Exhibit C:

Amstrup, S.C., E.T. DeWeaver, D.C. Douglas, B.G. Marcot, G.M. Durner, C.M. Bitz, and D.A. Bailey. 2010. Greenhouse gas mitigation can reduce sea ice loss and increase polar bear persistence. Nature 468:955-960.

LETTER

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Greenhouse gas mitigation can reduce sea-ice loss and increase polar bear persistence

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On the basis of projected losses of their essential sea-ice habitats, a United States Geological Survey research team concluded in 2007 that two-thirds of the world's polar bears (*Ursus maritimus*) could disappear by mid-century if business-as-usual greenhouse gas emissions continue[1–3]. That projection, however, did not consider the possible benefits of greenhouse gas mitigation. A key question is whether temperature increases lead to proportional losses of sea-ice habitat, or whether sea-ice cover crosses a tipping point and irreversibly collapses when temperature reaches a critical threshold[4–6]. Such a tipping point would mean future greenhouse gas mitigation would confer no conservation benefits to polar bears. Here we show, using a general circulation model[7], that substantially more sea-ice habitat would be retained if greenhouse gas rise is mitigated. We also show, with Bayesian network model outcomes, that increased habitat retention under greenhouse gas mitigation means that polar bears could persist throughout the century in greater numbers and more areas than in the business-as-usual case[3]. Our general circulation model outcomes did not reveal thresholds leading to irreversible loss of ice[6]; instead, a linear relationship between global mean surface air temperature and sea-ice habitat substantiated the hypothesis that sea-ice thermodynamics can overcome albedo feedbacks proposed to cause sea-ice tipping points[5,6,8]. Our outcomes indicate that rapid summer ice losses in models[9] and observations[6,10] represent increased volatility of a thinning sea-ice cover, rather than tipping-point behaviour. Mitigation-driven Bayesian network outcomes show that previously predicted declines in polar bear distribution and numbers[3] are not unavoidable. Because polar bears are sentinels of the Arctic marine ecosystem[11] and trends in their sea-ice habitats foreshadow future global changes, mitigating greenhouse gas emissions to improve polar bear status would have conservation benefits throughout and beyond the Arctic[12].

Polar bears are dependent on the sea ice for access to their marine mammal prey[13,14], and occur only in Northern Hemisphere marine areas that are ice covered for long enough periods to allow sufficient foraging opportunity. Observed declines in summer sea ice have been associated with declining physical stature and condition, poorer survival and declining population size[2,15,16]. The anticipated future loss of sea-ice habitats resulting from global warming[1] was the principal driver of polar bear declines projected by the United States Geological Survey (USGS) studies[3,17]. Improved management of hunting and other human activities was found unable to materially alter this outcome (see plate 6 in ref. 3).

The USGS studies relied on general circulation model (GCM)-projected losses of Arctic sea ice based on the Special Report on Emissions Scenarios (SRES)[18] A1B 'business as usual' greenhouse gas emissions scenario. Recent emissions trends make it clear that without mitigation little departure from the 2007 polar bear projections could be expected[19]. Also, the hypothesis that the climate system contains tipping elements[4] means that habitats supporting cold-dependent species could disappear abruptly and irreversibly when a particular global mean surface air temperature (GMAT) is exceeded[6]. It has been proposed[20] that existing greenhouse gas emissions already have committed the earth to temperatures that will rise above the tipping point for loss of perennial Arctic sea ice. The perception that nothing can be done to avoid catastrophic losses and ultimate disappearance of polar bears was exemplified in 2007 when the general media proclaimed polar bears were irreversibly doomed[21].

We used projections of twenty-first century GMAT and sea-ice extent from the Community Climate System Model version 3 (CCSM3)[7] to test the hypothesis that a tipping point[4–6,8] will lead to irreversible loss of sea-ice habitats as GMAT increases. We used a Bayesian network model[3] to evaluate whether mitigating greenhouse gas rise could improve the future outlook for polar bears compared to previous projections.

CCSM3 simulations were forced with greenhouse gas concentrations from five emissions scenarios (Supplementary Table 1): SRES[18] A1B and B1 (the 2000 (Y2K) climate change commitment scenario)[22]; the Level 1 stabilization scenario (CCSP450) of the United States Climate Change Science Program[23]; and the alternative scenario (AS)[24]. We pooled the AS and CCSP450 realizations into a 5-run mitigation (MIT) ensemble.

