

Harvest Assessment for the Baffin Bay and Kane Basin Polar Bear Subpopulations

Final Report to the Canada-Greenland Joint Commission on Polar Bear

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Executive Summary

Background

The Baffin Bay (BB) and Kane Basin (KB) polar bear subpopulations are jointly managed by Canada (Nunavut) and Greenland. The Canada-Greenland Joint Commission on Polar Bear (JC) facilitates coordination between the two jurisdictions. In 2011, due to concerns about potentially unsustainable harvest and the demographic effects of observed, long-term changes in sea-ice habitat, the JC tasked its Scientific Working Group (SWG) with reassessing the status of the BB and KB subpopulations. Both subpopulation were surveyed in the 1990s. However, by 2011 these earlier surveys were considered too old to provide a reliable basis for assessment or future harvest management. Consequently, the SWG undertook a research program using genetic capture-recapture (BB and KB), radiotelemetry (BB and KB), and aerial surveys (KB) from 2011–2014 to obtain updated information on subpopulation size, status, delineation, habitat quality, and habitat use (SWG 2016).

Results from these recent studies suggest that, over the last few decades, the BB subpopulation has undergone significant changes in range, movements, habitat use, body condition, and reproductive performance concurrent with a decline in sea-ice extent, duration, and quality. Baffin Bay is a relatively abundant subpopulation with an estimated 2,826 bears in 2011–2013 (95% CI = 2,059–3,593). However, due to differences in capture-recapture (CR) sampling designs, results from the surveys in the 1990s and 2010's cannot be directly compared to assess trends in the size of the subpopulation. For KB, recent studies suggest that the subpopulation is transitioning from a multiyear sea-ice system towards a sea-ice regimen characteristic of the seasonal ice ecoregion, where sea ice melts almost entirely during the summer. The KB subpopulation has responded to changing sea ice by expanding its range since the 1990s, especially during summer. Larger and more variable home ranges, and the use of lower sea-ice concentrations in summer and fall, have also been observed (SWG 2016). The current abundance of the KB subpopulation was estimated at 357 bears in 2012–2014 (95% CI = 221–493), with the available evidence suggesting this subpopulation has been stable or increasing since the 1990s.

Harvest assessment approach

Following a review of research findings for BB and KB (SWG 2016), the JC provided the SWG with three potential alternatives for subpopulation Management Objectives: (1) maintain a relatively stable subpopulation size; (2) maintain a subpopulation size that achieves maximum sustainable yield, with respect to a potentially changing environmental carrying capacity; and (3) reduce subpopulation size by approximately 30% in 10–15 years. Management Objectives 1 and 2 were considered potential objectives for both BB and KB, while an exploration of Management Objective 3 was associated with concerns about human-bear conflicts, and was requested for BB only. The JC requested that the SWG use the best-available information to provide advice on harvest management strategies, including levels of Total Allowable Harvest, under which these objectives could be achieved. The JC provided two levels of risk tolerance (“low” and “medium”) for not meeting each objective.

In this report, we use the ecological and demographic data from SWG (2016) to evaluate a suite of potential harvest strategies for the BB and KB subpopulations. We evaluated all strategies against the specific management objectives and risk tolerances provided by the JC, and for each strategy we also recorded other metrics of biological or management interest (e.g., the probability of severely depleting adult male bears). We interpreted the JC’s request for advice on “low” and “medium” risk tolerance to mean a 90% and 70% chance of successfully meeting a management objective, respectively (alternatively, a 10% and 30% chance of failing to meet a management objective).

We performed a quantitative risk assessment using a demographic model based on the life history of polar bears, which can include the effects of environmental change (Regehr et al. 2017). The potential effects of future changes in sea-ice conditions on subpopulation size and status, and the resulting implications for harvest management, were incorporated in the analyses by using projected trends in carrying capacity (K , the capacity of the environment to support a given number of polar bears). In addition to this direct environmental effect, the model included a mechanistic submodel of Allee effects in the mating system, which limited reproduction under conditions of low subpopulation density or imbalanced numbers of adult females and males. We considered several different scenarios of the vital rates (e.g., rates of reproduction and survival) for each subpopulation due to uncertainty and potential bias in some demographic parameters from CR studies for both BB and KB.

For each combination of management objective and vital rates scenario, we evaluated multiple harvest strategies. Harvest strategies were defined in terms of the key elements that can be identified and adaptively managed by authorizing agencies, including harvest rate and harvest level (measured in number of independent bears [i.e., not including cubs-of-the-year or yearlings] removed annually), the sex and age composition of the harvest, the management interval, and the quality (i.e., level of statistical precision) of available survey data. We evaluated 10, 15, and 20-year management intervals, defined as the number of years between successive changes to the harvest based on new data from subpopulation surveys. The management interval often used as an objective in Canada is 15 years. For BB and KB, the interval between the two most recent surveys was 18 years (1993 to 2011), although some management adjustments occurred during this period. Thus, a management interval of 15–20 years approximates current practices for these subpopulations. A management interval of 10 years was used to illustrate the effects of more frequent subpopulation surveys and management changes.

