polar bears (*Ursus maritimus*) have been a conservation concern for decades. They were first listed as globally Vulnerable on the IUCN Red List in 1982, with the most recent review and renewal of that status in 2015 (www.iucnredlist.org/species/22823/14871490) as Vulnerable A3c (defined as population reduction ≥ 30 % projected, inferred, or suspected to be met in the future up to 100 years, based on a decline in area of occupancy, extent of occurrence, and/or habitat quality; IUCN 2012, Regehr et al. 2016). The species also was listed in 2008 as globally Threatened under the U.S. Endangered Species Act (U.S. Fish and Wildlife Service 2008) and listed in 2018 as a Species of Special Concern

in Canada (COSEWIC 2018). These listings highlighted the major threat of declines in quality and quantity of Arctic sea ice which adversely affects access to seal prey and other stressors associated with anthropogenetic activities.

Recent research has investigated how polar bear demographics are influenced by factors such as environmental conditions, prey availability, and harvest levels (e.g., Bromaghin et al. 2015, 2021; Laidre et al. 2020; Lunn et al. 2016, Regehr et al. 2021; Rode et al. 2021, Rode et al., 2023). Few studies and projections of polar bear populations, however, have included the full suite of environmental, biotic, and anthropogenic stressors, and their potential interactions, at regional or global scales. One approach that has been used to evaluate such a suite of effector

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variables involves Bayesian network (BN) models, constructed as causal networks that combine the influence of multiple stressors on population outcomes. For example, Fahd et al. (2021) used a BN to evaluate potential mortality impacts on polar bears from oil spill events.

Amstrup et al. (2008) were the first to construct a BN to model the probability of polar bear population responses to multiple categories of stressors across the global range of the species. That work, identified herein as the Phase I Polar Bear BN Model 2008 (Phase I), provided an analysis[1] of the 19 recognized polar bear populations, assessed within four circumpolar Arctic ecoregions, using sea-ice projections from global climate models participating in the Coupled Model Intercomparison Project (CMIP3; Meehl et al. 2007). The results from that work contributed significantly to the 2008 decision by U.S. Secretary of Interior Kempthorne to list polar bears as globally Threatened because of impending threats from climate warming and other stressors. Subsequent analyses further supported those findings (Amstrup et al. 2009, Amstrup et al., 2010).

A major review and revision of the Phase I model was completed by Atwood et al. (2015, 2016), resulting in updated projections of polar bear population outcomes. That Phase II Polar Bear BN Model 2016 (Phase II) incorporated updated Arctic sea ice projections by CMIP5 climate models (Taylor et al. 2012) and new research findings on polar bear population status, response to stressors, and prey relationships.[2]

Here, we report on the new Phase III Polar Bear BN Model 2023 (Phase III), based on the latest CMIP6 Arctic sea ice projections (Eyring et al. 2016) and polar bear research. The Phase III model was developed by evaluating and revising the Phase II model structure components and interactions, and revising the case scenarios to provide updated projections of polar bear population outcomes over the 21st century. The general goal of this Phase III assessment was to revisit the Phase II model to determine if new research about polar bears or new model projections of sea ice would qualitatively alter any of the previous key projections about polar bear population outcomes under scenarios of future greenhouse gas emissions.

2. Methods

Our methods consisted of (1) reviewing research on polar bear ecology completed since the Phase II model, and determining if changes were needed for a revised BN model structure; (2) running both the Phase II and the Phase III model using CMIP6 Arctic sea ice projections; and (3) comparing the Phase II and III BN results of polar bear population projections to determine how the updated Phase III BN changed polar bear population projections.

2.1. Review of recent polar bear research and model revision

After evaluating research published since Phase II up to July 2022, we reviewed the structure of the Phase II BN model (Atwood et al. 2016), amended the model structure and probability values if supported by new findings, and documented all changes with the supporting literature. For consistency with previous BN model versions, we used the Bayesian network modeling construct Netica® (Norsys Corp., www.norsys.com). The Phase II BN structure consisted of 10 interlinked submodels of greenhouse gas forcing scenarios, sea ice projections, marine prey and conditions, terrestrial food/prey and conditions, overall habitat suitability, event-driven mortality, anthropogenic stressors, other biotic stressors, polar bear demography, and polar bear persistence.

We revisited the Phase I demarcation of polar bear populations into four Arctic ecoregions to determine if any recent findings about sea ice

dynamics supported, or suggested amendments to, those regional delineations. We also revisited and updated the specification of past and present time periods, given the passage and overlap of years since the Phase II BN was published.

2.2. Using IPCC CMIP6 Arctic sea ice projections

Once revised, we ran the Phase III BN to generate "normative" (expected, used as baseline comparison) conditions for each analysis scenario defined by time period, Shared Socioeconomic Pathway (SSP; O'Neill et al. 2014) greenhouse gas forcing, and ecoregion. As per Atwood et al. (2015), we defined normative as the most-expected outcomes based on best estimates of likely input values. To predict future response by polar bears, we ran three SSP greenhouse gas scenarios representing a broad range of socioeconomic pathways: SSP2.6 as a sustainable development scenario in which global CO2 emissions are cut severely reaching net-zero after 2050 and stabilizing end-of-century temperatures around 1.8C higher than preindustrial levels; SSP4.5 as a "middle of the road" scenario in which emissions start to drop after mid-century but do not reach net-zero and temperatures increase 2.7C by century's end; and SSP8.5 as an energy-intensive fossil-fuel based scenario in which emissions roughly double by mid-century and temperatures increase 4.4C by century's end. For each SSP scenario, we used monthly sea ice projections, over 2015–2100, from a selected ensemble of 12 general circulation models (GCMs[3]) as detailed in Table S1 of Rode et al. (2022). We represented the variability (uncertainty) among the 12 models by prescribing the probability states of each sea ice input node in the BN model based on the ensemble's frequency distribution across those states (Atwood et al. 2015).

2.3. Comparisons with previous model results

We made several comparisons among BN model results to determine the potential influences on projected polar bear population outcomes from the CMIP6 Arctic sea-ice projections and from our model amendments. We specifically compared results between the previously published Phase II BN using CMIP5 sea-ice projections, and our current Phase III BN using CMIP6 sea-ice projections. We made additional comparisons of our Phase III BN using CMIP6 sea ice projections, by rerunning the Phase II BN model also using the CMIP6 projections. In all three modeling generations, the analyses focused on comparing the relative degree of similarity or change of polar bear populations, for each of four ecoregions, to baseline conditions. We did not attempt to measure and predict absolute population sizes or demographic trends, as data were unavailable for such analyses for most populations at the global scale. Population outcome states were defined and described for each model phase as qualitative comparisons given their respective inputs in each model (Phase I, Amstrup et al. 2008; Phase II, Atwood et al. 2016; Phase III, Appendix A, this paper).

We also compared results of sensitivity analyses based on each of the three BN model phases. As with the analysis conducted and presented for the Phase I and II BN models, we used Netica to calculate mutual information sensitivity of the polar bear population outcome node to all other variables in the model, particularly the input nodes. This sensitivity measure is calculated as the expected reduction in mutual information of the population outcome posterior probabilities in the model, given the findings (normative, in this case) of the values of each other variable in the model (see Marcot 2012 for formula). The greater the value of mutual information, and the greater the relative percentage of mutual information contributions among other variables, the more

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[1] The Phase I BN model and links to associated publications are available at: https://www.abnms.org/bn/146.

[2] The Phase II BN model and links to associated publications are available at: https://www.abnms.org/bn/148.

[3] Increasingly, GCMs are being referred to as ESMs, Earth System Models (e. g., Newman et al. 2022), because in addition to simulating physical oceanic and atmospheric processes, newer models are simulating chemical and biological elements of the climate system.

sensitive the outcome is to that variable. These comparisons of model outcomes and sensitivity tests help reveal the degrees to which polar bear population projections were influenced more by recent research leading to model amendments or by updates to the sea-ice projections.

3. Results

3.1. Model evolution and review of recent polar bear research

The evolution of the polar bear BN model structure from Phase I to Phase II was described by Atwood et al. (2016). Those changes resulted in expansion of model structure and components, including increases in numbers of model variables (nodes), links among variables, and probability values (Table 1). Among substantial changes, the Phase II model added a submodel for terrestrial food/prey and conditions to explicitly denote the influence of human provisioned food abundance, terrestrial and marine prey food access, and terrestrial refuge quality (defined as stability in structure and freedom from human and natural disturbance where polar bears can wait out an ice-free period while avoiding excessive energy expenditure). The Phase II model also added a variable for bearded seal prey abundance, added four additional variables for the event-driven mortality submodel, and retained the six variables for the anthropogenic stressors submodel (Table 1). Phase I and II models both used 6 time periods with only the ones representing current conditions slightly altered from "now" 1996–2006 in Phase I, to "recent" 2007–2012 in Phase II (Table 2). Updates were made for the CMIP sea-ice projections, and the emissions scenarios used and the number of GCMs selected (Table 2).

For the Phase III model, we conducted a broad review of the literature and compiled 131 references pertinent to the Phase II BN structure of the 10 interlinked submodel categories as described above. Our literature review (Appendix A Model Documentation) generally supported the Phase II BN model structure but also identified the need for more explicit depictions of prey and terrestrial conditions. Consequently, we added a node on Alternative Marine Foraging Habitat, linking to the Overall Marine Conditions node in the Marine Prey and Conditions submodel (see Appendix Table B1 for the updated conditional probability table values), and we added an explicit link from the Ecoregion node to Overall Terrestrial Conditions in the Terrestrial Food/Prey and Conditions submodel (see Appendix Table B2 for the updated conditional probability table values). Our final, revised Phase III BN model structure largely replicated the Phase II model structure with the additions noted above (and as illustrated in Appendix Fig. C1). In general, reducing some of the states in other variables slightly dropped the total number of probability values in the Phase III model compared to Phase II (Table 1).

The major updates to the sea ice input nodes in the Phase III model consisted of using the CMIP6 sea-ice projections, the selection of three SSP emissions scenarios, and use of the ensemble of 12 GCMs (Table 2). The four sea ice input metrics were the same for all three BN phases (albeit with slightly altered variable names between Phase I and II models), consisting, as named in Phase II and III models: Foraging Sea Ice Area, Sea Ice Distance Change, Foraging Sea Ice < 50 % Absence Change, and Foraging Sea Ice Quality. Values for three of the sea ice input metrics (Table 2) were derived from the GCM projections, whereas one metric – denoted as Foraging Habitat Character in the Phase I model, and as Foraging Sea Ice Quality in Phase II and III models – was more of a heuristic variable created to denote how sea ice thickness and deformation potentially affected the mobility of polar bears. We updated the higher state cutoff values for Foraging Sea Ice < 50 % Absence Change based on Molnar et al. (2020). We also updated two time periods in the Phase III model to modernize the Baseline (1996–2006) and Recent (2012–2021) periods (termed Now and Early Century in the Phase I model, and Recent and Early Century in the Phase II model, respectively), and we retained the Historic and the three future periods as used in the previous models (Table 2).

Table 1

Comparison of three generations of polar bear Bayesian network models. Variables listed here by submodel categories are input nodes parameterized with unconditional prior probability values, and the final outcome node parameterized with conditional probability values. DLP = defense of life and property. Baseline = 1996–2006.

Attribute	Phase I	Phase II	Phase III
Source	Amstrup et al. 2008	Atwood et al. 2016	This study
No. nodes	Input: 17 Summary: 21 Total: 38	Input: 23 Summary: 26 Total: 49	Input: 23 Summary: 27 Total: 50
No. links	44	53	55
No. probability values	1667	2940	2934
Marine prey and conditions submodel inputs	Relative ringed seal availability Alternate prey availability	Ringed seal abundance Bearded seal abundance Secondary and new prey abundance	Same as Phase II
Terrestrial food/ prey and conditions submodel inputs	(not included)	Human provisioned food abundance Terrestrial and marine prey food access Terrestrial refuge quality	Same as Phase II
Event-driven mortality submodel inputs	Intentional takes	Human-bear DLP lethal interactions Hunting mortality (legal) Oil spills, small operational Oil spills, large exploratory Other events (lethal effects)	Human-bear DLP lethal interactions Hunting mortality (legal) Oil spills, small Oil spills, large Other events (lethal effects)
Anthropogenic stressors submodel inputs	Bear-human interactions Oil and gas activity Shipping Tourism Hydrocarbons/ oil spill Contaminants	Human-bear sub-lethal interactions Oil, gas, and mining activity Shipping Tourism Hydrocarbons/oil spill Contaminants	Same as Phase II
Other biotic stressors submodel inputs	Parasites and disease Predation	Same as Phase I	Same as Phase II
Polar bear population outcome	Overall Population Outcome: - larger - same as now - smaller - rare - extinct	Influence on Population Trend: - increased - same as recent - decreased - greatly decreased	Relative Influence on Population Trend: - increased - same as baseline - decreased - greatly decreased

Our review of the literature since 2015 on polar bear population genetics and behavior and sea ice dynamics also led to our retaining use of the four ecoregions as delineated in the Phase I and Phase II models. Knowledge about sea ice drift and ocean circulation dynamics continued to justify the delineation of two Arctic Basin ecoregions where, during summer in the Polar Basin Divergent Ice Ecoregion (which includes the

Table 2

Source material and model structure for arctic sea-ice projections used in three generations of polar bear Bayesian network models. See Table 1 for cited sources.

Attribute	Phase I	Phase II	Phase III
Time periods modeled	Historic 1985–1995 [a] Now 1996–2006 [a] Early century 2020–2029 Mid-century 2045–2054 Late century 2070–2079 End of century 2090–2099	Historic 1985–1995 [a] Recent 2007–2012 [a] Early century 2020–2030 Mid-century 2045–2055 Late century 2070–2080 End of century 2090–2100	Historic 1985–1995 [a] Baseline 1996–2006 [a] Recent 2012–2021 [a] Mid-century 2045–2055 Late century 2070–2080 End of century 2090–2100
Source for future sea-ice projections	CMIP3 (Meehl et al., 2007)	CMIP5 (Taylor et al. 2012)	CMIP6 (Eyring et al. 2016)
Emissions scenarios included [b]	SRES-A1B (Nakićenović et al. 2000)	RCP 2.6, RCP 4.5, RCP 8.5 (van Vuuren et al. 2011)	SSP 2.6, SSP 4.5, SSP 8.5 (Tebaldi et al. 2021)
GCM sea ice projections [c]	10 CMIP3 GCMs used	13 CMIP5 GCMs used	12 CMIP6 GCMs used
Sea ice submodel inputs [d]	a. Foraging habitat quantity change b. Shelf distance change c. Foraging habitat absence change d. Foraging habitat character	a. Foraging sea ice area b. Sea ice distance change c. Foraging sea ice < 50 % absence change d. Foraging sea ice quality	Same as Phase II

[a] Time periods in the past for which we used monthly-averaged passive microwave satellite imagery to derive values of sea-ice concentration (Cavalieri et al. 1996). For future time periods, we used projections from CMIP data repositories as noted. Also note that the state "early century" in the Phase I and II models was revised to "recent" in the Phase III model. For all 3 BN model Phases, 1996–2006 was the baseline period against which sea ice changes were quantified for other decades.