Reduced radiative forcing with greenhouse gas mitigation resulted in cooler temperatures, greater sea-ice retention (Supplementary Figs 3 and 4) and less change in important polar bear habitat features (Fig. 1). Importantly, the relationship between GMAT and projected habitat change was largely linear (Fig. 2). Even in September, the month of minimum ice cover, as GMAT increased sea ice and polar-bear-habitat availability smoothly decreased—regardless of the greenhouse gas scenario (Supplementary Figs 5 and 6).

We rejected the null hypothesis that there is a tipping point[4–6,8] of perennial Arctic sea-ice collapse by our failure to find a critical temperature threshold in our GCM outcomes. Our model outcomes support the alternative hypothesis that sea-ice thermodynamics can dominate and reduce the destabilizing effects of the ice-albedo feedback on summer sea-ice cover[6,25,26].

To test further for evidence of tipping-point behaviour, we compared rapid ice-loss events (RILEs)[9,27] in CCSM3 realizations using A1B[18] greenhouse gas levels and levels from a 2020 commitment integration in which greenhouse gas concentrations followed A1B until 2020 and were fixed at 2020 levels thereafter. In the A1B reference run, a RILE occurred between 2020 and 2030, and September Arctic sea ice largely disappeared by mid-century (Fig. 3). If RILEs represent tipping-point behaviour, as suggested[5], the 2020 commitment run should have shown either no RILE or the same kind of permanent ice loss following a RILE as the reference run—depending on whether the climate system in that realization crossed the tipping point.

A RILE did occur in the 2020 commitment run. Instead of proceeding towards permanent ice loss as in the reference run, however, the

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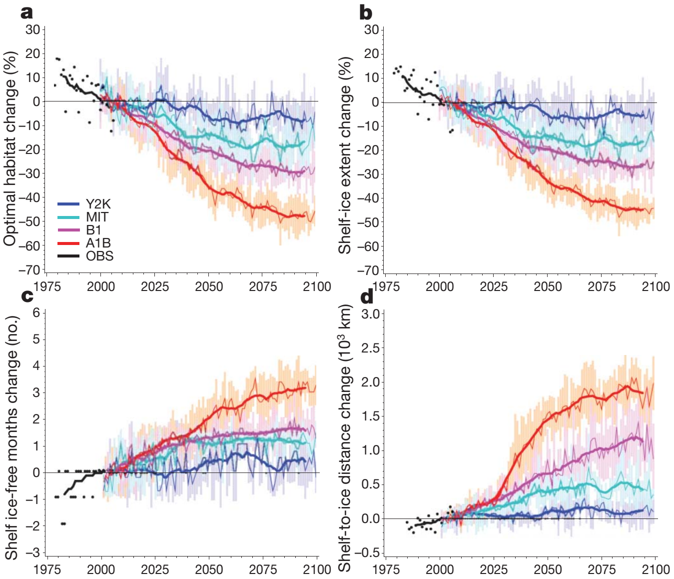

4 **Figure 1 | Changes from the present in polar bear habitat features varied greatly among greenhouse gas scenarios. a–d,** The DIV is illustrated here. Shown are changes in optimal polar bear foraging habitat (**a**), extent of sea ice over continental shelves (**b**), number of months continental shelves are ice free (**c**) and the distance from the shelf edge to the edge of the perennial pack ice as projected by CCSM3 with four greenhouse gas scenarios (defined in text) (**d**). Thin lines plot annual averages of the model runs under each greenhouse gas scenario, with error bars showing data ± 1 s.d. Bold lines are 10-year centred running averages of the annual mean values. OBS is observed passive microwave satellite data, black dots are the annual satellite observed values.

RILE in the 2020 commitment run was followed by partial recovery and substantial retention of September sea-ice cover through the century (Fig. 3). Because the 2020 commitment run was integrated from the same 2020 initial state as the A1B reference, it experienced the same near-term natural variability, including a RILE during the 2020s. The 2020 commitment run did not proceed to an irreversible and unstoppable loss of remaining ice[6], presumably because the long-term ice loss in CCSM3 is dictated by greenhouse gas radiative forcing and consequent global warming, which are substantially lower for the 2020 commitment run than A1B. This outcome indicates that RILEs are caused by the increased volatility of a thinner and more sensitive sea-ice cover, rather than the sea ice crossing an albedo-induced threshold from which it cannot return[9,28,29].