Strategies using three harvest sex ratios (SR) were examined; $SR = 1$ (i.e., a 1:1 male-to-female ratio) reflecting conditions where harvest is not selective for either males or females; $SR = 2$ reflecting the target ratio for sex-selective harvest currently implemented in Canada, and reflecting the reported sex ratio of the combined Canada-Greenland harvest 1998–2013; and, for each subpopulation, a ‘*status quo*’ sex ratio of the combined Canada-Greenland harvest 1998–2013, based on results from recent genetic sampling (2011–2013) indicating that sex was incorrectly reported for a substantial number of harvested bears.

All population projections assumed a state-dependent (i.e., dependent on current conditions) management approach, under which harvest levels did not remain constant in the future, but rather were updated according to the management interval. This means that the harvest strategies are tied directly to the timeline for reassessing subpopulation abundance and vital rates.

Baffin Bay

For the BB subpopulation, projections included a proxy for changes in K estimated from the number of ice-covered days per year in the BB region, which decline by approximately 5.5% per decade when projected forward in time. Use of a projected, declining trend in K is consistent with evidence for range contractions, and changes in nutritional condition and reproductive rates

of BB polar bears associated with sea-ice loss (SWG 2016). In the demographic model, we assumed that the current rates of survival and reproduction for BB polar bears reflect a subpopulation that is near its maximum net productivity level (MNPL, the subpopulation size that results in the greatest net annual increment in numbers resulting from reproduction minus losses due to natural mortality). In other words, we assumed that subpopulation size has been held below K due to harvest, and that BB bears are not currently experiencing strong density-dependent suppression of survival or reproduction. Our projections did not include potential density-independent effects of sea-ice loss, which could reduce subpopulation resilience and capacity to support harvest in the future. If such changes occur rapidly compared to the schedule for future subpopulation surveys and harvest changes (as determined by the management interval), the risk of negative population outcomes would be higher than estimated from our projections.

We evaluated three scenarios of the vital rates for the BB subpopulation. Each scenario used the same rates of reproduction (litter production rate and cub-of-the-year litter size) as calculated from the recent genetic CR data (2011–2013) but differed in the rates of survival. Scenario 1 used estimates of unharvested survival (S^*) calculated from CR data for the period 2011–2013. Scenario 2 used estimates of S^* calculated from CR data for the period 1998–2010. Scenario 3 used estimates of S^* representing the “average” rates seen amongst polar bear subpopulations; this provided a benchmark for comparison with other subpopulations. Of the three scenarios, we considered Scenario 2 a more likely representation of the status of the BB subpopulation, because it used data specific to BB and could reproduce plausible trends in subpopulation abundance and sex ratio that were consistent with the available scientific information and Traditional Ecological Knowledge. Additionally, unlike Scenario 1, estimates of S^* for the period 1998–2010 were less susceptible to terminal bias (i.e., bias at the end of a time series of estimates, a common problem in CR studies).

Scenario 2 resulted in an unharvested asymptotic population growth rate $\lambda = 1.08$ (SE = 0.02) annually (i.e., 8% per year). For harvest strategies with $SR = 1.25$ (i.e., a 1.25:1 male-to-female sex ratio in the harvest, the estimated *status quo* for BB based on genetic data), an age composition based on historic harvest data, and a 15-year management interval, present-day harvest rates of up to 4.3% and 5.7% were consistent with Management Objective 2 under “low” and “medium” risk tolerances, respectively. We focused on Management Objective 2 for the BB

subpopulation because this objective is more relevant to sustainable harvest when K is declining. Applying these harvest rates to the current subpopulation size of 2,826 would result in present-day harvest levels of up to approximately 120 and 160 bears per year, depending on risk tolerance. Under this harvest strategy, the present-day harvest level would be maintained for a 15-year period, at which point a new subpopulation survey should have been completed and the harvest should have been re-calculated. Over the next 35 years (approximately three polar bear generations), the harvest level would be expected to decline due to declining K with sea-ice loss, and possibly due to other demographic effects.

The harvest strategies listed above (i.e., present-day harvest rates of up to 4.3% and 5.7%) should be interpreted with caution for several reasons. First, strategies at the upper end of this range were associated with up to a 12% probability of severely depleting adult male bears, and up to a 4% probability of extirpation (i.e., reduction to a very small and non-viable subpopulation size) after 35 years. Second, recent subpopulation studies provided evidence for ecological effects of sea-ice loss that could, now or in the future, translate into negative demographic effects above and beyond the declining trend in K and Allee effects included in our model. Although there were several reasons to place less confidence in the relatively low estimates of S^* from 2011–2013 (Scenario 1), it is possible that these lower estimates reflected, to some extent, a reduced capacity for subpopulation growth due to sea-ice loss. If that is the case, the risks of negative population outcomes could be much higher than estimated under Scenario 2. Our analyses did not make purposefully-conservative assumptions, and therefore could have understated the future effects of sea-ice loss. Such risks could be reduced through a precautionary approach to harvest management.