[b] SRES = Special Report on Emissions Scenarios, A1B = balanced emissions scenario; RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway.

[c] GCM = Global Circulation Model. CMIPx = Coupled Model Intercomparison Project, x = model generation used. Phase I used the GCM multi-model mean, and the minimum and maximum GCM; Phases II and III used GCM model frequency distributions.

[d] Letters denote equivalent sea ice submodel input variables used across model phases, with altered titles. Variables a, b, and c used GCM ice projections while variable d was based on expert judgment.

Barents, Kara, Laptev, Chukchi, and Southern Beaufort Seas), sea ice pulls away from the shore, whereas in the Polar Basin Convergent Ice Ecoregion (which includes the Northern Beaufort Sea and East Greenland polar bear populations, and the Queen Elizabeth region that connects them) sea ice converges toward the shore; and sea ice completely melts during summer in the Seasonal Ice Ecoregion (which includes Davis Strait, Baffin Bay, Foxe Basin, southern and western Hudson Bay), and sea ice is constrained geographically by fjords, bays, islands, and channels in the Archipelago Ecoregion (which includes Gulf of Boothia, M'Clintock Channel, Lancaster Sound, Viscount-Melville Sound, Norwegian Bay, and Kane Basin). We also reviewed the status of polar bear population and subpopulation units as evaluated by IUCN and found no evidence to redefine the ecoregion associations. Scharf et al. (2019) analyzed seasonal shifts in sea-ice foraging habitat of polar bears between the Beaufort and Chukchi Seas off northern Alaska, suggesting a separation of subpopulations but not a new delineation or separation of the Divergent Ice Ecoregion per se.

One additional consideration for geographic delineation was based on recent studies of polar bears in specific locations where sea ice melts completely in summer but where calving ice from tidewater glaciers is retained in protected fjords and used by seals, and thereby creates viable habitat that polar bears occupy until the sea ice refreezes. Examples have been noted along the coast of Greenland and in the Svalbard Archipelago of Norway (Aars et al. 2015, Carr et al. 2014, Cowton et al. 2018, Laidre and Stirling 2020, Laidre et al. 2022, Lydersen et al. 2014), and similar situations may possibly occur elsewhere (e.g., Nova Zemlya, New Siberian Islands, and Franz Josef Land in Russia). Such locations may provide summer refugia as long as the tidewater glaciers persist. However, because global climate models do not resolve the presence or absence of tidewater glaciers at the heads of ocean fjords, we chose not to delineate broadly distributed specific sites as a fifth polar bear ecoregion.

3.2. Updated sea ice projections and population response

We applied the CMIP6 sea ice projections to our Phase III BN model, producing updates on the relative probability of polar bear population outcome states by time period, GHG emissions scenario, and ecoregion (Fig. 1). Consistent with Phase I and Phase II model results, polar bear populations in all four ecoregions are projected by the Phase III model to incur increasing probabilities of being decreased or greatly decreased, over time and across increasing emissions (SSP2.6, SSP4.5, and SSP8.5). The highest probabilities of decreased or greatly decreased population outcomes were projected for the Polar Basin Divergent Ice Ecoregion, with ≥ 90 % probability by the end of the century under the worst-case emissions scenario (SSP8.5), with the next highest probabilities of decrease for the Seasonal Ice and Polar Basin Convergent Ice Ecoregions, and the lowest probabilities for the Archipelago Ecoregion (Fig. 1, Appendix Fig. C2). Under the SSP8.5 emissions scenario, probabilities of polar bear populations being decreased or greatly decreased from mid- to end-century ranged from about 60 % to over 80 % for the Archipelago Ecoregion, and 80 % to ≥ 90 % for all other ecoregions.

3.3. Comparisons of model performance

We compared results of the Phase III model with CMIP6 sea ice projections to results of the Phase II model with CMIP5 sea ice projections, and also to the Phase II model run with CMIP6 sea ice projections. Among all updates in model structures, sea ice projections, and scenarios, all three model phases separately predicted increasing probability of declines in polar bear populations over time in all four ecoregions.

The relative effects of updating the model structure or updating the sea-ice projections played out differently among the four ecoregions. Compared to the Phase II model using CMIP5 projections, results from the Phase III model using the CMIP6 projections indicated a slightly more dire outcome for polar bear populations during the mid- to end-century in the Archipelago Ecoregion, with higher probabilities of greatly decreased populations in the Archipelago Ecoregion even under the more mitigated SSP2.6 emissions scenario (Fig. 2). However, caution is warranted when comparing BN results based on CMIP5 versus CMIP6 sea ice projections in the Archipelago Ecoregion because many CMIP6 models possessed finer spatial resolution that resolved more of the Archipelago's narrow southern channels which led to the presence of more open water surface (i.e., less polar bear habitat) during summer months compared to the CMIP5 models.

The Phase III model introduced a link from Ecoregion to Overall Terrestrial Conditions to reflect recent research suggesting lower-quality onshore habitat conditions in the Seasonal Ice Ecoregion in the short-term (Appendix Table B2). Model predictions for the Seasonal Ice Ecoregion from the Phase III model were relatively similar to those from the Phase II model. Populations in the Polar Basin Divergent Ice Ecoregion had a high probability of decreased rather than greatly decreased
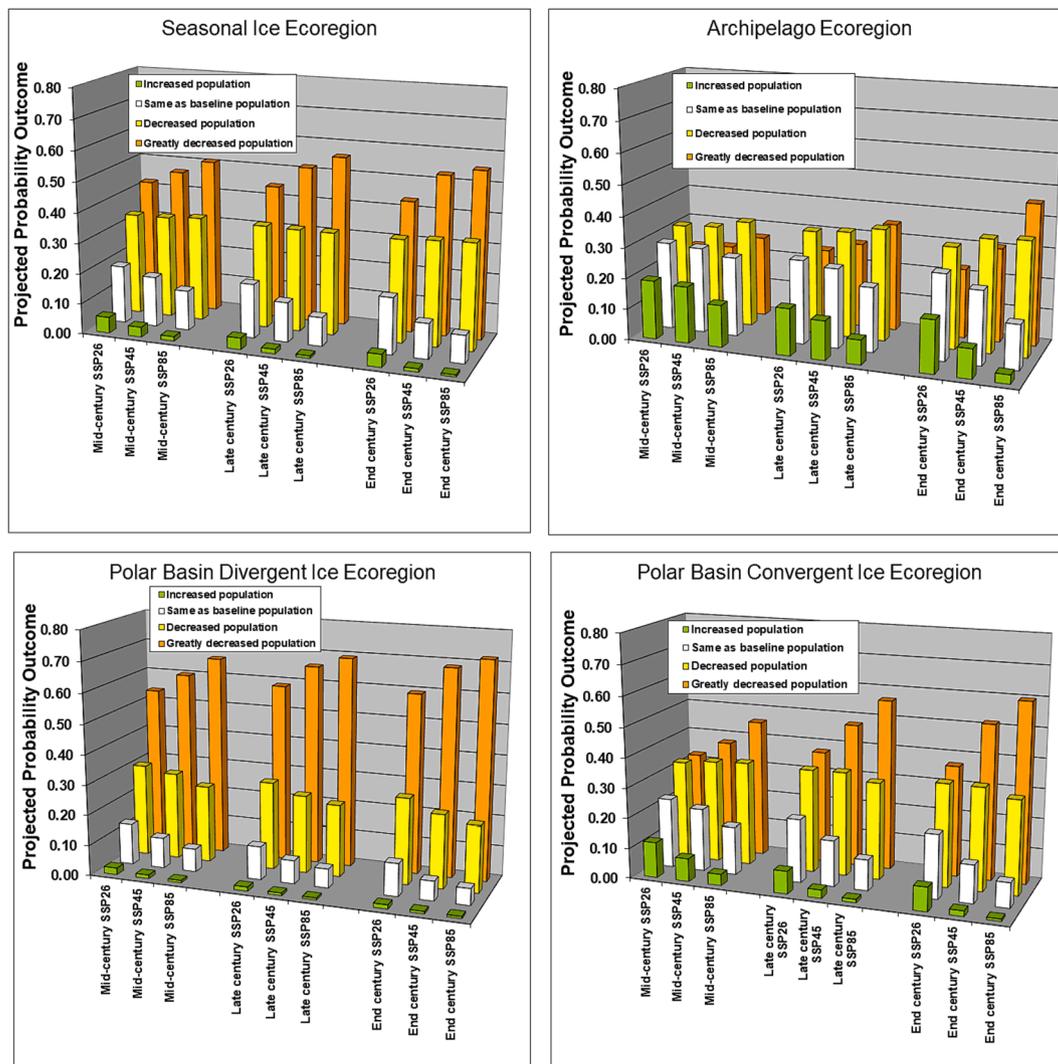
Fig. 1. Projected probabilities of polar bear population outcomes from the Phase III polar bear Bayesian network model (this study) when using CMIP6 (Coupled Model Intercomparison Project Phase 6) sea-ice projections, for four future time periods (see Table 2), under three SSP (Shared Socioeconomic Pathway) greenhouse gas emissions scenarios (2.6, 4.5, 8.5), based on frequency distributions of GCM (global circulation model) outcomes. Greater values denote higher probabilities of four polar bear outcomes (increased, same, decreased, and greatly decreased population) compared to current conditions.

population outcomes, and generally were similar between the two models in the Polar Basin Convergent Ice Ecoregion, with the exception of slightly higher probabilities of being greatly decreased under SSP2.6 (Fig. 2).

Running the Phase II model and comparing its results with CMIP5 and CMIP6 sea ice projections (Appendix Fig. C3) resulted in similar outcomes to running the Phase II and III models with their respective sea ice projections (Fig. 2). This was not unexpected, as most of the recent BN model updates were minor compared with some differences between the sea ice projections. The exception was that the Polar Basin Divergent Ice Ecoregion that showed a greater probability of populations being decreased, and a lower probability of being greatly decreased, in all time periods and SSP scenarios, because of changes in model structure between Phases II and III (Fig. 2) that more explicitly expressed potential use of terrestrial conditions, but showed little difference due to the updated sea-ice projections (Appendix Fig. C3). Overall, however, there was no qualitative change in predicted polar bear population outcomes when running the Phase II model with either the CMIP5 or CMIP6 sea ice projections, as anticipated by Douglas and Atwood (2022).

We compared the results of model sensitivity analyses among all three BN model phases (Appendix Tables B3, B4, B5) to detect possible changes in the degree to which polar bear population predictions were influenced by differences in the model input variables and the general submodel structures. In our current Phase III model, population outcome was most sensitive (mutual information > 0.02) to Foraging Sea Ice Area, Foraging Sea Ice < 50 % Absence Change, Ringed Seal Abundance, and Foraging Sea Ice Quality (Appendix Table B5). In general, most of the sensitivity effect was attributable to the Sea Ice and Ecoregion (Analysis Scenario) submodels, contributing 79 % of sensitivity in the Phase I model and 65 % in the Phase II and III models (Table 3). In the Phase I model, population outcome was next most sensitive to the Anthropogenic Stressors and the Other Biotic Stressors submodels, whereas sensitivity to the Marine Prey and Conditions submodel was greater in the Phase II and III BN models where that submodel was made more explicit. The combined effects of ecoregion, sea ice conditions, and seal and alternative marine prey collectively accounted for 79 % of the sensitivity in Phase I, 83 % in Phase II, and 84 % in Phase III. Lastly, compared with the Phase II model, the Phase III model included greater relative sensitivity to the input variables pertaining to terrestrial conditions and subsequent adult survival effects, and lesser relative sensitivity to marine conditions and recruitment (Fig. 3, Appendix Table B6).
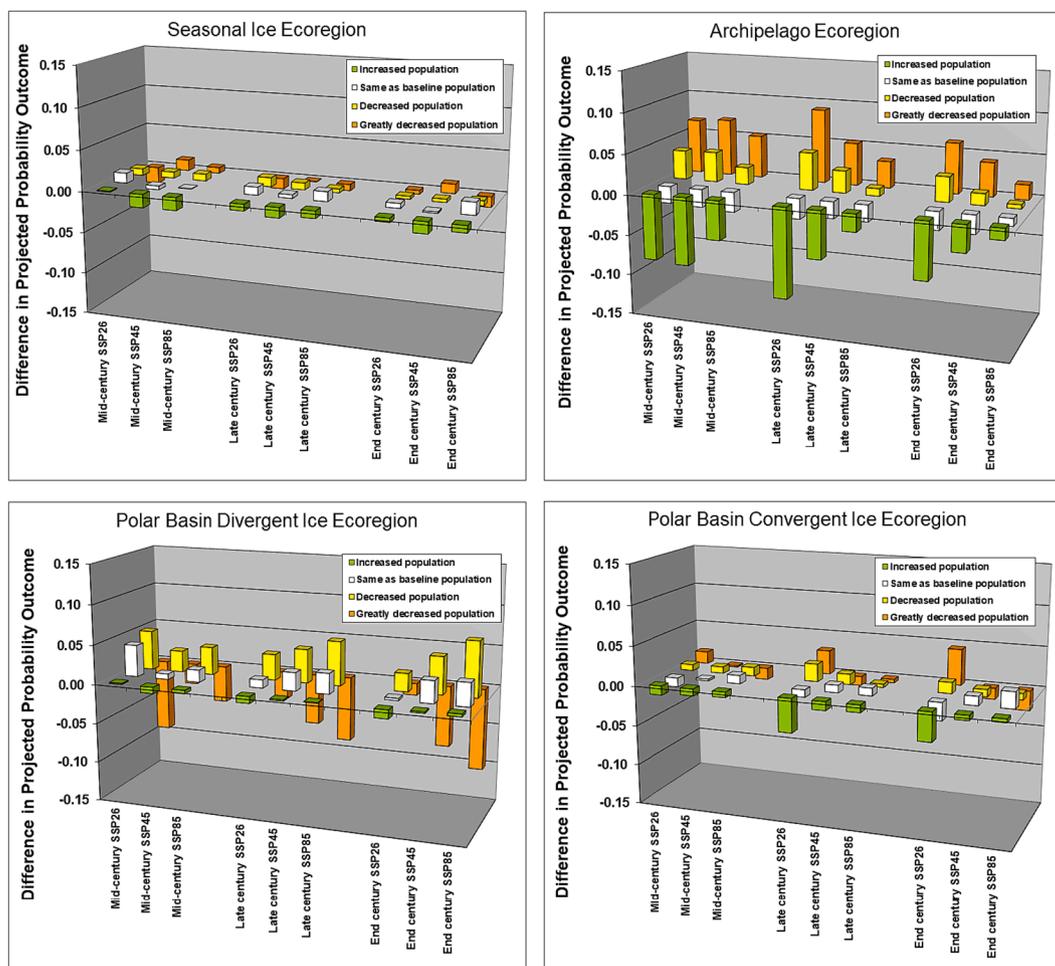
Fig. 2. Differences in projected outcomes of polar bear populations, by ecoregion, time period (see Table 2), and greenhouse gas emissions scenarios, comparing the difference between the Phase III BN model (this study) using CMIP6 sea ice projections and the Phase II BN polar bear model using CMIP5 projections (Atwood et al. 2016), with both model phases using frequency distribution values of the sea-ice projections. Greater values denote higher probabilities of polar bear declines in the Phase III model outcomes than in the Phase II model outcomes. For these comparisons, the CMIP6 emissions scenarios SSP 2.6, 4.5, and 8.5 and the CMIP5 scenarios RCP 2.6, 4.5, and 8.5, were respectively considered analogs.