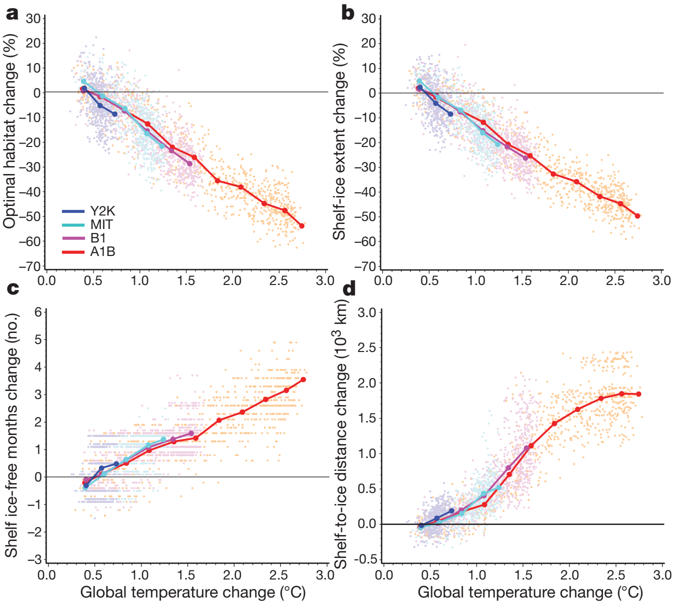

Figure 2 | Relationship between GMAT change and change in polar bear habitat features is essentially linear. a–d, The DIV is illustrated here. The optimal polar bear foraging habitat (**a**), extent of sea ice over continental shelves (**b**), number of months continental shelves are ice free (**c**) and the distance from the shelf edge to the edge of the perennial pack ice (**d**). Linear relationship between habitat and GMAT changes does not support the tipping-point hypothesis. Projections are from CCSM3 running four different greenhouse gas scenarios (defined in text).

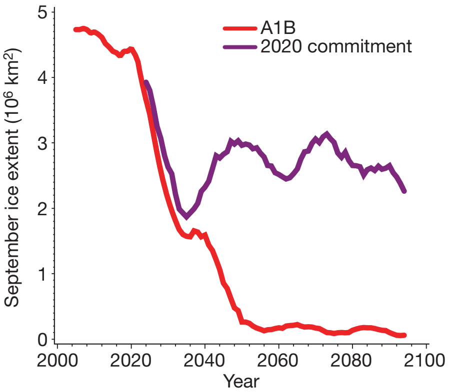

Figure 3 | September sea-ice extent (50% concentration) recovers from a RILE in a 2020 greenhouse gas commitment realization. In the 2020 commitment realization, which was integrated from the same initial state as the A1B reference realization, greenhouse gas concentrations followed the A1B scenario until 2020, and were fixed thereafter. RILEs occurred in both realizations during the decade of the 2020s. In contrast to the reference run (red line), the substantial sea-ice recovery in the 2020 commitment scenario (purple line) supports the concept that RILEs represent natural sea-ice variability superimposed on a secular warming-induced sea-ice decline, rather than tipping points. All lines represent 10-year running averages compiled from the annual data.

The linear relationship between GMAT and sea-ice habitat change, and the return of sea ice after the RILE in our 2020 commitment experiment confirm that there is no tipping point[4–6,8] for summer Arctic sea ice in the CCSM3 climate model. We recognize that the absence of tipping points in a climate model does not guarantee that tipping-point behaviour will not occur in the real world. We recognize also that absence of tipping-point behaviour in one GCM does not necessarily mean that tipping points would not be present in other GCMs. Because sea-ice loss in CCSM3 is more sensitive to GMAT rise than other GCMs[30], however, it provides an appropriate and important platform to test the tipping-point hypothesis (Supplementary Information). If the most sensitive of GCMs to greenhouse gas forcing does not illustrate tipping-point behaviour, we would not expect such behaviour in other, less sensitive models.

The finding that RILEs in model outcomes result from increased volatility of an ice cover that is progressively thinning because of warming temperatures—rather than tipping-point behaviour—is consistent with recently observed summer sea-ice declines. The sea-ice loss between September 2006 and September 2007, which was roughly equal to the entire loss of September ice extent between 1979 and 2006, encouraged speculation that a tipping point might have been crossed[5]. Yet, the 2008 and 2009 minima, although well below the long-term mean, were less severe than the record set in 2007[6,10]. Major losses of summer sea ice can thus occur, both in models and in observations, without pushing the sea ice past a tipping point into a permanent state of ice-free summers[6,10,26]. Instead of tipping-point behaviour, recent observations and model outcomes illustrate great natural variability superimposed on a secular warming-induced sea-ice decline. Controlling temperature increase, therefore, is the key to preserving sea-ice habitat.