Simulations for Management Objective 1 (maintaining a relatively stable subpopulation size) demonstrated that this objective likely cannot be achieved in the mid- to long-term due to projected declines in K , which would reduce subpopulation size regardless of harvest level. Simulations also suggested that Management Objective 3 for the BB subpopulation (reduction of 30% in 10–15 years) is probably not feasible at the level of risk tolerance stated by the JC. The largest-possible subpopulation reduction that remained within risk tolerance (with some caveats—see main text) was approximately 25% over 15 years. This required a 1:1 male-to-female sex ratio in the harvest, a 5-year management interval, and improved precision in the vital rates estimated from future subpopulation surveys. Under this harvest strategy, a present-day

harvest rate of 8.7% (approximately 245 bears per year) would be applied for a 5-year period, at which point a new subpopulation survey would have been completed and the harvest would be re-calculated. Over a 15-year period, the harvest level would need to decline rapidly as subpopulation size declined. Results suggested that attempting a managed subpopulation reduction without a near-optimal, state-dependent approach—for example, applying a fixed-level harvest of 245 bears per year without new subpopulation surveys—would be associated with high probabilities of severe male depletion and extirpation after 15 years.

Kane Basin

For the KB subpopulation, projections included interannual variation in K but no declining trend, reflecting evidence that decreasing sea ice in the multiyear-ice region of KB may have positive ecological effects in the near term (e.g., increased marine productivity as the system transitions to annual sea-ice dynamics; SWG 2016). Similar to BB, we assumed that the estimated rates of survival and reproduction for KB polar bears reflect a subpopulation that is currently functioning near MNPL.

We evaluated two scenarios of the vital rates that differed in terms of estimated survival rates for young bears. Scenario 1 used time-constant estimates of S^* calculated from CR data for the period 1992–2014; and Scenario 2 used similar estimates, but with mean values of S^* for bears less than or equal to 2 years of age modified, to reproduce the estimated increase in subpopulation abundance from 224 bears in the 1990s to 357 bears in the 2010s (SWG 2016). We considered Scenario 2 a more likely representation of the status of the KB subpopulation, because under Scenario 1 the unmodified estimates of S^* for bears age 2 years or less were low (range across age classes of 0.45–0.73) compared to other subpopulations of similar productivity, and had high statistical uncertainty due to sparse data (e.g., less than 4 cubs-of-the-year were sampled per year 2012–2014). Additionally, use of survival rates under Scenario 1 suggested a poor demographic status for the KB subpopulation, yielding an unharvested population growth rate of 1% per year ($\lambda = 1.01$ [SE = 0.04]). This low rate is inconsistent with multiple lines of evidence for the KB subpopulation, including estimated increases in subpopulation size since the 1990s (SWG 2016), the likely positive trends in marine productivity in the region, recent information on nutritional condition and reproduction, and available Traditional Ecological Knowledge.

Scenario 2 for the KB subpopulation resulted in an unharvested population growth rate of 5% per year ($\lambda = 1.05$ [SE = 0.06]). For harvest strategies with a $SR = 0.94$ (the estimated *status quo*, based on genetic data), an age composition based on historic harvest data, and a 15-year management interval, present-day harvest rates up to 1.7% and 1.1% were consistent with Management Objectives 1 and 2, respectively, at the “medium” level of risk tolerance. At the “low” level of risk tolerance, Management Objectives 1 and 2 could not be met in the absence of harvest, due to variability in subpopulation trajectories resulting from high uncertainty in the vital rates. Applying harvest rates of 1.1% to 1.7% to the current subpopulation size of 357 would result in a present-day harvest levels of up to approximately 4–6 bears per year. Under this harvest strategy, the present-day harvest level would be maintained for a 15-year period, at which point a new subpopulation survey would be completed and the harvest would be re-calculated. Over the next 35 years, the harvest level would be expected to remain stable or increase due to stable or potentially increasing K . Harvest strategies at the upper end of this range were associated with up to a 17% probability of severely depleting adult male bears, and up to a 3% increased probability of extirpation compared to projections with no harvest, after 35 years.