Table 3

Comparison of general sensitivity analysis of submodel components among three phases of polar bear Bayesian network models (see Table 1 for submodel variables and sources). Values are the overall percent of mutual information sensitivity of specific variables within each submodel.

Submodel	Phase I	Phase II	Phase III
Sea ice and ecoregion	79 %	65 %	65 %
Marine prey and conditions	0.4 %	18 %	19 %
Anthropogenic stressors	11 %	3 %	3 %
Other biotic stressors	10 %	14 %	12 %
Total sensitivity	100 %	100 %	100 %

4. Discussion

As a general lesson and as demonstrated with our incremental polar bear BN modeling evolution, it can be critical to intermittently review model structures, and redo analyses with updated input variables, based on new ecological research and new climate model projections. Attending to model evolution helps update and revise knowledge and expectations of species status, particularly when models are used in listing decisions of at-risk species. Reviewing recent research findings and revising models accordingly also serves to document knowledge discovery and the implications of uncertainty, and helps identify key priorities for future inventory, monitoring, and research to reduce main sources of uncertainties.

Bayesian network models of the type we have described here are necessarily broad in geographic scope, particularly when projecting species response at ecoregional scales. This has the advantage of evaluating environmental conditions (and impending changes) and projecting population response across broad scales of space and time. However, such outcomes cannot be used to predict site-specific responses, for example when storm conditions might force polar bears ashore and into suboptimal habitat conditions (e.g., Kellner et al. 2023). Nor are our models intended to inform demographic viability analyses that require far more detailed focus on the influence of environmental factors on body condition, denning success, and more (e.g., Atwood et al. 2021, Bromaghin et al. 2021, Molnár et al. 2020, Rode et al. 2018b). Further, sensitivity analysis results should be interpreted as representing the relative expected or known influence of covariates and stressors, as well as the degree of uncertainty about the influence of those factors. One way to help determine the potential role of such uncertainty would be to vary the factors' influence by modifying their conditional probability table values in the model within reasonable ranges of values (that could be prescribed by expert knowledge), and observe the degree to which such variations could influence model outcomes. Such further analyses are beyond the scope of this paper, but we suggest this as a possible method.

Still, to evaluate the pertinence of existing models, including BN models and other model forms, and to guide and document model
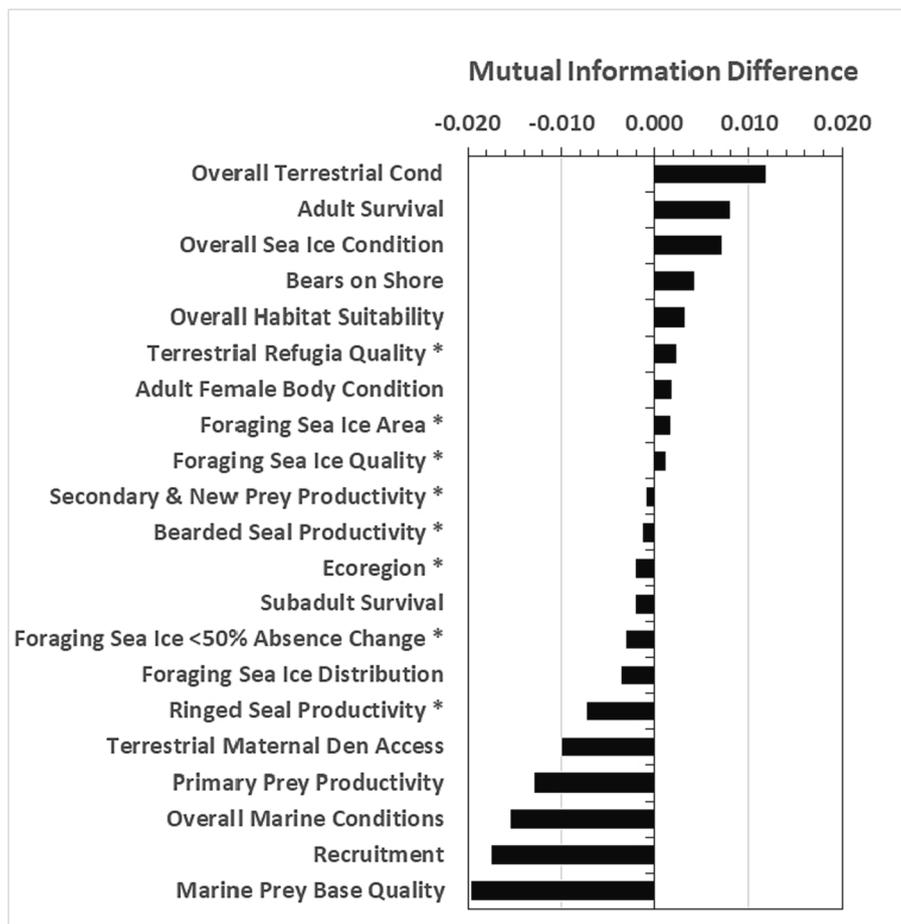
Fig. 3. Changes in sensitivity (mutual information) of variables used in the polar bear Bayesian network models, between the Phase II (Atwood et al. 2016) model using CMIP5 sea ice projections and the Phase III (current study) model using CMIP6 sea ice projections. Greater values denote higher sensitivity in the Phase III model. Shown are variables with > +0.001 or < -0.001 difference in mutual information values. * = input variables.

updates, we encourage conducting the kind of comprehensive literature review such as what we have provided (Appendix A Model Documentation). Such reviews can help inform appropriate interpretations of model structures and analysis outcomes. One example here involves the risks of using global climate model projections of sea ice in the Archipelago Ecoregion, which showed some of the greatest changes between the CMIP5 and CMIP6 models. In this case, several CMIP6 models provided higher spatial resolution of fjords farther south that melt during summer in that ecoregion (Douglas and Atwood 2022). Because size of the Archipelago is small and dominated by land relative to the three other ecoregions, the differences in spatial resolution between CMIP5 and CMIP6 models may have biased the comparisons we have presented and should be treated with caution.

What will the next iteration of polar bear research and sea ice projections reveal? As recognized by Amstrup et al. (2008) in the Phase I model, most climate models (across all CMIP generations) simulate contemporary sea ice losses at a slower rate than what has been observed (Kim et al. 2023, Stroeve et al. 2007, Rantanen et al. 2022, Rode et al. 2022). This tendency of "faster than forecasted" extends also to the opening of trans-arctic shipping routes (Cao et al. 2022) as a potentially increasing anthropogenic stressor on polar bears; to trends in increasing terrestrial temperatures (van Oldenborgh et al. 2009) that might affect onshore polar bears; and to much more. This tendency of model predictions lagging behind actual rates of change has held true through the subsequent polar bear modeling phases reviewed here, although the latest generation of models in CMIP6 do better at simulating contemporary trends in sea ice melt (Notz and SIMIP_Community, 2020). We anticipate that, although this "faster than forecasted" misalignment may

be resolved in subsequent model generations, an important question will likely persist regarding the degree of climate inertia that could continue adverse trends, at least until such time that global emissions of greenhouse gases could slow and eventually stop the current cascade of climate and other stressors.

The incremental evolution of models such as these can be used to portend stressors on polar bear (and other) populations that can help reveal research needs. For example, Atwood et al. (2016 Table 1) identified six research needs from the Phase II modeling effort regarding threats to polar bear conservation and to reduce model uncertainties. Their list included research information needs pertaining to threats of global warming-induced fragmentation and loss of sea ice habitat, and threats of human activities. Research has progressed on at least 4 of the 6 major topics listed by Atwood et al. (2016), including: quantifying the effects of habitat fragmentation and loss on polar bear movement and energetics (Pagano et al. 2020); evaluating the potential for cumulative exposure to local and transported pollutants, contaminants, and pathogens to impact fitness (Atwood et al. 2017); identifying the factors that increase the risk of human-polar bear conflict and determining the potential for cumulative lethal removals (legal harvest, illegal harvest, and defense of life kills) to adversely impact populations (Atwood and Wilder 2021, Wilder et al. 2017); and determining the potential for industrial and recreational activities to influence suitability of terrestrial habitats (Rode et al. 2018a; Wilson and Durner 2020). The key point is that the Phase II polar bear model was used for multiple purposes including a gap analysis to help inform and prioritize new research. In a similar example, the BN models used to evaluate stressor effects and to project future population conditions of Pacific walrus (*Odobenus*

rosmarus divergens) were also used to identify and prioritize key uncertainties and information needs that guided subsequent research activities (Jay et al. 2011).

5. Conclusion

We revised a Bayesian network model to update projected 21st century polar bear population outcomes based on recent research findings on the species and newer Arctic sea ice projections by global climate models. Our current findings largely corroborate previous findings, suggesting probabilities of decreased or greatly decreased population levels over the next 75 years, with the worst outcomes occurring under scenarios of high greenhouse gas emissions and possibly for the Archipelago Ecoregion.

Our results continue to suggest key stressor effects from diminishing quantity and quality of sea ice, and its secondary effects on key prey species and on forcing polar bears ashore into suboptimal environments. Consequences to polar bears are most dire under the higher fossil-fuel-based development scenarios (particularly SSP8.5), as supported by previous findings. Our updates suggest that, in general, polar bear populations are as or more at risk than previously projected, and that these risks vary by ecoregion. We suggest continued model evolution to re-evaluate population predictions, especially as new research findings on the species, sea-ice, and climate-change projections become available.

CRediT authorship contribution statement

Bruce G. Marcot: Conceptualization, Methodology, Writing – original draft. **Todd C. Atwood:** Methodology, Writing – review & editing. **David C. Douglas:** Methodology, Writing – review & editing. **Jeffrey F. Bromaghin:** Methodology, Writing – review & editing. **Anthony M. Pagano:** Methodology, Writing – review & editing. **Steven C. Amstrup:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The polar bear Bayesian network model and case file data are available at: https://doi.org/10.59381/qkfmbhxrbx.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111130.

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APPENDIX A. Documentation of the revised polar bear Bayesian network model projecting population outcomes under anthropogenic and climate stress.

for: Marcot, B. G., T. Atwood, D. C. Douglas, J. F. Bromaghin, A. M. Pagano, and S. C. Amstrup. Submitted. Incremental evolution of modeling a prognosis for polar bears in a rapidly changing Arctic. for: Ecological Indicators

Acronyms used:

Ecoregions
SEI = Seasonal Ice Ecoregion
AE = Archipelago Ecoregion
PBDE = Polar Basin Divergent Ice Ecoregion
PBCE = Polar Basin Convergent Ice Ecoregion

Sea ice modeling
GCM = Global Circulation Model
SSP = Shared Socioeconomic Pathway
CMIP = Coupled Model Intercomparison Project

Polar bear elements
DLP = defense of life and property
HPF = human-provisioned food

Polar Bear Bayesian Network Submodels

[1] Analysis scenario
[2] Sea ice submodel
[3] Marine prey and conditions submodel
[4] Terrestrial food/prey and conditions submodel
[5] Overall habitat suitability submodel
[6] Event-driven mortality submodel
[7] Anthropogenic stressors submodel
[8] Other biotic stressors submodel
[9] Demographic submodel
[10] Polar bear persistence submodel