We derived Bayesian network projections, informed by CCSM3 habitat projections, for polar bear populations in four ecoregions

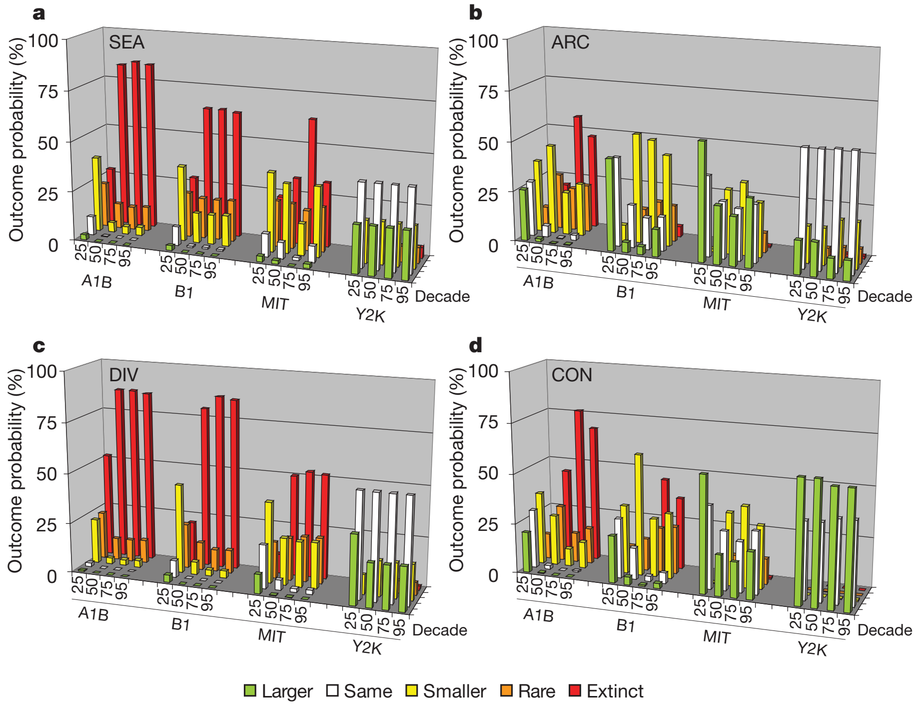

Figure 4 | Future polar bear persistence varies among ecoregions and greenhouse gas scenarios. Bayesian network model projected outcomes (coloured bars) are shown for each of four greenhouse gas scenarios, four future decades, and four ecoregions. Although substantial risk of extirpation continues for the SEA and DIV even with mitigation, increased levels of greenhouse gas mitigation improve the probability of future polar bear persistence in all ecoregions. In the *x*-axis legend, we refer to the decades of 2020–2029, 2045–2054, 2070–2079 and 2090–2099 as years 25, 50, 75 and 95.

(Supplementary Fig. 8). With A1B habitat values, polar bears were most likely to disappear from the Seasonal Ice Ecoregion (SEA) and Polar Basin Divergent Ice Ecoregion (DIV) by mid-century, and to be substantially reduced in the Archipelago Ecoregion (ARC) and the Polar Basin Convergent Ice Ecoregion (CON). With MIT habitat values, extinction probabilities were much lower in all ecoregions (Fig. 4). Contrary to the A1B case, when greenhouse gas mitigation was combined with best on-the-ground management practices (for example, controlling hunting and other interactions with humans) extinction was not the most probable outcome in any ecoregion, and future population sizes in the CON and ARC could be equivalent to or even larger than at present (Fig. 5). Greenhouse gas mitigation that keeps GMAT rise below 1.25 °C combined with traditional wildlife management could, it seems, maintain polar bear numbers at sustainable although lower-than-present levels throughout the century. (Supplementary Information).