Under Scenario 2, harvest rates that met management objectives for the KB subpopulation were lower than the observed harvest rate for the period 1998–2014, during which subpopulation size likely increased (SWG 2016). This inconsistency was due primarily to high statistical uncertainty in estimates of S^* for bears age 2 years or less, a consequence of small sample sizes and relatively short study periods of research in KB. If alternative assumptions were made for uncertainty in estimates of S^* for bears age 2 years or less (e.g., if the precision of these estimates was increased to match the precision of survival estimates for older bears), present-day harvest rates up to 2.2% to 2.8% (8–10 bears per year) were consistent with Management Objective 1 at a “medium” risk tolerance, when following a state-dependent approach with a 15-year management interval.

Considering all available ecological and demographic data for the KB subpopulation, present-day harvest rates up to approximately 2.8% (10 bears per year) seem unlikely to cause negative population outcomes under a state-dependent approach with effective monitoring. It is possible that the logistical challenges of studying the KB subpopulation may lead to continued difficulty in obtaining accurate and precise estimates of vital rates, despite increased survey

efforts. We therefore suggest developing a suite of ecological and demographic indicators to monitor subpopulation status, including accurate information on the level and composition of the harvest, marine productivity, habitat availability, reproductive rates, and estimates or indices of subpopulation size (via aerial survey or CR).

Monitoring requirements and further research

The results in this report are intended to help inform and guide subsequent decisions of the JC with respect to determining appropriate levels of harvest for these two shared subpopulations of polar bears. Both BB and KB are experiencing long-term trends in the extent, duration, and quality of sea-ice habitat. Our analyses identify harvest strategies that are designed to maintain subpopulation size near MNPL with respect to a changing K , and to limit negative effects of harvest on the probability of subpopulation persistence. All of the harvest strategies presented in this report require the existence of a coupled research-management system under which both the sustainable harvest rate and the harvest level are adjusted periodically, based on new scientific information from subpopulation surveys and other sources. For both BB and KB, our analyses demonstrate that shorter management intervals and more precise data can substantially reduce the risk of negative population outcomes associated with a given harvest strategy. A state-dependent management approach is an effective means of reducing the risk of overexploitation while maintaining opportunities for use. This is especially important if sea-ice loss is currently having ecological effects on polar bears that may signal negative demographic effects in the future (BB); or if a less-conservative harvest strategy is selected when the currently available estimates of vital rates have high uncertainty and appear inconsistent with other lines of evidence (KB). Harvest strategies that appear sustainable over the next three polar bear generations under a state-dependent approach could lead to subpopulation depletion or extirpation under a fixed-level approach that removes the same number of bears annually without reassessment.

In addition to regular, periodic surveys to estimate subpopulation size and vital rates, we recommend more frequent but less intensive monitoring of sea-ice habitat, movement and habitat use, nutritional condition, and reproductive indices based on research and harvest data, and Traditional Ecological Knowledge. Continuous genetic monitoring of the harvest to detect recoveries of genetically marked animals, and improving the accuracy of harvest reporting, are

also needed. Systematic analysis of all harvest data, especially for the BB subpopulation, could provide complimentary estimates of harvest rate and other demographic parameters. During the intervening years between scheduled subpopulation surveys, these monitoring programs may provide a mechanism to detect sudden shifts in environmental conditions or subpopulation status that might necessitate a change in harvest strategy (e.g., a shortening of the management interval). Also, these monitoring programs will provide information essential for designing and implementing periodic subpopulation assessments. We suggest that future subpopulation assessment protocols consider the use of integrated population models, which can analyze data from multiple sources (e.g., different types of research, harvest, and Traditional Ecological Knowledge) in a unified framework, potentially leading to improved assessments of overall subpopulation status.

For the BB and KB subpopulations, the harvest sex ratios in recent decades, based on genetic sex determination, indicate weaker selection for males compared to the reported sex ratio and the management goal of a 2:1 male-to-female ratio. In most of our simulations, a harvest strategy with $SR = 2$ (instead of the lower *status quo* values of SR) did not result in higher harvest rates that met management objectives. This is because, for both subpopulations, estimates of S^* were lower for males than females, and females currently comprise approximately 70% of independent bears. These factors, if combined with a strongly male-selective harvest, often led to the severe depletion of adult males in our simulations, which had negative effects on reproduction and increased the probability of extirpation due to Allee effects in the mating system. These findings do not provide evidence against the conservation value of sex-selective harvest for polar bears. Rather, they indicate that depletion of males may be an emerging conservation concern for the BB and KB subpopulations. Given the current regulation of harvest in Canada (Nunavut) based on a sex 2:1 male-to-female sex ratio, it is important to further investigate this issue and particularly the lower estimates of survival for male bears. Our finding of skewed sex ratios in both subpopulations, despite an overall harvest that may not be strongly selective, suggests that these lower survival rates have a biological basis. Concurrent monitoring of the sex ratio in the harvest, the sex and age composition of the subpopulation, and the litter production rate, are necessary to determine the extent to which reduction of male bears could negatively affect the productivity of the BB and KB subpopulations.