Node Name Node Title [Submodel]	Node Description	States
	Input Nodes	
RSProd Ringed Seal Productivity [3] Marine prey and conditions submodel	This node expresses the observed and expected relationship between sea ice coverage and phenology and seal productivity. For example, evidence suggests that earlier spring break-up of sea ice in western Hudson Bay was related to declining pup survival (Ferguson et al. 2005). Declining sea ice likely will directly reduce the availability of birthing and haul-out habitat for seals. Earlier break-up also may adversely impact pup survival by interrupting the lactation period. Ringed seals have the longest lactation period of the Phocidae and need stable ice until neonates are weaned (Lydersen and Kovacs 1999). Decreased snow cover is a primary threat to Arctic ringed seals (Kelly et al. 2010). Projections show that as spring snow declines, pup survival is likely to decline (Iacozza and Ferguson 2014). Ringed seals at the core of their range show declines in condition with later spring breakup and shorter open water season (Ferguson et al. 2020). There was a gradual decline in ringed seal density from 1995 to 2013 in Hudson Bay (Ferguson et al. 2017). Projections show median declines in population size of ringed seals in Amundsen Gulf and Prince Albert Sound, ranging from 50% to 99% by 2100 (Reimer et al. 2019). Harwood et al. (2020) reported long-term declines in ringed seal body condition in Amundsen Gulf. Ringed seals in Bering and Chukchi Seas were reported to grow faster and have thicker blubber, and females matured earlier in 2003 to 2012 compared to 1975 to 1984 (Crawford et al. 2015). There is concern that snow accumulation on ice is declining and limiting opportunities for ringed seals to construct birthing lairs (Huntington et al. 2016). In some areas, declines in sea ice may improve biological productivity, which may benefit seals in the near-term. Earlier breakup of ice may benefit ringed seals via influencing quality of food during the open water season (Nguyen et al. 2017). Insley et al. (2021, Arctic 74:131) found increasing presence of subarctic prey (borealization) in stomachs of ringed seals from Amundsen Gulf. However, increased primary productivity will be greatest during summer (after break-up) and benefits may be mitigated by reduced biomass in coastal/shelf area due to increased river runoff and associated changes in turbidity and salinity (e.g., Bluhm and Gradinger 2008).	Elevated Same as Baseline Reduced
BSProd Bearded Seal Productivity [3] Marine prey and conditions submodel	This node expresses changes in bearded seal productivity that are likely to occur as sea ice cover declines and its character changes. Bearded seals are believed to have a patchy distribution throughout their range. Because of this, encounter rates with polar bears likely are lower than for ringed seals. However, bearded seals are considerably larger than ringed seals, so biomass consumed by polar bears is not inconsequential. For example, Pilfold et al. (2012) reported that bearded seals contributed 33% to the overall prey biomass of polar bears in the Beaufort Sea.	Elevated Same as Baseline Reduced

Node Name Node Title [Submodel]	Node Description	States
	Bearded seals prefer drifting pack ice over shallow water/coastal areas. Because of this, they may be more vulnerable to reductions in biomass in coastal areas due to increased river runoff and associated changes in turbidity and salinity (e.g., Bluhm and Gradinger 2008). Indigenous knowledge suggests inland water bodies and terrestrial habitat may become more important as sea ice declines (Gryba et al. 2021). Bearded seals in the Bering and Chukchi seas were reported to have slightly thicker blubber, and females matured earlier in 2003 to 2012 compared to 1975 to 1984 (Crawford et al. 2015). The association of bearded seals with the sea ice edge suggests that bearded seal habitat will shift spatially further north as the climate warms (Breed et al. 2018), although ice far off the shelf is not good habitat for a primary benthic feeder. Indigenous knowledge indicates that some bearded seals have thinner blubber in recent years in Alaska (Huntington et al. 2016). Juvenile bearded seals have changed sea ice preferences over time from ice edges to habitat interior from the edge where suitable ice concentration still exists (Olnes et al. 2021).	
MrnPryOth Secondary and New Prey Productivity [3] Marine prey and conditions submodel	This node expresses changes in the productivity of secondary prey that are likely to occur as sea ice cover declines and its physical character changes. Secondary prey can include beluga whales, harp seals, hooded seals, spotted seals, ribbon seals, and other marine mammals (e.g., Atlantic walrus is predated in eastern Canada; Galicia et al. 2016). For example, as pack ice becomes less available in the Bering Sea, ribbon seal range likely will expand northward to maintain access to pack ice during the birthing period (Lowry and Boveng 2009). Likewise, spotted seals regularly haul out on shore and are less reliant on sea ice, and may expand northward as summer ice cover declines (Kovacs et al. 2011). Florko et al. (2018) reported an increase in harbor seal abundance in western Hudson Bay as sea ice coverage declined. Last, ribbon, harp, and hooded seals can spend long periods pelagically in areas without ice (Kovacs et al. 2011), making them somewhat resilient to loss of sea ice habitat. As summer ice melts more extensively in the Archipelago Ecoregion, it is reasonable to expect that alternate prey species may venture deeper into that region and provide at least a transient improvement in prey availability. An increase in prey diversity is expected to result in increased polar bear abundance, conditioned on the conservation of sea ice habitat (Hamilton and Derocher 2019). It is unclear, however, that such changes could persist as bears are forced onto smaller and smaller areas of ice. Although some species are expected to become more abundant regionally, without a sea ice hunting platform the overall availability of prey to polar bears may not increase.	Elevated Same as Baseline Reduced

IceArea Foraging Sea Ice Area [2] Sea ice submodel	This node expresses the proportional change in the area of polar bear habitat over time and is derived from the satellite passive microwave record for the observational period, and from GCM outputs of sea ice for the future periods (SSP2.6, SSP4.5 and SSP8.5 forcing). Habitat is expressed as the number of square kilometer months of optimal habitat (i.e., ice-covered areas with <300 m bathymetry, higher ice concentration, and closer to land) (Durner et al. 2009) in the two polar basin ecoregions (PBDE and PBCE), and as square kilometer months of ice within the other ecoregions (AE and SIE, which are essentially all shelf; see Amstrup et al. 2008). Because the AE and SIE are almost entirely shallow water areas, the 'optimal' habitat in those areas equates to essentially the ice extent months for each region. We further expressed this as the average percent change in quantity of these ice habitats, from the 1996–2006 baseline period to the projected future period of interest. For all future time periods, the 1996–2006 baseline calculation used GCM outputs from the historical forcing experiment (i.e., model simulations of sea ice conditions at the turn of the century). Hence the change in this metric was calculated for each GCM model (under each scenario SSP2.6, SSP4.5 and SSP8.5) relative to itself (under the historical forcing). Changes calculated entirely within the period of observations were derived from the satellite passive microwave record of sea ice (Cavalieri et al. 1996). While there is increasing evidence (e.g., Durner et al. 2019, Pagano et al. 2020, Kellner et al. 2023) of bears exploiting low concentration sea ice for short periods, there is no evidence as of yet to suggest population-level benefit to that behavior. Interpreting the percent difference must take into account that a given percent change may not be directly comparable between ecoregions. The absolute change in the AE, for example may be very small, but because it is measured from essentially 0, it may seem like a large percentage.	>= 0 -5 to 0 -10 to -5 -20 to -10 -40 to -20 < -40 (proportional change)
IceQual Foraging Sea Ice Quality [2] Sea ice submodel	This node expresses a subjective assessment of the quality of sea ice for foraging by polar bears. Observations of the changes in sea ice characteristics in several Arctic seas and regions (e.g., southern Beaufort and Chukchi Seas [Mahoney et al. 2012], and Hudson Bay [Gagnon and Gough 2005; also see Kwok 2018, Sahanatien and Derocher 2012, Bateson et al. 2019]) 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 (Fischbach et al. 2007; Merkel and Aars 2022), increased movement tortuosity (Biddlecomb et al. 2021), and may have reduced its quality as a foraging substrate because the extensive ice deformation can result in ice covered refugia for ringed seals that are difficult for polar bears to get into. Observations of attempted predation on ringed seals by polar bears in the southern Beaufort Sea may signal changes in spring ice conditions (Stirling et al. 2008). However, very thick and dense ice in the AE and the northern part of the PBCE may limit access to prey, and foraging ice quality might first improve with global warming and then decline. For example, in Kane Basin, the transition from historically thick multi-year ice to thinner ice resulted in range expansion and better body condition of bears (Laidre et al. 2020). In M'Clintock Channel, local sea ice changes may have resulted in a transient benefit to the subpopulation via an increased	Elevated Same as Baseline Reduced

	biological productivity (Dyck et al. 2021). However, Florko et al. (2021) reported there was no evidence of improved foraging conditions for the Viscount Melville subpopulation.	
IceShelf Sea Ice Shelf Distance Change [2] Sea ice submodel	This metric expresses the distance (in kilometers) that the summer ice retreats from traditional autumn/winter foraging areas, which are over the continental shelves and other shallow water areas within the polar basin. It was calculated by extracting the largest contiguous expanse of pack ice whose pixels have >50 percent concentration and calculating the mean of the linear distances between all pixels in the shelf waters to the nearest pack ice during the month of minimum non-zero ice extent. It was expressed as the difference between this mean distance, averaged for the period 1996–2006, and the average distance as calculated for other time periods of interest. For all future time periods, the 1996–2006 baseline calculation used GCM outputs from the historical forcing experiment (i.e., model simulations of sea ice conditions at the turn of the century). Hence the calculated change in this metric was calculated for each GCM model (under each scenario SSP2.6, SSP4.5 and SSP8.5) relative to itself (under the historical forcing). Changes calculated entirely within the period of observations were derived from the satellite passive microwave record of sea ice (Cavalieri et al. 1996). The metric was derived only for the polar basin regions (PBDE and PBCE) because polar bears in the AE and SIE typically go to shore when the summer ice retreats, as opposed to retreating with the ice as bears in the polar basin tend to do. The distance that summer ice retreats northward into the polar basin largely dictates the energy required to swim between land and remnant summer pack ice (Pagano et al. 2020). States are discretized ranges of the continuous variable, measured as kilometers.	< 0 0 to 200 200 to 500 500 to 800 >= 800 (kilometers)
IceChng Foraging Sea Ice <50% Absence [2] Sea ice submodel	This node expresses the length in months of reduced ice cover from the continental shelf regions historically preferred by polar bears. The metric was the number of months during which the continental shelf had reduced sea ice habitat, defined as <50 percent of the shelf area having ice cover with >50 percent ice concentration (based on research indicating a preference by polar bears for areas covered by >50% sea ice concentration; Durner et al. 2009). Any reference to this condition being "ice-free" is meant to describe reduced preferred polar bear habitat and not necessarily the complete absence of sea ice (Douglas and Atwood 2022) and is not equivalent to the length of the "open water season" and fasting duration. The metric expresses the difference in months between the forecasted number of months with reduced foraging habitat for future time periods and the number of months as calculated for the baseline period 1996–2006. For all future time periods, the 1996–2006 baseline calculation used GCM outputs from the historical forcing experiment (i.e., model simulations of sea ice conditions at the turn of the century). Hence the calculated change in this metric was calculated for each GCM model (under each scenario SSP2.6, SSP4.5 and SSP8.5) relative to itself (under the historical forcing). Changes calculated entirely within the period of observations were derived from the satellite passive microwave record of sea ice (Cavalieri et al. 1996).	< 0 0 to 1 1 to 2 2 to 4 4 to 6 >= 6 (months)

	Polar bears in some regions already experience ice free periods. The impact of the length of the ice-free period is dependent mainly on the productivity of the environment and the availability of refugia habitat (such as terrestrial habitat free from human disturbance) and alternative food resources, and has a different impact in the Beaufort Sea, for example, than it does in the SIE, which is relatively productive. Differential impacts can also occur between subpopulations within the same ecoregion. For example, in the PBDE, the ice-free period in the Chukchi Sea subpopulation has increased substantially, but no adverse impacts to body conditions (Rode et al. 2021) or population dynamics have been observed (e.g., Regehr et al. 2018) because of the much higher productivity in the Chukchi. The length in months of reduced ice habitat expressed in the conditional probability table must be interpreted with regard to the fact that in large parts of these areas even at a mean 1–3 months of increased ice absence, actual absence in some parts of these regions would still be 0. An absence difference of >3 months means a mean absence of 4 or 5+ months in the PBDE, and 7, 8, or 9+ months in the SIE, but only 3+ months in portions of the AE or PBCE.	
HumFood Human Provisioned Food Availability [4] Terrestrial food/prey and conditions submodel	This node expresses the availability of human-provisioned food (HPF) and can include remains from harvest of whales, other marine mammals, and other game. We note that the availability of HPF will vary between ecoregions and subpopulations in ecoregions. This node also can refer to other organic refuse or food sources for polar bears, including food present at garbage dumps near settlements. The availability of HPF is most pertinent during summer and autumn months when many bears are on land, as that is likely when the biggest nutritional contribution is realized (Herreman and Peacock 2013). This node is mostly relevant to a few subpopulations in the PBDE (Southern Beaufort Sea; Wilson et al. 2017, Lillie et al. 2018) and the SIE (Western Hudson Bay; Heemskerk et al. 2020).	Elevated Same as Baseline Reduced Absent
PryAcc Terrestrial Prey and Food Accessibility [4] Terrestrial food/prey and conditions submodel	This node expresses the availability of terrestrial prey and other food resources, including scavenge subsidies (other than human-provisioned) on land. Food resources could include Arctic char (*Salvelinus alpinus*), bird colonies, berries, vegetation, seaweed, caribou, geese, beach cast marine prey (e.g., seal carcasses that wash ashore). There is evidence in the literature that polar bears have historically exploited terrestrial-based foods. For example, Laidre et al. (2018) surmised that scavenging on beached whale carcasses likely facilitated survival of bears in past interglacial periods, and Galicia et al. (2016) reported polar bears in Foxe Basin now have greater access to bowhead whales killed by orcas that have expanded their range northward. There also is some evidence that use of terrestrial-based food is increasing in some ecoregions (e.g., Born et al. 2011; Iverson et al. 2014). In general, the availability of terrestrial food may facilitate use of terrestrial habitat when sea ice habitat is unavailable. However, we note that in most cases, terrestrial food is not available in sufficient quantity or nutrient content to mitigate declines in body condition associated with bears foregoing foraging on marine mammal prey (Rode et al. 2015). Last, Florko et	Elevated Same as Baseline Reduced Absent