METHODS SUMMARY

Relationships between temperature and habitat. We evaluated relationships between GMAT change and four habitat variables important to polar bear foraging success: resource-selection-function-based optimal habitat[1]; the temporal and spatial extent of sea ice over shallow continental shelf waters[2,14,17]; and the distance ice retreated from the continental shelf. GMAT change was calculated as the difference between the mean temperature of 1980–1999 (13.67 °C), and the future temperatures projected by CCSM3 under the different greenhouse gas scenarios. **Effects of habitat alteration on polar bears.** We projected the effects of habitat alteration on polar bear persistence with a Bayesian network model[3] modified to

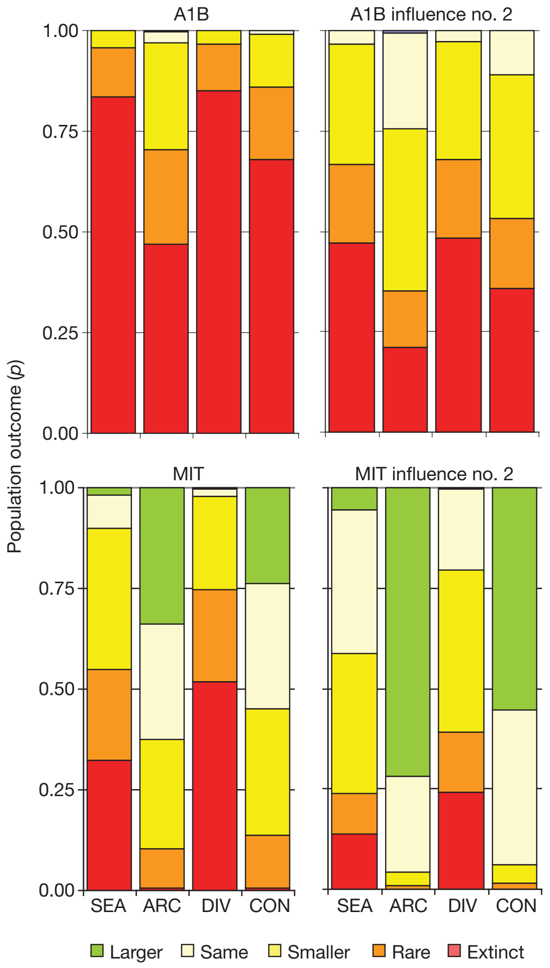

Figure 5 | Greenhouse gas mitigation and best possible wildlife management could allow polar bears to persist throughout current range. Bayesian network outcomes with habitat inputs from the MIT scenario are shown for the last decade of the twenty-first century. When temperature rise is kept at or below the MIT scenario and when on-the-ground management of harvest, bear–human interactions, oil and gas activities etc. is maximized (influence run no. 2), extinction is not the most probable outcome in any of the four ecoregions.

include inputs from other subject matter experts. Our Bayesian network model incorporated changes in four habitat variables projected for each of four ecoregions (Supplementary Fig. 8), with four greenhouse gas scenarios. The Bayesian network model also was informed by the broad range of other currently available information including: potential anthropogenic stressors; the established links between reduced physical stature and survival and declining sea-ice availability among polar bears in parts of their range[2,15–17]; qualitative information indicating that similar processes are underway in parts of the polar bear range where quantitative data are not yet available; the fact that polar bears ultimately are dependent on the sea ice[13,14] for consistent foraging success; and knowledge that if greenhouse-gas-induced warming continues to increase, essential polar bear sea-ice habitats ultimately will disappear[13].

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.C.A. conceived the project, assembled the team, and led writing. E.D. helped refine the project and analysed habitat/GMAT and RIGEs. D.C.D. staged sea-ice data and did the spatial analysis related to sea-ice metrics. B.G.M. conducted Bayesian network model runs and compiled outcomes. G.M.D. led development of the resource selection function approach to habitat analysis. C.M.B. proposed and helped interpret the 2020 CO_2 stabilization experiments. D.A.B. set up and ran the climate model simulations. E.D., C.M.B. and D.A.B. led interpretation of GCM outcomes. S.C.A., B.G.M. and D.C.D. interpreted biological outcomes. E.D. and D.C.D. developed all graphics. All authors contributed to writing and responding to review comments.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to S.C.A. (samstrup@pbears.org).