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Introduction

Background on the Joint Commission, and the Baffin Bay and Kane Basin subpopulation reassessments

The Canada-Greenland Joint Commission on Polar Bear (JC) was established with the signing of a “*Memorandum of Understanding between the Government of Canada, the Government of Nunavut, and the Government of Greenland for the Conservation and Management of Polar Bear Populations*” on 30 October 2009 (Anon. 2009). The primary objectives of this Memorandum of Understanding are to: “(1) to manage polar bear within the Kane Basin and Baffin Bay management units in order to ensure their conservation and sustainable management into the future, and, (2) establish an effective system of management which will include adhering to the principles of conservation”. The JC subsequently established a Scientific Working Group (SWG) to provide scientific advice and recommendations with respect to the conservation and management of the Baffin Bay (BB) and Kane Basin (KB) polar bear subpopulations. In 2010, the JC tasked the SWG with using the best-available scientific information to:

- (1) Propose Total Allowable Harvest (TAH) levels for the Kane Basin and Baffin Bay subpopulations.
- (2) Provide science advice to the Joint Commission for monitoring the effects of habitat changes on polar bears.

The SWG reviewed the available scientific information and reported (SWG 2010) that for both subpopulations the most recent status updates indicated that 100% of population viability analysis (PVA) simulations, using current harvest levels, resulted in subpopulation declines after 10 years (PBSG 2010). The SWG also noted that PVA simulations are typically run 10–15 years beyond the point in time that abundance and vital rates were estimated. Given that the most recent estimates of demographic parameters for the BB and KB subpopulations were from the mid- to late 1990s (Taylor et al. 2005, 2008a; PBSG 2010), the SWG concluded that the available information was outdated and it was unknown whether demographic parameters had changed over time. These factors, in combination with the large-scale environmental changes in BB during recent decades, led the SWG to recommend that a high priority be given to

developing new estimates of subpopulation abundance, subpopulation delineation, and vital rates (SWG 2010).

As a result, the JC tasked the SWG with evaluating various methods for assessing the number of polar bears in BB and KB (JC 2010). The SWG considered the pros and cons of physical CR, genetic CR, and aerial surveys; and concluded that physical CR was the preferred method to obtain robust ecological and demographic data (SWG 2011). However, due to the lack of support for physical CR among Inuit in Nunavut, and concerns that variability in sea-ice conditions can make it difficult to obtain accurate abundance estimates from aerial surveys, the JC recommended development of a 3-year research program based on genetic CR methods using biopsy darting. Following this recommendation, field research programs were conducted 2011–2014 as part of comprehensive reassessments of the BB and KB polar bear subpopulations (SWG 2016).

Estimation of sustainable harvest for polar bears

Historically, polar bear management was based on the assumption that sea-ice habitat was relatively stable over the long term and that, once subpopulation size (N) had been estimated, conservation could be achieved through harvest management (SWG 2011). Sustainable harvest, therefore, would depend on estimates of abundance and vital rates (e.g., probabilities of survival and reproduction), the harvest level, and the sex and age composition of the harvest. Early modeling suggested that sex-selective harvest at a rate of 4.5% of total population size, was sustainable for polar bears under optimal conditions (Taylor et al. 1987a, b). Recently, Regehr et al. (2015, 2017) also found that a 4.5% harvest rate, with a 2:1 male-to-female sex ratio in the harvest, was reasonable under many biological and management conditions, provided that population surveys were conducted periodically and harvest levels were adjusted when necessary. Regehr et al. (2017) also noted that sustainable harvest rates could be lower or higher than 4.5% under some conditions. This finding is consistent with recent studies that have provided a better understanding of how vital rates vary across subpopulations and change over time (e.g., Amstrup et al. 2001; Taylor et al. 2002, 2005, 2006; PBSG 2006, 2010; Regehr et al. 2007, 2010).

In recent decades, management and conservation of polar bears, particularly in Canada, have been informed by predictive modeling that incorporates subpopulation-specific vital rates.

The development of RISKMAN (Taylor et al. 2001), a stochastic population model, made it possible to perform detailed harvest assessments for multiple subpopulations, providing managers with a better understanding of the risk associated with different harvest strategies (Taylor et al. 2002, 2005, 2006, 2008a). However, RISKMAN was primarily intended to inform near-term management under stable conditions. It did not include a detailed model of density dependence, allow for future changes in environmental conditions or demographic parameters, or provide a way to directly assess how the frequency and intensity of subpopulation surveys can affect the risk of different management actions.