	al. (2021) projected a 50% decline in Arctic cod through the end of the century under a high (RCP 8.5) GHG emission scenario, which will likely adversely affect the availability of some marine prey and increase the importance of access to alternative foods.	
TerrRef Terrestrial Refugia Quality [4] Terrestrial food/prey and conditions submodel	This node characterizes stability in structure and freedom from human and natural disturbance of a place where polar bears can wait out the ice-minimum period, avoiding excessive expenditure of energy. The characterization includes quality of sites used for terrestrial non-maternal denning, summertime denning (i.e., non-maternal), resting, and unobstructed movement. Refugia quality can be compromised by erosion, fire (e.g., peat ridges adjacent to Hudson Bay), reduction in consolidated glacial ice or retraction of glaciers, and the presence of anthropogenic infrastructure that inhibits movement and/or use of an area. We note that terrestrial refugia is most important for the SIE, where use of terrestrial habitat has long been a life history characteristic, and the PBDE, where use of terrestrial habitat is becoming more common (Rode et al. 2022). Degradation of refugia quality by coastal erosion is a threat for the PBDE, as is the presence of anthropogenic infrastructure. However, Rode et al. (2018) reported that fewer than 10% of subpopulations are currently exposed to human recreational activities likely to result in disturbances. Last, reduction of consolidated glacial ice and/or glacial retraction is a threat in parts of the SIE, and possibly the AE in the future (Laidre et al. 2022).	Improved Not Degraded Degraded
HumPB Human-Bear Sublethal Interaction [7] Anthropogenic stressors submodel	This includes sublethal disturbance that may increase as a result of increased human-bear interactions due to food stressed bears more frequently entering Arctic communities (e.g., Born et al. 2011). Whereas human-polar bear conflict is relatively rare compared to conflict with brown and black bears (Smith and Herrero 2018), there is concern within communities that interactions and conflicts have increased as bears spend more time on land (Schmidt et al. 2022). Sublethal "take" of bears, like disturbance of resting individuals, 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 reduce habitat quality. We believe that bear-human interactions will increase as the ice-minimum season lengthens (Atwood and Wilder 2021).	Elevated Same as Baseline Reduced
OilAcct Oil, Gas, and Mining Activity [7] Anthropogenic stressors submodel	This node characterizes the potential for oil, gas and mining activity to influence the distribution of polar bears. Specifically, it refers to activities and infrastructure that may physically displace bears from habitat that was formerly available to them. Industry plans and agency permitting activities indicate that oil and gas extraction and exploration 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. Industrial activity is expected to be greatest for the near-shore region and along coastlines. Wilson and Durner (2020) reported that unmitigated seismic activity could disturb up to 20% of terrestrial dens. Moreover, Owen et al. (2021) found that sound from some forms of	Elevated Same as Baseline Reduced

	anthropogenic activities can be detected within maternal dens at distances up to and exceeding 1.6 km from the source. Additionally, Larson et al. (2020) found significant probabilities of various sound sources to disturb denning bears, but also reported the 1.6 km activity buffer probably is sufficient to mitigate most disturbance. Last, Wilson et al. (2017) estimated that a "worst case" oil spill could affect 40% of polar bears in the Chukchi Sea, and Fahd et al. (2021) used Bayesian network modeling to demonstrate how an oil spill might impact polar cod populations and cascade up the food chain to high-level predators including polar bears.	
Ship Shipping [7] Anthropogenic stressors submodel	As sea ice extent declines spatially and temporally, it is predicted that shipping in Arctic regions will increase. Cao et al. (2022) report that shipping routes are opening up faster than GCM-based predictions). Increased shipping could lead to direct disturbances of polar bears as well as to increased levels of contamination. The best information available to assess the potential for increased shipping activity relies on climate model projections to determine potential navigability and season duration (e.g., Smith and Stephenson 2013). It is predicted that by mid-century, changing sea ice conditions will enable expanded September navigability for common open-water ships crossing the Arctic along the Northern Sea Route, robust new routes for ice-strengthened ships, and new routes through the Northwest Passage. As a result, shipping activity is likely to affect a portion of all ecoregions. Here, we address only the physical presence of more vessel traffic. Lomac-MacNair et al. (2019) reported on seal and polar bear response to an icebreaker vessel in northwest Greenland, and Lomac-MacNair et al. (2021) noted polar bear response to vessel surveys in northeastern Chukchi Sea. Contamination (e.g., bilge, oil, wastewater), 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. Though it is important to note that iron ore shipping traffic in Baffin Bay (originating from iron ore mines on Baffin Island) will traverse ringed seal hotspots and has the potential to separate mother and pups, destroy birthing lairs, and result in collisions (Yurkowski et al. 2018) We note that shipping likely will increase in the foreseeable future. That said, there may be variability in the distribution of shipping activity based on route availability and efficiencies made as trans-Arctic shipping becomes more common. For example, 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.	Elevated Same as Baseline Reduced
Tour Tourism [7] Anthropogenic stressors submodel	As sea ice extent declines spatially and temporally, access and opportunities for Arctic tourism also will increase (Peacock et al. 2010). We define tourism as including activities centered on polar bears, such as recreational viewing, as well as general recreational travel throughout polar bear habitat. 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). We believe that tourism will increase in all areas of the Arctic through the foreseeable future. However, currently	Elevated Same as Baseline Reduced

	half or less respondents to a survey about the potential for anthropogenic activities to affect polar bears thought recreation was currently a negative impact (Rode et al. 2018).	
OilSpill Hydrocarbons, Oil Spill [7] Anthropogenic stressors submodel	This node refers to the release of oil or oil related products into polar bear habitat, defined here only as nonlethal and displacement effects, including mortality of prey (Fahd et al. 2021). Hence, it has ramifications for both habitat quality and population dynamics directly. Hydrocarbon exploration and development are expanding and proposed to expand further in the Arctic. Greater levels of such activity are most likely to increase the probability of oil spills. Increased shipping may result in higher levels of hydrocarbons released into Arctic waters.	Elevated Same as Baseline Reduced
Cont Contaminants [7] Anthropogenic stressors submodel	This node reflects the possible increase or decrease of contamination in the Arctic because of modified pathways. Contaminants can act to make habitat less suitable and directly affect survival, endocrine and immune system function, lipid metabolism (Morris et al. (2019), and reproduction. Effects of contaminant exposure to polar bears have been reviewed (Dietz et al. 2022; Morris et al. 2022; Routti et al. 2018, 2020). Increased precipitation and glacial melt have recently resulted in greater influx of contaminants into the Arctic region from the interior of Eurasia through large northward flowing rivers. Melting of multi-year ice has released previously bound contaminants into the environment (Ma et al. 2011). Similarly, differing atmospheric circulation patterns have altered potential pathways for contaminants from lower latitudes (Dastoor et al. 2022), which may result in exposure to "new" (for polar bears) contaminants. For example, Liu et al. (2018) reported "hundreds" of new pollutant analytes detected in polar bear serum. 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. Last, we acknowledge that contaminant exposure may also vary relative to feeding behavior and that as diets change, so may contaminant concentrations in polar bears (e.g., McKinney et al. 2017).	Elevated Same as Baseline Reduced
DLP Human-Bear DLP Lethal Interactions [7] Anthropogenic stressors submodel	This node expresses change in the occurrence of human-bear DLP (defense of life and property) interactions over time. These interactions result in death, as when problem bears are shot in defense of life and property. Human-bear DLP interactions are a concern throughout the polar bear's range and we believe that bear-human interactions will increase as summer sea ice extent declines (e.g., Heemskerk et al. 2020). We recognize that there is growing concern over the perceived increase in the frequency of human-polar bear conflict as land use by bears has increased (Schmidt et al. 2022). That said, human-polar bear conflict is currently low compared to conflict with black and brown bears (Smith and Herrero	Elevated Same as Baseline Reduced

	2018), and the occurrence of fatal interactions between humans and polar bears is considered to be low (Wilder et al. 2017). The Polar Bear Alert Program in Churchill, Manitoba provides a non-lethal example of methods to mitigate human-bear DLP (Atwood and Wilder 2021). However, there are regions in the Arctic where DLPs have increased, for example in Arviat, Nunavut and Kaktovik, Alaska (Smith et al. 2022).	
Hunt Hunting Mortality [6] Event-driven mortality submodel	This node represents direct mortality from legal hunting alone and includes subsistence use. These sources of mortality are controllable by regulation. We expect hunting mortality to occur for the foreseeable future across polar bear range where hunting is legal. This is based on the importance of subsistence harvest to Native communities and the recognition by many management authorities that it is important to maintain subsistence harvest as long as possible. Vongraven et al. (2022) conducted a thorough analysis of long-term, range-wide harvest data and found that in the last 5-10 years monitored subpopulations all had harvest rates near sustainable limits.	Elevated Same as Baseline Reduced
OilOpn Oil Spills, Small [6] Event-driven mortality submodel	This node refers to the occurrence of oil spills of limited spatial extent that would result in mortality of bears directly affected by oiling. Oiling has been shown to reduce the ability of polar bears to thermoregulate (Hurst et al. 1991) and ingestion of oil by polar bears is lethal (Hurst and Øritsland et al. 1982). There is some indication that activity by smaller operators is increasing in parts of the PBDE. Spills from small operations are expected to be relatively small in volume (e.g., < 6,000 barrels; Amstrup et al. 2006a) and limited in spatial scale and present a risk at the scale of a proportion of a subpopulation. Wilson et al. (2018) estimated that a "medium density" oil spill could affect 20% of polar bears in the Chukchi Sea. Polar bears are often distributed over the continental shelf and other shallow waters, areas that overlap oil extraction activities. Because of this overlap, polar bears are at risk of being exposed to oil spills. Although this node primarily considers immediate, acute lethal effects on polar bears, we also acknowledge that the effects of an oil spill could persist for an extended period (i.e., multiple years, given the ice formation-thaw cycle). We also note that exposure to oil and related products could have sublethal effects, which are accounted for in a separate node.	Elevated Same as Baseline Reduced
OilExp Oil Spill, Large [6] Event-driven mortality submodel	This node refers to the occurrence of oil spills that have the potential to be large in spatial scale. Although the risk of a spill is diminished from that of small-scale operators, if a spill were to occur, it could be catastrophic. A catastrophic spill would present a risk at the scale of ≥ 1 subpopulation. Wilson et al. (2018) estimated that a "worst case" oil spill (e.g., 25,000 barrels at an uncontrollable flow rate) could affect 40% of polar bears in the Chukchi Sea. As with the "small" node, this node specifically considers the risk of the release of oil or oil related products into polar bear habitat that would result in mortality of bears directly affected by oiling. Although this node primarily considers immediate, acute lethal effects on polar bears, we also acknowledge that the effects of an oil spill could persist for an extended period (i.e., multiple years,	Elevated Same as Baseline Reduced

	given the ice formation-thaw cycle). We also note that exposure to oil and related products could have sublethal effects, which are accounted for in a separate node. For a large spill, such effects are expected to persist for decades, similar to the *Exxon Valdez* (Peterson et al. 2003). We assumed that a catastrophic spill could oil a significant proportion of one or more subpopulations and have persistent (i.e., multi-year) lethal effects due to oil being bound and re-released as part of the freeze-thaw cycle of sea ice.	
OthMor2 Other Events (Lethal Effects) [6] Event-driven mortality submodel	This node refers to the likelihood of mortality from various sources, including illegal killing, drowning, den failure, and management and research activities. Because there is little data on cause-specific mortality of polar bears, the probabilities for this node were developed based on expert understandings of polar bears and their ecosystem. Unmitigated seismic activity could disturb up to 20% of terrestrial dens, a proportion of which could result in mortality (Wilson and Durner 2020).	Elevated Same as Baseline Reduced
ParDis Parasites and Disease [8] Other biotic stressors submodel	This node reflects possible change in exposure to disease and parasites that may result from changing environmental conditions. As the climate warms, regions of the Arctic are likely to become more hospitable to endemic and emerging parasites and disease agents. It is believed that polar bears have been free of most disease and parasite agents, but comprehensive surveillance has been lacking. There is evidence suggesting that polar bears are now exposed to a variety of zoonotic agents and parasites including *Brucella abortus*, *Toxoplasma gondii*, *Coxiella burnettii*, rabies, and trichinella (e.g., Rah et al. 2005; Kirk et al. 2010; Atwood et al. 2017). It is also known that polar bears have a relatively naive immune system (Weber et al. 2013), which may make them vulnerable to invading pathogens. 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. For the Southern Beaufort Sea subpopulation, Atwood et al. (2017) reported increased seroprevalence of several pathogens and documented the first exposure of polar bears to terrestrial pathogens. Whiteman et al. (2019) observed heightened immune system function for onshore Southern Beaufort Sea bears, which suggests that as they spend longer time on land they may experience more infections. Last, Pilfold et al. (2021) documented a general increase in seroprevalence of several pathogens in Western Hudson Bay bears.	Elevated Same as Baseline Reduced

| *Pred*

Predation

[8] Other biotic stressors submodel | This node characterizes the likelihood of intra- and interspecific predation over time and relative to changing environmental conditions. Predation on polar bears by other species appears to be uncommon. However, as bears spend more time on land, young bears may be subject to increased levels of predation from other polar bears (Amstrup et al. 2006b), wolves (Richardson and Andriashek 2006), and perhaps grizzly bears. Increased use of land during summer, and a growing reliance on scavenging beach-cast and aggregated marine mammals, may put younger bears at greater risk of lethal encounters with adults. Local ecological knowledge suggests that most cases of predation involve adult males killing cubs of the year (e.g., Born et al. 2011).