METHODS

GCM and scenarios. We used five emissions scenarios in our CCSM3 experiments. The Y2K scenario fixes atmospheric greenhouse gas concentrations at year 2000 levels[22]. The CCSP450[23] scenario keeps end of century total anthropogenic radiative forcing below 3.4 W m^{-2}, whereas the AS[24] does not allow anthropogenic radiative forcing to exceed 1.5 W m^{-2} above year 2000 levels. In A1B and B1, CO$_2$ rises to 689 p.p.m. and 537 p.p.m. by 2100 (using the CCSM3 concentration values, see Supplementary Fig. 1 and Supplementary Table 1). Greenhouse gas concentrations for the CCSP450[23] and SRES[18] scenarios were calculated from the emissions specified for these scenarios with the Model for the Assessment of Greenhouse Gas Induced Climate Change[22], a globally averaged gas-cycle/climate model. See ref. 12 for discussion of the CCSP greenhouse gas concentrations, and ref. 31 for details of the SRES[18] integrations. Greenhouse gas concentrations used in the AS are in supporting table 2 found at http://www.pnas.org/content/101/46/16109/suppl/DC1.

We obtained eight realizations each for A1B and B1, four realizations each for CCSP450 and Y2K, and one realization of the AS. Because net radiative forcing in the AS and CCSP450 were similar (Supplementary Fig. 2), and because global temperature change (Supplementary Fig. 3) and change in sea-ice extent (Supplementary Fig. 4) projected by the single AS run were very similar to members of the 4-run ensemble of CCSP450, we combined the single AS run with the 4 CCSP450 runs to create a 5-run mitigation ensemble (MIT). This left us with 4 forcing ensembles with which to compare the projected effects on the future welfare of polar bears: A1B, B1, Y2K and MIT.

GMAT change was calculated as the difference between the annual mean temperature of 1980–1999 (13.67 °C), and the future temperatures projected by CCSM3 under the different greenhouse gas scenarios we examined. We derived the 1980–1999 mean from 8 CCSM3 model runs incorporating greenhouse gas increases observed through the twentieth century (20C3M ensemble)[32].

Ecoregions. We evaluated how mitigation might affect polar bears occupying four Arctic ecoregions defined by temporal and spatial differences in observed ice melt, freeze, advection, bathymetry, proximity to land, and polar bear responses to those patterns (Supplementary Fig. 8). Each ecoregion is large, composed of several recognized subdivisions of the global polar bear population[3,33], and not entirely homogeneous. Nonetheless, they offer useful subdivisions of the worldwide polar bear distribution because areas within each tend to be more similar than they are to portions of other ecoregions.

The SEA includes Hudson Bay, Foxe Basin, Baffin Bay and Davis Strait. There, sea ice melts entirely in summer and the ~7,500 bears occurring there are forced ashore for extended periods during which they are largely food deprived. The ARC—the channels between the Canadian Arctic Islands—is presently home to ~5,000 bears and is characterized by heavy sea ice, much of which is present year round. The polar basin (the portion of the Arctic Ocean centred on the North Pole and ringed by the continental shelves of Eurasia, North America, Greenland and the Canadian Archipelago; Supplementary Fig. 8) was divided into a DIV, including the Southern Beaufort, Chukchi, East Siberian-Laptev, Kara and Barents Seas, and a CON including the east Greenland Sea, the continental shelf areas adjacent to northern Greenland and the Queen Elizabeth Islands, and the northern Beaufort Sea. Extensive formation of annual sea ice occurs in the DIV where ~8,500 bears currently occur. That ice typically is advected towards the central polar basin, out of the polar basin through Fram Strait, or against the CON. The CON is currently home to ~2,400 polar bears. Differences among ecoregions acknowledge that global warming effects on sea-ice habitats have different starting points[14] and that the nature of sea-ice changes is likely to be different.

Habitat metrics. We examined the relationship between GMAT change and four habitat variables known to be important to polar bears. First, we adopted the resource selection function (RSF) approach previously described[1] to convert GCM projections of sea-ice extent to projections of optimal polar bear habitat. RSFs are quantitative expressions of the habitats animals choose to utilize, relative to available habitats and resources[34]. Sea-ice concentrations for the observational period were estimated from monthly passive-microwave (PMW) satellite imagery[35]. Choices polar bears made from among available habitats were determined from 1985–1995 satellite radiolocations[1]. Optimal habitat was defined as any mapped pixel with an RSF value in the upper 20% of the seasonally averaged (1985–1995) RSF scores, and could be expressed as the sum of qualifying mapped pixels over any period of interest. We assessed changes in habitat availability by comparing annual sums of optimal habitat among projected time periods[1].