At present, the primary threat to polar bears throughout their range is the reduction in sea-ice habitat area, duration, and quality as a consequence of climate change (Derocher et al. 2004; Laidre et al. 2008, 2015; Wiig et al. 2015; Atwood et al. 2016). In 2009, the Polar Bear Range States (2015) agreed that the impacts of climate change constitute the most important threat to polar bear conservation and recommended that best management practices should “Consider the cumulative effects of climate change and human activities on polar bear subpopulations when making management decisions using tools such as predictive modeling”. Hence, in many situations sound harvest management will no longer rely solely on an estimate of abundance and a fixed annual harvest rate (e.g., 4.5%), or on predictive modeling that assumes stable conditions. The current demographic status of the world’s 19 polar bear subpopulations is variable (PBSG 2017) due to ecological variation, different rates of habitat change, and the influence of anthropogenic stressors (Vongraven and Peacock 2011; Atwood et al. 2016). Furthermore, although national and international agreements provide common standards for polar bear conservation, near-term management goals can vary across jurisdictions as a function of environmental, social, and other factors (Polar Bear Range States 2015). In light of this variability and the primary threat of habitat loss due to climate change, there is a need for improved risk assessment tools that can incorporate a broad range of environmental and direct human-caused factors to address specific management goals.

Harvest assessment for the Baffin Bay and Kane Basin subpopulations

Recent reassessments of the BB and KB polar bear subpopulations provided the ecological and demographic data necessary for harvest risk assessments (SWG 2016). However, the SWG was unable to provide harvest options as part of its final report because the JC had not provided specific guidance on (i) management objectives for each subpopulation, (ii) the expected frequency and intensity of future monitoring, and (iii) risk tolerance with respect to the effects of human-caused removals. Subsequently, the JC requested that the SWG propose TAH levels for both the BB and KB subpopulations based on the abundance estimates in SWG (2016), historical harvest levels, an expected 7–15 year frequency between subpopulation surveys, and that TAH be evaluated relative to the following management objectives (JC 2016):

- 1a) Maintaining a stable subpopulation at the current subpopulation estimate, with a low tolerance for the risk of declines below 90% of this level.
- 1b) Maintaining a stable subpopulation at the current subpopulation estimate, with a medium tolerance for the risk of declines below 90% of this level.
- 2a) A TAH that would ensure a maximum sustainable yield, with a low level of risk tolerance for the subpopulation declining below this level.
- 2b) A TAH that would ensure a maximum sustainable yield, with a medium level of risk tolerance for the subpopulation declining below this level.

Lacking further guidance, the SWG interpreted “low” and “medium” tolerance for the risk of a subpopulation decline below a specified level, to mean requiring a 90% or 70% probability of maintaining a subpopulation size above the specified level, respectively.

In addition to the management objectives above, the JC subsequently requested that the SWG explore possible methods to achieve a managed reduction of the BB subpopulation, from the current estimate of 2,826 animals (SWG 2016) to approximately 2,000 animals, over a 10–15 year period (JC 2017). Possible reasons for considering a managed reduction could be to reduce human-bear conflicts in circumstances where densities of polar bears have increased or nutritionally-stressed bears are increasingly coming in close proximity to humans, which may occur as sea-ice loss continues (Wilder et al. 2017).

In this report, we used recent estimates of abundance and vital rates (SWG 2016) in a matrix-based demographic model (adapted from Regehr et al. 2015, 2017) to evaluate TAH for the BB and KB polar bear subpopulations, relative to management objectives provided by the JC.

The demographic model is based on the life history of polar bears, and provides several advantages compared to other predictive modeling tools, including (i) an ability to incorporate the effects of a changing habitat (e.g., through a variable or declining K), (ii) a species-specific model of density dependence, which is important when evaluating the combined effects of habitat change and human-caused removals; (iii) an integrated model of Allee effects in the mating system, based on the work of Molnár et al. (2008, 2014); and (iv) a direct link between research and management actions, so that harvest strategies can be evaluated in light of the frequency and intensity of future subpopulation surveys.

For each subpopulation, we used data from SWG (2016) to develop alternative scenarios of the vital rates, which either represented plausible conditions for the current status of the subpopulation or provided a useful benchmark (e.g., for comparison with a subpopulation of “average” productivity). We considered multiple scenarios because estimates of demographic parameters from CR studies for polar bears can include uncertainty that is not reflected in the statistical distributions of the parameters, as well as multiple types of bias (Regehr et al. 2009; Chapter 3 in SWG 2016). To obtain robust results from predictive modeling it is important that demographic parameters be evaluated for biological realism and within the framework of other available information (e.g., Skalski et al. 2012).

Our analyses focused on harvest management strategies that were defined in terms of the harvest rate (percentage of the total subpopulation size removed per year), harvest level (measured in number of independent bears removed per year), sex and age composition of removed animals, management interval (number of years between successive subpopulation surveys and management changes), and the precision of demographic parameters estimated from subpopulation surveys. All harvest strategies were evaluated using a state-dependent (i.e., dependent on current conditions; Lyons et al. 2008) management approach, under which both the harvest rate and harvest level were updated periodically according to the management interval. State-dependent management has many features in common with the “adaptive management” approach recommended by the Range States (Polar Bear Range States 2015). It also has many advantages over other management approaches (e.g., a fixed-level harvest), both in terms of mitigating harvest risks and making it possible to maximize long-term yield (Regehr et al. 2017). Because our analyses incorporated multiple types of variability (e.g., statistical uncertainty and

environmental variation), results are presented in a probabilistic manner that is consistent with management objectives provided by the JC.