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 (Allen et al. 2022). At present, intraspecific predation is not thought to be influential at the population level anywhere in the polar bear range, though it appears that the frequency of such events may be increasing. | Elevated
Same as Baseline
Reduced |

	Intermediate (Summary) Nodes	
PrimPrey Primary Prey Productivity [3] Marine prey and conditions submodel	This node is informed by the "ringed seal productivity" and "bearded seal productivity" nodes. Ringed and bearded seals are considered primary prey for polar bears based on the findings of numerous studies of diet composition (e.g., Thiemann et al. 2008) and prey selection (Pilfold et al. 2012). This node expresses changes in primary prey productivity that are likely to occur as sea ice cover declines and its physical character changes. This is largely expert opinion because there is little information available regarding the potential for future changes in the prey base, with the exception of status assessments (NOAA 2012; Cameron et al. 2010). However, recent work (e.g., Iacozza and Ferguson 2014) suggests that decreased future snow depth over ice may have significant consequences to ringed seal abundance through reduced pup survival. Such an outcome is most likely for the SIE and PBDE. As ice thins in the AE, it is reasonable to expect a transient increase in the abundance of primary prey, perhaps until the mid-century mark, followed by a decline as sea ice cover once again becomes limiting. Several recently published studies have provided new information on ringed seal-habitat relationships. For example, ringed seals at the core of their range have showed declines in condition with later spring break-up and a shorter OW season; seals at the periphery of their range showed the opposite effect (Ferguson et al. 2017). A gradual decline in condition and density, along with an increase in biomarkers of physiological stress, of ringed seals is believed to have occurred from 1995-2013 in several regions of the Arctic (Ferguson et al. 2020). Reimer et al. (2019) projected median declines in ringed seal population size for Amundsen Gulf and Prince Albert Sound (Northern Beaufort Sea subpopulation region) ranging from 50% to 99% by century's end, and Harwood et al. (2020) reported a long-term decline in ringed seal body condition in Amundsen Gulf. In some areas of the Arctic, ringed seal productivity appears to have increased. For example, Crawford et al. (2015) found that ringed seals in the Bering and Chukchi seas were growing faster, had thicker blubber, and females matured earlier in 2003-2012 compared to 1975-1984. Based on the literature, we weighted the relative importance of ringed and bearded seals in developing the probabilities for this table. Given that ringed seals usually represent a greater proportion of polar bear diet (e.g., Born et al. 2011), the proportion of ringed seal in the diet has been linked to survival (Rode et al. 2022), and ringed seals are likely more available to all age and sex classes than bearded seals, it received a greater weight (0.6).	Elevated Same as Baseline Reduced
MrnPry Marine Prey Base Quality [3] Marine prey and conditions submodel	This node expresses changes in primary and secondary prey productivity that are likely to occur as sea ice cover declines and its physical character changes. As with the prey nodes, the probabilities for this node are largely based on expert opinion because there is little information available to suggest how the prey base is likely to change in the future. In developing the probabilities for this node, primary prey was given slightly greater weight than secondary prey because the importance of primary prey has been established in the literature, although there is relatively little information available on the likelihood/importance of prey switching. However, there is evidence (e.g., Peacock	Elevated Same as Baseline Reduced

	et al. 2013) to suggest that increased abundance of alternate prey may elevate total survival of polar bears.	
Ice Overall Sea Ice Conditions [2] Sea ice submodel	This node expresses the combination of the quantitative and qualitative ways the retreat of sea ice may affect use of continental shelf habitats. Analyses indicate that, in addition to reductions of total ice extent (expressed under *IceArea*), we will see seasonal retreats of the sea ice (*IceFor*) away from coastal areas now preferred by polar bears, and these retreats (or ice-free periods) are projected to progressively become longer. These changes will affect polar bears by reducing the total availability of ice substrate, altering the spatial distribution of foraging patches, and making ice unavailable for extended periods in many regions year-round. These changes may lead to a shift from year-round to seasonal occupancy in affected areas. We defined "greatly reduced" overall sea ice conditions as when "foraging sea ice area" decreased by greater than 40% and the availability of "foraging sea ice distribution" was greatly reduced. Note that because the PBCE includes populations that have different starting values for overall sea ice conditions, the values in the CPT express an average— similar to the approach taken for this area when estimating values for *IceFor*. Similarly, in the SIE, there is a difference between several populations, so table values are an average.	Improved Same as Baseline Reduced Greatly Reduced
IceFor Foraging Sea Ice Distribution [2] Sea ice submodel	This node combines the influence of Sea Ice Shelf Distance Change (*IceShelf*), Foraging Sea Ice <50 percent Absence Change (*IceChng*), and Ecoregion (*EcoReg*), expressing how the spatiotemporal retreat of sea ice may affect use of continental shelf habitats. Our analyses indicate we will see seasonal retreats of the sea ice farther away from coastal areas now preferred by polar bears, and these retreats (or ice-free periods) are projected to progressively become longer. These changes will make ice unavailable for extended periods in many regions bears now occur year-round. This will result in the opportunity for seasonal occupancy but not the year-round occupancy bears have had in the past. In addition, we assumed that if parent node IceShelf is ≥800 km then *IceChng* would almost always be greater than 1 month and probably much more (regardless of the distribution of patches) and perhaps in the neighborhood of ≥ 3 months. Thus, when *IceShelf* is ≥ 800 km, there is a good chance that sea ice phenology will be altered over shelf regions and the distribution of foraging sea ice will be greatly reduced. However, even if *IceChng* is < 3 months, the arrangement/juxtaposition of ice patches would be so dynamic that patch availability would likely be greatly reduced. Sahanatien and Derocher (2012) provide a good assessment of how changing ice phenology and increased fragmentation are likely to adversely affect access to foraging habitat.	Improved Same as Baseline Reduced Greatly Reduced

AltMarForHab [3] Marine prey and conditions submodel Alternative Marine Foraging Habitat	This node refers to glacial mélange (fast ice and glacial fronts) that provide access to marine prey (Laidre et al. 2022, Freitas et al. 2008), and can include some other alternative marine foraging habitats. Fast ice is fastened to the coastline and/or sea floor and does not move with wind and currents.	Elevated Same as Baseline Reduced
Mrn Overall Marine Conditions [3] Marine prey and conditions submodel	This node expresses how quantitative changes in sea ice and qualitative changes in prey base quality and contribution of glacial melange habitats (where present) act in combination to determine overall conditions in the marine ecosystem. In developing the CPT for this node, we gave greater weight of importance to "overall sea ice conditions" because sea ice coverage influences access to prey. Evidence suggests that polar bears prefer sea ice habitats over or adjacent to coastal areas (e.g., Ferguson et al. 2000, Durner et al. 2009). Seasonal retreat of sea ice away from coastal areas reduces access to prey (Whiteman et al. 2015, Ware et al. 2017). The ice-minimum period is projected to become longer through time, which will further reduce access to prey present in productive shallow waters. Thus, even though prey abundance may remain stable, access to prey will decline in response to declining seasonal sea ice extent. As access to prey declines, so will overall marine conditions.	Improved Same as Baseline Reduced
Len Bears on Shore [4] Terrestrial food/prey and conditions submodel	This node expresses the proportion of an ecoregion's population of bears that may come ashore and the length of time each year that bears may spend on shore occupying terrestrial habitat. As overall sea ice conditions decline, we expect greater use of onshore habitat by bears as posited by Schliebe et al. (2008) and demonstrated by Rode et al. (2022) and Pongracz and Derocher (2017). Moreover, the likelihood of bears using onshore habitat increases when the availability of terrestrial food resources increases (Wilson et al. 2017). However, using the SIE as evidence, we believe the primary driver of onshore occurrence is the absence or reduced availability of summer sea ice. We defined "greatly increased" as a condition where the majority of bears in a given ecoregion spend the majority of the annual period on shore. Characterization of the use of onshore habitat is particularly important for the SIE, where use of onshore habitat has long been a part of bear life history. This node also may be important for other ecoregions over time. For example, in parts of the PBDE, bears are spending more time on shore during the ice-minimum season. We expect base conditions to vary by ecoregion.	Greatly Increased Increased Same as Baseline Less than Baseline

TerrPry Overall Terrestrial Prey/Food Availability [4] Terrestrial food/prey and conditions submodel	This node characterizes the availability of food resources relative to requirements of bears during their stay on shore. The node is informed by "human-provisioned food availability" and "terrestrial prey access" and, in turn, influences the length of time bears may spend on shore during the ice-minimum season. In developing the CPT for this node, we relied on expert knowledge and put equal weight on both informing nodes. We noted that "human provisioned food availability" is mostly relevant to the PBDE and SIE.	Elevated Same as Baseline Reduced Absent
EvMort Event-Driven Mortality [6] Event-driven mortality submodel	This node expresses the combination of different forms of mortality polar bears may be exposed to through time. There was little information available on cause-specific mortality of polar bears, so in developing the conditional probability table we relied on expert knowledge to base table entries on the relative importance of the different forms of mortality.	Elevated Same as Baseline Reduced
Hab Overall Habitat Suitability [5] Overall habitat suitability submodel	This node expresses overall habitat suitability as a combination of the quality of marine and terrestrial habitats used by polar bears. In developing the conditional probability table for this node, greater importance was given to "overall marine conditions" because non-denning polar bears spend the majority of the year on the sea ice foraging on marine mammals. However, we note that over time, the use of terrestrial habitat is likely to increase. The "greatly reduced" state was defined as occurring when both overall marine and terrestrial conditions were "degraded." Based on projections of sea ice extent, we believe overall sea ice conditions will degrade over time. One near-term exception may be the AE, where climate-mediated reductions in sea ice volume (through thinning of multi-year ice) may result in a temporary improvement of "overall marine conditions." We believe overall terrestrial conditions are likely to change through time and further impact overall habitat suitability. There is some evidence to suggest that polar bears may have the ability to forage adaptively (e.g., Iverson et al., 2014), but it is unclear if such foraging behavior can constitute a meaningful energetic benefit. In the absence of such data, we considered the contribution of "overall terrestrial conditions" to be secondary to that of "overall marine conditions."	Elevated Same as Baseline Reduced Greatly Reduced
Terr Overall Terrestrial Conditions [4] Terrestrial food/prey and conditions submodel	This node expresses change in overall terrestrial conditions as functions of refugia quality and the length of time bears spend on shore, as influenced by ecoregion. Refugia quality expresses the ability of bears to stay on shore and be free of disturbance. As disturbance increases, refugia quality declines, which then degrades overall terrestrial conditions. The length of time spent on shore also influences overall terrestrial conditions—the longer bears spend on shore, the more likely that terrestrial conditions become degraded (e.g., resource scarcity). The relationships among refugia quality, time spent on shore in a mostly fasting state, and overall terrestrial habitat conditions are informed by Pilfold et al. (2016) and Blanchet et al. (2020).	Improved Same as Baseline Degraded

OthMor Other Mortality or Removal Events [6] Event-driven mortality submodel	This node refers to mortality from small- and large-scale oil operations, and from a "catch-all" node of other mortality events. The "other events" includes (but is not limited to) drowning, illegal killing, den failure, and management and research actions. In developing the CPT, we attributed greater importance to large oil spills given the potential for severe and lingering lethal effects.	Elevated Same as Baseline Reduced
AdSur Adult Survival [9] Demographic submodel	This node represents the sum of trends of adult survival. This node is influenced by "overall habitat suitability," "other biotic stressors," and "event-driven mortality." The causal link between sea ice habitat and adult survival is based on the literature, which documents declines in survival and/or subpopulation abundance concurrent with deteriorating sea ice conditions (Regehr et al. 2007, 2010; Bromaghin et al. 2015, 2021; Obbard et al. 2015, 2018; Lunn et al. 2016). We also recognize that some subpopulations may experience periods of stability or even transient increases in survival and condition as sea ice conditions change (Stapleton et al. 2016; Lunn et al. 2016; Aars et al. 2017; Regehr et al. 2018; Dyck et al. 2020; Laidre et al. 2020; Bromaghin et al. 2021). In developing the conditional probability table for this node, we gave "overall habitat suitability" greater weight of importance than "event-driven mortality." We justify the weighting scheme based on the preponderance of evidence suggesting that reductions in "overall habitat suitability" will have the most profound effect on persistence of polar bears. Although "event-driven mortality" and "other biotic stressors" also will have adverse effects, it is not expected to eclipse those of habitat suitability. The "greatly reduced" state was defined as occurring when survival was likely to exhibit a sustained declining trend.	Elevated Same as Baseline Reduced Greatly Reduced
SaSur Subadult Survival [9] Demographic submodel	This node represents the sum of trends of post-dependent young (aged 2–4 years) surviving to be recruited into the "adult" age class. This node is influenced by "overall habitat suitability," "other biotic stressors," and "event-driven mortality." As with "adult survival," the causal link between sea ice habitat and subadult survival is based on the literature, which documents declines in survival and/or subpopulation abundance concurrent with deteriorating sea ice conditions (Regehr et al. 2007, 2010; Bromaghin et al. 2015; Obbard et al. 2015, 2018; Lunn et al. 2016; Sciullo et al. 2017). We also recognize that some subpopulations may experience periods of stability or even transient increases in survival and condition as sea ice conditions change (Stapleton et al. 2016; Lunn et al. 2016; Aars et al. 2017; Regehr et al. 2018; Dyck et al. 2020; Laidre et al. 2020; Bromaghin et al. 2021). In developing the conditional probability table for this node, we gave "overall habitat suitability" greater weight of importance than "event-driven mortality." We justify the weighting scheme based on the preponderance of the evidence suggesting that reductions in "overall habitat suitability" will have the most profound effect on persistence of polar bears. Although "event-driven mortality" and	Elevated Same as Baseline Reduced Greatly Reduced

	"other biotic stressors" also will have adverse effects, those effects are not expected to eclipse that of habitat suitability. The "greatly reduced" state was defined as occurring when subadult survival was likely to exhibit a sustained declining trend.	
AFBod Adult Female Body Condition [9] Demographic submodel	This node expresses how habitat conditions, sublethal stressors, and some biotic stressors can influence the body condition of adult females. In developing the conditional probability table for this node, we gave "overall habitat suitability" the greatest weight, acknowledging that empirical evidence supports the link between declines in sea ice habitat with declines in adult female body condition (e.g., Rode et al. 2010). Several additional studies support the general conclusions drawn in Rode et al. (2010), including Pilfold et al. (2016), Obbard et al. (2016), Sciullo et al. 2017), Molnár et al. (2020), and Atwood et al. (2021). We acknowledge there is no information available establishing a relationship between sublethal effects or parasites and disease to polar bear body condition. However, there is information for other species (e.g., Pioz et al. 2008; Sheriff et al. 2009), and we relied on that for guidance in completing the CPT. We defined "greatly decreased" body condition as occurring when declines in condition could lead to reproductive failure. We believe that sea ice projections support the notion that "overall habitat suitability" is likely to decline through time and thus adversely influence adult female body condition. Likewise, there is supposition that exposure to parasites and disease agents and other sublethal stressors is likely to increase as the Arctic warms (e.g., Moore and Huntington 2008). Given that, we believe that adult female body condition likely will decline with increasing sea ice habitat degradation and loss.	Increased Same as Baseline Decreased Greatly Decreased
DenAcc Terrestrial Maternal Den Access [4] Terrestrial food/prey and conditions submodel	This node expresses change in maternal den access as a function of changes to foraging sea ice absence that triggers polar bears to come on shore and increasing summer reliance on terrestrial refugia (Rode et al. 2015, Pongracz et al. 2017, Atwood et al. 2016). The highest quality foraging sea ice is over and adjacent to productive shallow waters (i.e., continental shelf water). These areas are generally close to coastal habitat and provide easy access to terrestrial maternity dens. However, climate warming has led to an increase in the length of the ice-minimum season and an increase in the distance from foraging habitats and most coastal regions— notably in the PBDE (it is currently not germane to the PBCE and irrelevant to the SIE). If the distance between available autumn sea ice and the coast increases—as it is projected to—then access to maternal dens may become restricted as bears would have to cross expanses of open water to reach onshore denning habitat. Polar bears already using terrestrial refugia in summer have access to terrestrial den habitat where not already available. There is some evidence to suggest that for subpopulations that den on both land and ice, denning on land may improve post-emergence cub survival (Rode et al. 2018). Based on projections of sea ice extent and duration of the ice-minimum season, we believe that access to terrestrial denning habitat may become compromised in the future for polar bears that remain on the sea ice in the summer. This is a more pressing concern for the PBDE than for other areas, given the pattern of ice recession.	Elevated Same as Baseline Reduced