Estimates of optimal habitat were limited to the polar basin because only there did we have access to the radio-tracking data necessary to build RSF models. The importance of sea ice over continental shelves, however, is widely recognized as an important component of polar bear habitat[1,14]. Therefore, we derived a second habitat variable we called 'total shelf-ice habitat' from both observed and projected Arctic-wide sea-ice concentration maps. Total shelf-ice habitat was defined as the aerial cover (km^2) of all pixels with $\geq$50% ice concentration that were mapped over the continental shelves (<300 m depth). Waters with less than 50% ice cover were denoted ice-free because available data indicate that areas with sea-ice coverage <50% may not be preferred[1,15]. Unlike optimal habitat, total shelf-ice habitat could be calculated in all ecoregions and therefore provided a means of quantifying projected changes in habitat availability throughout the range of polar bears. We compared shelf-ice habitat expressed as the annual 12-month sum of sea-ice extent over the continental shelves in each ecoregion. Because SEA and ARC are almost entirely continental shelf area, the total shelf-ice habitat in those ecoregions equated to the total annual area (sum of 12 months) of $\geq$50% concentration sea ice.

The third habitat variable, one of the most important variables representing seasonal changes in habitat available to polar bears[2,15–17,36], was calculated as the change from present in the number of months that ice was projected to be absent (ice-free months) from the continental shelves. An ice-free month occurred in an ecoregion when <50% of the shelf area was covered by sea ice of $\geq$50% concentration. Outside the polar basin this variable represented simply the ice-free season because the SEA and ARC are composed almost entirely of continental shelf.

Recognizing that the magnitude of the separation of the sea ice from preferred foraging areas also might be important, we calculated a fourth habitat variable as the change in average distance from the continental shelf to the ice pack during the month of minimum ice extent (shelf-to-ice distance). Shelf-to-ice distance was calculated, for the month of minimum ice extent, as the mean distance from every shelf pixel in either of the polar basin ecoregions to the nearest ice-covered pixel (>50% concentration) in the main body of perennial ice. We did not calculate shelf-to-ice distance in SEA and ARC because they are almost entirely comprised of continental shelf.

We plotted GMAT change against these habitat features to evaluate potential nonlinearities in the relationships. Figure 2 and Supplementary Figs 5 and 6 illustrate annual mean GMAT values (x-axis) and corresponding habitat values (y-axis) for each year of each simulation (small dots). Each scenario is shown in a different colour. Large connected dots in each plot are centred on the means, over all years, of the annual GMAT values and values of the habitat-related variables, where GMAT lies within 0.25 °C bins centred on 0.25 °C, 0.5 °C, 0.75 °C, etc., for all simulations performed for each scenario. Large dots are not in exact vertical alignment because the means of the GMAT values in each bin differ among scenarios.

Bayesian network model. The effects of future habitat alteration on probabilities of future polar bear persistence were projected with a beta version[37] of the Bayesian network model used previously[3]. The beta model was reviewed by two other polar bear experts and modified accordingly. Some conditional probabilities were modified to incorporate reviewers' suggestions and observations noted since building the original model. The beta model includes a finer division of bins for sea-ice habitat variables, but upper and lower bounds were retained to ensure that the range of possible entries in conditional probability tables was consistent with the assignments in ref. 3. The final structure (nodes and links) of the beta model is nearly identical to that of the alpha model[3].

Our beta model incorporated changes in the four habitat variables projected under different greenhouse gas scenarios. We calculated the average per cent of future changes, from the 2001–2010 decade, in annual optimal and shelf-ice habitat. Changes in the number of ice-free months and the shelf-to-ice distance were expressed as the average increases (months of ice absence and kilometres of ice retreat) at each decade.

The Bayesian network model also was informed by the broad range of other currently available information including: potential anthropogenic stressors; the established links between reduced physical stature and survival and declining sea-ice availability among polar bears in parts of their range[2,15–17,36]; available qualitative information indicating that similar processes are underway in parts of the polar bear range where quantitative data are not yet available; the fact that polar bears ultimately are dependent on the sea ice[13,14] for consistent foraging success; and that if greenhouse-gas-induced warming continues to increase, essential polar bear sea-ice habitats ultimately will disappear[13]. These additional factors were incorporated into the model as ordinal or qualitative categories or as background with which conditional probability tables were parameterized. The beta model incorporated 4 greenhouse gas scenarios and was applied to each of the four ecoregions at four future decadal time periods: 2020–2029, 2045–2054, 2070–2079 and 2090–2099. At each time period, states of these variables could represent a condition similar to present, better than present, or worse than present (see tables 3 and 4 in ref. 3).

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