The final results of this analysis are a series of potential harvest strategies for the BB and KB subpopulations. It is intended that these results help inform and guide subsequent decisions of the JC with respect to its determination of appropriate levels of harvest for these two shared subpopulations of polar bears.

Methods

Demographic and management model

We performed population projections using the matrix-based demographic model described in Regehr et al. (2015, 2017). The demographic model is based on the polar bear life cycle (Figure 1), with six female stages representing age and reproductive status, and four male stages representing age (Hunter et al. 2010; Regehr et al. 2010). Transitions between stages are defined by vital rates relative to a post-breeding census from the autumn or spring of year t to the autumn or spring of year $t + 1$, for the BB and KB subpopulations, respectively. Projections were referenced to independent bears (i.e., bears age ≥ 2 years that are not members of a family group) because cubs-of-the-year (C0) and yearlings (C1) are not included as individuals in the life cycle, but rather are used to define the reproductive status of an adult female (adult females with C0, stage 5; adult females with C1, stage 6). Projections were referenced to individual subpopulations and were not designed to consider immigration, emigration, or metapopulation dynamics. Unless otherwise noted, details of the projection model and its application follow from Regehr et al. (2015, 2017). A list of abbreviations, acronyms, symbols, and definitions is provided at the end of this report.

Density dependence

Including density dependence is necessary to evaluate the combined effects of habitat change and human-caused removals (Guthery and Shaw 2013). We constructed density-dependent curves of the vital rates (sample curves shown in Figure BB1) using methods and shape parameters described in Appendix S2 of Regehr et al. (2017). We assumed that available

vital rates for the BB and KB subpopulations (section Vital rates) corresponded to an estimated subpopulation size at maximum net productivity level (MNPL; section Abbreviations, Acronyms etc.) under asymptotic population dynamics.

The matrix model was used to project hypothetical polar bear subpopulations forward over annual time steps starting at $t = 1$ (section Population projections). At each time step, density was determined as the sum of metabolic energetic equivalent (*mee*) values in the subpopulation, divided by carrying capacity (K ; section Carrying capacity and environmental variation) expressed as energetic equivalents (Regehr et al. 2017). Under this approach, larger bears (e.g., adult males) occupied more energetic space and therefore had a greater density effect than smaller bears (e.g., subadult females). Regehr et al. (2017) found that individual variation in energetic requirements can influence population productivity because a given environment can generally support more females than males. We used *mee* values from Regehr et al. (2017) that were calculated from data on body mass and diet for the Chukchi Sea and Southern Beaufort Sea subpopulations (Table S2 in Regehr et al. 2017) because equivalent data were not available for the BB and KB subpopulations.

The demographic model incorporated a mechanistic submodel for Allee effects in the mating system, following the recommendation of Regehr et al. (2017). Molnár et al. (2008, 2014) proposed that, under some conditions, reproductive rates for polar bears may decline due to limitations in mate finding. Such declines can occur if adult males are depleted relative to adult females, which is possible under sex-selective harvest (McLoughlin et al. 2005; Taylor et al. 2008b); or if polar bear densities are low during the breeding season. Because Allee effects in the BB and KB subpopulations have not been studied directly, the submodel for Allee effects was based on equation 3 from Molnár et al. (2014) with input parameters for a “generic population”. For both the BB and KB subpopulations, we calibrated the Allee submodel by calculating the degree of mating season aggregation that would result in a litter production rate equal to the estimated value from recent subpopulation studies (section Vital rates). This ensured that reproductive rates at $t = 1$ were equivalent to observed values. In subsequent years of projections ($t = 2, 3, \dots$), the estimate of litter production rate from the Allee submodel was standardized by dividing by its value at $t = 1$. The resulting value was constrained to the interval $[0,1]$ and used to modify the value of litter production rate (β_4) obtained from the density-dependent curves of the vital rates. Under this approach, a subpopulation that did not experience

male depletion or significant reductions in abundance, did not experience declines in reproduction due to Allee effects.

For the BB subpopulation, we used an on-ice area of 656,000 km² (Stern and Laidre 2016) to calculate the densities of female and male bears available to breed at each time step (stages 4 and 10, respectively), which are inputs to the Allee submodel (Molnár et al. 2014). A mating season aggregation parameter of 0.43 resulted in a litter production rate of 0.93, as estimated from 2011–2013 field data (section Results). For the KB subpopulation, we used an on-ice area of 53,000 km² (Stern and Laidre 2016). We set the mating season aggregation parameter to 1.0 because the Allee submodel could produce a litter production rate of 0.71, as estimated from 2012–2014 field data (section Results), without a reduction in the effective subpopulation area.