Disturb Sub-lethal Human Disturbance [7] Anthropogenic stressors submodel	This node expresses the combination of the changes in non-lethal human disturbances to polar bears. Specifically, it covers the direct bear-human interactions that can occur in association with industrial development, tourism, and shipping. We assumed bear-human interactions to be the most influential factor. Although shipping and tourism could become a significant problem, they also are issues that could be subject to stringent regulations and flexible management to minimize effects on bears. Similarly, oil and gas companies can be subjected to appropriate regulatory responses if bear-human interactions become too frequent. Encounters in villages and hunting camps, however, may not be as easily regulated and it seemed more likely they would lead to negative effects. Increasing bear human interactions will result in conditioned bears; however, direct bear mortality is not included in this node. We expect that the magnitude of sub-lethal human disturbance will vary seasonally and over time, with the greatest effects occurring during the ice-minimum season and increasing as that season lengthens.	Elevated Same as Baseline Reduced
Recr Recruitment [9] Demographic submodel	This node reflects 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. There is a well-documented link between adult female body condition and recruitment for many species, including polar bears (e.g., Derocher and Stirling, 1995; Rode et al. 2010). There also is information documenting the importance of terrestrial denning habitat for polar bears in multiple ecoregions (Fischbach et al. 2007; Richardson et al. 2005; Andersen et al. 2012; Rode et al. 2018). New work confirms the importance of the duration of the fasting season and prey condition on polar bear recruitment (Molnar et al. 2020; Rode et al. 2021). "Greatly decreased" was defined as the likelihood that the trend in the number of cubs exhibited a sustained decline. In developing the CPT for this node, we put greater weight on the contribution of adult female body condition in influencing recruitment. While we note that access to terrestrial dens has the potential to become reduced over time (except for the SIE), as the ice-minimum season lengthens, we believe that the increased ice-minimum season will continue to have a greater adverse effect on adult female body condition. This position is based on the relationship between sea ice and condition as outlined by Rode et al. (2010).	Increased Same as Baseline Decreased Greatly Decreased
AntStr Anthropogenic Stressors (Sub-lethal) [7] Anthropogenic stressors submodel	This node combines sub-lethal anthropogenic stressors. It includes factors (other than the changes in sea ice quality and quantity), which may affect both habitat suitability and population dynamics. Although quantitative information is lacking on the effects of these stressors at the population level, we know qualitatively of effects on immune function, gene expression, and physiological stress. Given that, table entries were based on expert knowledge.	Elevated Same as Baseline Reduced

Pol Pollution (Sub-lethal) [7] Anthropogenic stressors submodel	This node 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 U.S. Fish and Wildlife Service listing decision for polar bears included pollution as one of the "other factors" along with direct human bear interactions that may displace bears or otherwise make habitats less satisfactory. We viewed the main effect of pollution as a potential effect on population dynamics, as it is likely to manifest as adverse impacts to immune function, reproductive performance, and survival. Although there is relatively little empirical data on the effects of hydrocarbon exposure on polar bears, information is available for other marine mammals. There is a large body of literature on the effects of contaminants on polar bears (e.g., Sonne 2010, Liu et al. 2018, Routti et al. 2018, 2019, Dominique et al. 2020.).	Elevated Same as Baseline Reduced
BioStr Other Biotic Stressors [8] Other biotic stressors submodel	This node expresses the changing vulnerability of polar bears to diseases and parasites, and to potential increases of intra- and interspecific predation. We recognize that predation/cannibalism is currently rare. We also recognize that while there is information summarizing exposure to disease agents, there is little such information relative to parasites — although there is no information that links these stressors to effects on vital rates. Given that, the conditional probability table for this node is based largely on expert knowledge.	Elevated Same as Baseline Reduced

	Outcome Node	
InflPopn Relative Influence on Population Trend [10] Polar bear persistence submodel	This node depicts the hypothesized relative influence of stressors on population trend as referenced by estimated or observed changes to abundance and distribution. The node is informed by "adult survival," "subadult survival," and "recruitment," and we gave the greatest weight to adult survival because it is the least sensitive to change. As such, it should take a substantial change in conditions to exert a meaningful influence on adult survival. The outcome states are qualitative because there is insufficient empirical data from a majority of the 19 polar bear subpopulations (e.g., Obbard et al. 2010) that would allow us to develop quantitative thresholds for transitioning from one state to another. As a result, we estimated the relative influence on population trend similar to Jay et al. (2011), Amstrup et al. (2008, 2010), and Johnson et al. (2013) by using transition thresholds that reflect qualitative changes in abundance, distribution (i.e., use and selection of ecosystem elements and features), and strength and presence of stressors.	Increased Same as Baseline Decreased Greatly Decreased

	Scenario Nodes		
Per Time Period [1] Analysis scenario	The seven states for this node correspond to decadal-scale periods spanning the years: historic (1985–1995, baseline (1996–2006), recent (2007–2012), early century (2020–2030), mid-century (2045–2055), late century (2070–2080), and end of century (2090–2100).	1985–1995 1996–2006 2007–2012 2020–2030 2045–2055 2070–2080 2090–2100
Scenario Scenario [1] Analysis scenario	The four states for this node correspond to four scenarios, one empirical (observations) and three hypotheticals. The hypothetical scenarios follow three "Shared Socioeconomic Pathways" used by the IPCC in their Sixth Assessment Reports for depicting different societal levels of future greenhouse gas emissions: low emissions (SSP2.6) attained by prompt and aggressive mitigation, high emissions (SSP8.5) that continue to increase at unabated rates; and an intermediate scenario (SSP4.5).	Observations SSP126 SSP245 SSP585
Ecoreg Ecoregion [2] Sea ice submodel	The states for this node correspond to the four ecoregions proposed by Amstrup et al. (2008). Ecoregions represent an intermediate-scale spatial grouping (i.e., between individual populations and the circumpolar distribution) of polar bears based on observed and forecasted patterns of sea ice dynamics and polar bear life history.	AE PBCE PBDE SIE
GCMset Scenario Data Type [1] Analysis scenario	The two states for this node correspond to the type of data used for the scenario under consideration: satellite (or observational) and modeled (from expert knowledge or climate model projections). The three sea ice input nodes (IceArea, IceShelf, and IceChng) used monthly sea ice concentration estimates obtained from the National Snow and Ice Data Center (Cavalieri et al. 1996) for the empirical state, and monthly sea ice projections from each of 12 CMIP6 earth system models selected by SIMIP Community (2020) for the future state. The three sea ice input nodes expressed values that quantified changes relative to the baseline period (1996-2006). For all climate model projections, a respective model's changes were quantified relative to that model's hindcast simulations during the baseline period (1996-2006) from the CMIP6 historical forcing experiment.	Empirical GCM12SIMIP

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APPENDIX B. TABLES B1-B6

for: Marcot, B. G., T. C. Atwood, D. C. Douglas, J. F. Bromaghin, A. M. Pagano, and S. C. Amstrup. Submitted. Incremental evolution of modeling a prognosis for polar bears in a rapidly changing Arctic. for: Ecological Indicators

Appendix Table B1. Updated conditional probability table values for node Overall Marine Conditions in the polar bear Bayesian network model. Note that this probability table has been updated from the previous polar bear Bayesian network model (Atwood et al. 2016) because of the addition of a new node Alternative Marine Foraging Habitat that now links to Overall Marine Conditions.

Input nodes			Overall Marine Conditions		
Overall Sea Ice Conditions	Marine Prey Base Quality	Alternative Marine Foraging Habitat	improved	same as Baseline	degraded
improved	elevated	elevated	100	0	0
improved	elevated	same as Baseline	95	5	0
improved	elevated	reduced	90	10	0
improved	same as Baseline	elevated	70	30	0
improved	same as Baseline	same as Baseline	60	40	0
improved	same as Baseline	reduced	50	50	0
improved	reduced	elevated	20	40	40
improved	reduced	same as Baseline	10	30	60
improved	reduced	reduced	0	20	80
same as Baseline	elevated	elevated	80	20	0
same as Baseline	elevated	same as Baseline	70	30	0
same as Baseline	elevated	reduced	60	40	0
same as Baseline	same as Baseline	elevated	10	90	0
same as Baseline	same as Baseline	same as Baseline	0	100	0
same as Baseline	same as Baseline	reduced	0	90	10
same as Baseline	reduced	elevated	0	50	50
same as Baseline	reduced	same as Baseline	0	40	60
same as Baseline	reduced	reduced	0	30	70
reduced	elevated	elevated	0	55	45
reduced	elevated	same as Baseline	0	45	55
reduced	elevated	reduced	0	35	65
reduced	same as Baseline	elevated	0	40	60
reduced	same as Baseline	same as Baseline	0	30	70
reduced	same as Baseline	reduced	0	20	80
reduced	reduced	elevated	0	40	60
reduced	reduced	same as Baseline	0	30	70
reduced	reduced	reduced	0	20	80
greatly reduced	elevated	elevated	0	35	65
greatly reduced	elevated	same as Baseline	0	30	70
greatly reduced	elevated	reduced	0	25	75
greatly reduced	same as Baseline	elevated	0	20	80
greatly reduced	same as Baseline	same as Baseline	0	15	85
greatly reduced	same as Baseline	reduced	0	10	90
greatly reduced	reduced	elevated	0	10	90
greatly reduced	reduced	same as Baseline	0	5	95
greatly reduced	reduced	reduced	0	0	100

Appendix Table B2. Updated CPT for node Overall Terrestrial Conditions. Note that this probability table has been updated from the previous polar bear Bayesian network model (Atwood et al. 2016) because of the addition of a new link from Ecoregion to Overall Terrestrial Conditions.

Input nodes			Overall Terrestrial Conditions		
Bears on shore	Terrestrial Refugia Quality	Ecoregion	improved	same as Baseline	degraded
greatly increased	improved	Archipelago	10	50	40
greatly increased	improved	Polar Basin Convergent	10	50	40
greatly increased	improved	Polar Basin Divergent	10	50	40
greatly increased	improved	Seasonal Ice	10	50	40
greatly increased	not degraded (Baseline)	Archipelago	0	40	60
greatly increased	not degraded (Baseline)	Polar Basin Convergent	0	40	60
greatly increased	not degraded (Baseline)	Polar Basin Divergent	0	40	60
greatly increased	not degraded (Baseline)	Seasonal Ice	0	40	60
greatly increased	degraded from Baseline	Archipelago	0	5	95
greatly increased	degraded from Baseline	Polar Basin Convergent	0	5	95
greatly increased	degraded from Baseline	Polar Basin Divergent	0	5	95
greatly increased	degraded from Baseline	Seasonal Ice	0	5	95
increased	improved	Archipelago	15	70	15
increased	improved	Polar Basin Convergent	15	70	15
increased	improved	Polar Basin Divergent	15	70	15
increased	improved	Seasonal Ice	15	70	15
increased	not degraded (Baseline)	Archipelago	0	50	50
increased	not degraded (Baseline)	Polar Basin Convergent	0	50	50
increased	not degraded (Baseline)	Polar Basin Divergent	0	50	50
increased	not degraded (Baseline)	Seasonal Ice	0	50	50
increased	degraded from Baseline	Archipelago	0	25	75
increased	degraded from Baseline	Polar Basin Convergent	0	25	75
increased	degraded from Baseline	Polar Basin Divergent	0	25	75
increased	degraded from Baseline	Seasonal Ice	0	25	75
same as Baseline	improved	Archipelago	40	60	0
same as Baseline	improved	Polar Basin Convergent	40	60	0
same as Baseline	improved	Polar Basin Divergent	40	60	0
same as Baseline	improved	Seasonal Ice	40	60	0
same as Baseline	not degraded (Baseline)	Archipelago	0	100	0
same as Baseline	not degraded (Baseline)	Polar Basin Convergent	0	100	0
same as Baseline	not degraded (Baseline)	Polar Basin Divergent	0	100	0
same as Baseline	not degraded (Baseline)	Seasonal Ice	0	100	0
same as Baseline	degraded from Baseline	Archipelago	0	60	40
same as Baseline	degraded from Baseline	Polar Basin Convergent	0	60	40
same as Baseline	degraded from Baseline	Polar Basin Divergent	0	60	40
same as Baseline	degraded from Baseline	Seasonal Ice	0	60	40
less than Baseline	improved	Archipelago	100	0	0
less than Baseline	improved	Polar Basin Convergent	100	0	0
less than Baseline	improved	Polar Basin Divergent	100	0	0

less than Baseline	improved	Seasonal Ice	100	0	0
less than Baseline	not degraded (Baseline)	Archipelago	75	25	0
less than Baseline	not degraded (Baseline)	Polar Basin Convergent	75	25	0
less than Baseline	not degraded (Baseline)	Polar Basin Divergent	75	25	0
less than Baseline	not degraded (Baseline)	Seasonal Ice	75	25	0
less than Baseline	degraded from Baseline	Archipelago	25	50	25
less than Baseline	degraded from Baseline	Polar Basin Convergent	25	50	25
less than Baseline	degraded from Baseline	Polar Basin Divergent	25	50	25
less than Baseline	degraded from Baseline	Seasonal Ice	25	50	25

Appendix Table B3. Sensitivity analysis of the polar bear Bayesian network model outcome node "Overall population outcome" from Phase I (Amstrup et al. 2008) to all input nodes. Mutual information measures the degree to which the posterior probability values of the outcome node change as a function of an incremental change in each input node (Marcot 2012).

Submodel \1	Node title	Mutual info
a	Foraging habitat quantity change	0.12974
a	Foraging habitat absence change	0.04876
a	Ecoregion	0.04166
d	Alternate regions available	0.02590
c	Intentional takes	0.01607
a	Shelf distance change	0.01393
a	Foraging habitat character	0.01037
c	Bear-human interactions	0.00821
d	Parasites and disease	0.00506
c	Hydrocarbons/oil spill	0.00271
c	Oil and gas activity	0.00254
c	Shipping	0.00198
c	Predation	0.00092
c	Contaminants	0.00073
b	Alternate prey availability	0.00069
b	Relative ringed seal availability	0.00065
c	Tourism	0.00040

\1 Submodels:
a = Sea ice, Ecoregion
b = Marine prey
c = Anthropogenic stressors
d = Other

Appendix Table B4. Sensitivity analysis of the polar bear Bayesian network model outcome node "Relative influence on population trend" from Phase II (Atwood et al. 2016) to all input nodes. Mutual information measures the degree to which the posterior probability values of the outcome node change as a function of an incremental change in each input node (Marcot 2012).

Submodel \1	Node title	Mutual info
a	Foraging sea ice area	0.06946
a	Foraging sea ice <50% absence change	0.03332
b	Ringed seal abundance	0.03125
a	Ecoregion	0.02110
a	Foraging sea ice quality	0.02099
d	Terrestrial refugia quality	0.01805
d	Parasites and disease	0.01202
c	Hunting mortality (legal)	0.00675
b	Bearded seal abundance	0.00515
b	Secondary and new prey abundance	0.00438
d	Sea ice shelf distance change	0.00130
c	Human-bear DLP lethal interactions	0.00039
d	Terrestrial and marine prey/food	0.00032
d	Predation	0.00018
c	Hydrocarbons/oil spill	0.00004
c	Contaminants	0.00004
c	Oil spills, small operation	0.00002
c	Oil spills, large exploration	0.00002
c	Human-bear sub-lethal interactions	0.00001
c	Oil, gas, and mining activities	0.00001
c	Tourism	0.00001
c	Shipping	0.00001
c	Other events (lethal effects)	0.00001
c	Human provisioned food abundance	<0.00001

\1 Submodels:
a = Sea ice, Ecoregion
b = Marine prey
c = Anthropogenic stressors
d = Other

Appendix Table B5. Sensitivity analysis of the polar bear Bayesian network model outcome node "Relative influence on population trend" from Phase III (this study) to all input nodes. Mutual information measures the degree to which the posterior probability values of the outcome node change as a function of an incremental change in each input node (Marcot 2012).

Submodel \1	Node title	Mutual info
a	Foraging sea ice area	0.07111
a	Foraging sea ice <50% absence change	0.03030
b	Ringed seal abundance	0.02402
a	Foraging sea ice quality	0.02219
d	Terrestrial refugia quality	0.02038
a	Ecoregion	0.01914
d	Parasites and disease	0.01184
c	Hunting mortality (legal)	0.00661
b	Alternative marine foraging habitat	0.00488
b	Bearded seal abundance	0.00397
b	Secondary and new prey abundance	0.00348
a	Sea ice shelf distance change	0.00136
d	Terrestrial and marine prey/food	0.00039
c	Human-bear DLP lethal interactions	0.00038
d	Predation	0.00018
c	Hydrocarbons/oil spill	0.00004
c	Contaminants	0.00004
c	Oil spills, small operation	0.00002
c	Oil spills, large exploration	0.00002
c	Human-bear sub-lethal interactions	0.00001
c	Oil, gas, and mining activities	0.00001
c	Tourism	0.00001
c	Shipping	0.00001
c	Other events (lethal effects)	0.00001
c	Human provisioned food abundance	< 0.00001

\1 Submodels:
a = Sea ice, Ecoregion
b = Marine prey
c = Anthropogenic stressors
d = Other

Appendix Table B6. Difference between sensitivity analysis outcomes from polar bear Bayesian network models from Phase III (current study; Appendix Table B5) and Phase II (Atwood et al. 2016; Appendix Table B4), sorted here by decreasing values of differences in mutual information (Phase III - Phase II). Mutual information and variance of beliefs are measures of the degree to which the posterior probability values of the outcome node change as a function of an incremental change in another node (Marcot 2012). * = input node; DLP = defense of life and property.

Node	Mutual Info
Overall Terrestrial Conditions	0.01181
Adult Survival	0.00800
Overall Sea Ice Conditions	0.00705
Bears on Shore	0.00409
Overall Habitat Suitability	0.00322
* Terrestrial Refugia Quality	0.00233
Adult Female Body Condition	0.00179
* Foraging Sea Ice Area	0.00165
* Foraging Sea Ice Quality	0.00120
Overall Terrestrial Prey/Food Availability	0.00008
* Terrestrial & Marine Prey/Food Access	0.00007
* Sea Ice Shelf Distance Change	0.00006
* Predation	0.00000
Pollution (sub-lethal)	0.00000
Other Mortality or Removal Events	0.00000
* Hydrocarbons/Oil Spill	0.00000
* Contaminants	0.00000
* Oil spills, small operational	0.00000
* Oil spills, large exploratory	0.00000
* Shipping	0.00000
* Human-Bear Sub-Lethal Interactions	0.00000
* Oil, Gas, & Mining Activity	0.00000
* Tourism	0.00000
* Other Events (lethal effects)	0.00000
* Human Provisioned Food Abundance	0.00000
* Human-Bear DLP Lethal Interactions	-0.00001
Sub-Lethal Human Disturbance, Village/Community Interactions	-0.00001
Anthropogenic Stressors	-0.00001
Other Biotic Stressors	-0.00009
* Hunting mortality (legal)	-0.00014
* Parasites & Disease	-0.00018
Event-Driven Mortality	-0.00019
* Secondary & New Prey Abundance (Productivity)	-0.00090

* Bearded Seal Abundance (Productivity)	-0.00118
* Ecoregion	-0.00196
Subadult Survival	-0.00199
* Foraging Sea Ice <50% Absence Change	-0.00302
* Foraging Sea Ice Distribution	-0.00357
* Ringed Seal Abundance (Productivity)	-0.00723
Terrestrial Maternal Den Access	-0.00992
Primary Prey Abundance (Productivity)	-0.01281
Overall Marine Conditions	-0.01540
Recruitment	-0.01749
Marine Prey Base Quality	-0.01958

APPENDIX C. FIGURES C1-C2

for: Marcot, B. G., T. Atwood, D. C. Douglas, J. F. Bromaghin, A. M. Pagano, and S. C. Amstrup. Submitted. Incremental evolution of modeling a prognosis for polar bears in a rapidly changing Arctic. for: Ecological Indicators

Appendix Figure C1. Revised polar bear Bayesian network model showing addition of the node Alternative Marine Foraging Habitat feeding into Overall Marine Conditions, and the link added from Ecoregion to Overall Terrestrial Conditions.
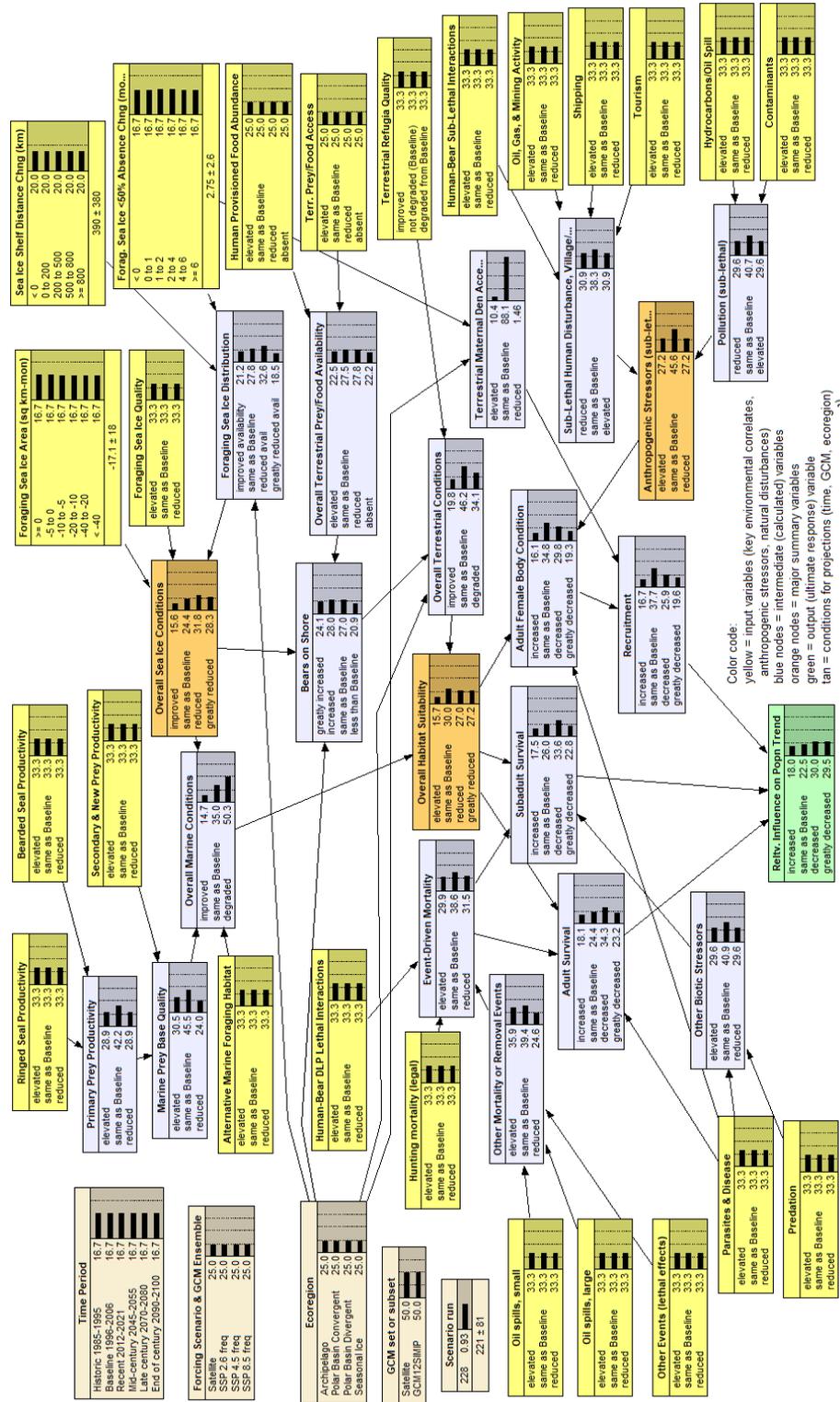
Appendix Figure C2. Summary of projected probabilities of decreased or greatly decreased polar bear populations under the Phase III (current study) Bayesian network model using Coupled Model Intercomparison Project CMIP6 sea-ice projections. Shown here are results by the four ecoregions and three future time periods (see text Table 2), under three SSP (Shared Socioeconomic Pathway) greenhouse gas scenarios (2.6, 4.5, 8.5), based on frequency distributions of GCM (global circulation model) outcomes.
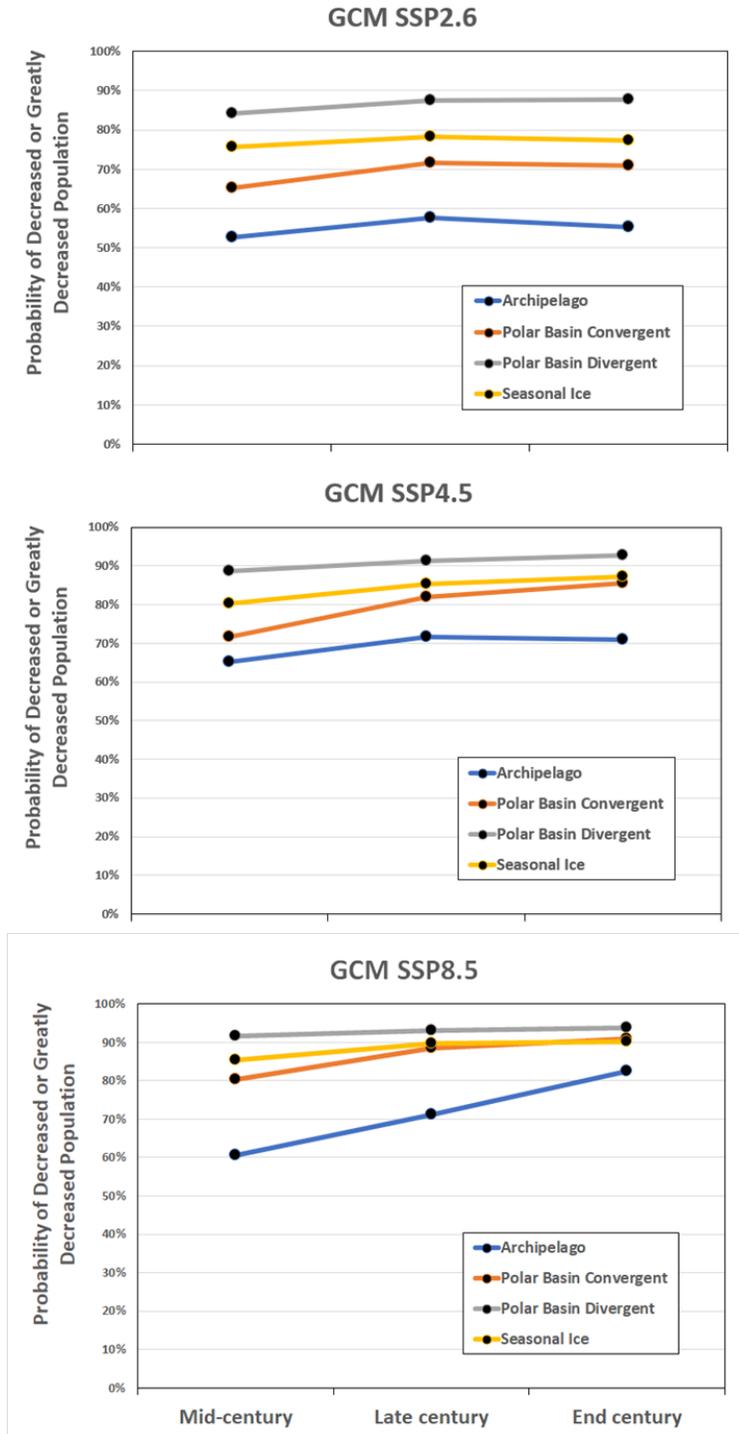
Appendix Figure C3. Differences in projected outcomes of polar bear populations, by ecoregion, time period, and IPCC CMIP (Coupled Model Intercomparison Project) sea-ice projection scenario, using the polar bear Bayesian network Phase II model (Atwood et al. 2016), comparing changes from CMIP5 to CMIP6 sea ice projections from IPCC, for three future time periods. Greater values denote higher probabilities under CMIP6 than CMIP5.