Carrying capacity and environmental variation

Modeling wildlife populations under climate change required consideration of the effects of variability and trends in the environment (Boyce et al. 2006). We derived a proxy metric to represent potential changes in K using satellite data of sea-ice extent. We calculated separate metrics for the BB and KB subpopulations, based on the number of ice-covered days per year within the management boundary for each subpopulation (Chapters 4 and 9 in SWG 2016). We used the number of ice-covered days because it integrates spatial and temporal variation in sea-ice availability in a manner that is biologically relevant to polar bears (Stern and Laidre 2016). For each subpopulation, we fit a linear model to the time series of ice-covered days from 1979–2014. We then used the fitted model to project correlated values of ice-covered days forward in time, using methods of Gelman and Hill (2007) to simulate uncertainty in the slope coefficient and residual standard errors. Finally, we standardized the metric by dividing the projected values of ice-covered days at year $t = 1, 2, \dots, k$, by the fitted value at year $t = 1$. This resulted in a dimensionless metric (κ) representing proportional changes in K . During population projections, carrying capacity at year t , calculated as $K(t) = K(t = 1) \times \kappa(t)$, operated on vital rates through the density-dependent relationships.

The number of ice-covered days in the BB management area declined over the period 1979–2014 (slope = -1.22 days/year, SE = 0.23, $P < 0.001$), from fitted values of 245 days in 1979 to 203 days in 2014. This is a decline of approximately 5.5% per decade. During harvest

assessment analyses for the BB subpopulation, projected values of κ were based on the estimated slope coefficient due to evidence for the effects of sea-ice loss on subpopulation ecology (SWG 2016). Therefore all population projections for BB included a proxy for K that varied from year-to-year, and declined by approximately 23% over three polar bear generations (section Population projections).

The number of ice-covered days in the KB management area declined over the period 1979–2014 (slope = -1.24 days/year, SE = 0.41, $P < 0.01$), from fitted values of 253 days in 1979 to 210 days in 2014. This is a decline of approximately 5.3% per decade. During harvest assessment analyses for the KB subpopulation, projected values of κ were based on a slope coefficient of 0, due to evidence for potential increases in productivity of the KB subpopulation associated with a transition from a multi-year ice region to seasonal ice conditions (SWG 2016). Therefore all population projections for KB included a proxy for K that varied from year-to-year, but remained stable over three polar bear generations (section Population projections). In other words, unlike for the BB subpopulation, projections for KB did not reflect the potential effects of long-term, decreasing trends in sea-ice cover.

In addition to density-dependent variation in the vital rates resulting from variation in K , we subjectively included additional density-independent variation as 25% of total uncertainty (i.e., temporal variation plus sampling uncertainty) in estimated vital rates, following the example of Taylor et al. (2002). Density-independent variation was implemented using the correlation matrix from Regehr et al. (2010), because that analysis estimated vital rates with a multistate CR model that was based on a life cycle graph similar to Figure 1.

Harvest and simulated population assessments

During population projections, harvest was implemented annually at a calculated level. Throughout our analyses the harvest level refers to the number of independent bears removed from a subpopulation by humans (i.e., the combination of subsistence harvest, sport hunting, removals of problem bears, defense kills, etc.). The calculated harvest level was updated every several years, according to the management interval (section Abbreviations, Acronyms etc.). To account for selectivity in human-caused removals and individual variation in the reproductive value of polar bears, harvest was implemented using stage-specific harvest vulnerability vectors. For females and males separately, we estimated harvest vulnerability by comparing the age

structure of the harvest to the estimated age structure of the subpopulation (section Population initialization). For the BB subpopulation, age structure of the harvest in Canada was estimated using data from 805 bears for which age had been determined from counts of cementum annuli (Christensen-Dalsgaard et al. 2010) or from individual capture histories, during the period 1998–2013. Because age determination for polar bears is referenced to the spring, whereas stage transitions in the life cycle graph were referenced to autumn for BB, we subtracted 1 from the known age of bears harvested January through August. For example, a 4-year-old male bear in the spring of calendar year t remained a member of stage 8 (3 years) until it transitioned to stage 9 (4 years) in the autumn of year t . Age structure of the Greenland harvest was determined from 212 bears taken during the period 2012–2015. We assumed this sample was representative of the Greenlandic harvest because cementum ages were not available for other years. Overall harvest vulnerability vectors were derived by averaging the Canadian and Greenlandic vectors, weighted by the total reported harvest in each country 1998–2014 (Table 8.6 in SWG 2016). The resulting harvest vulnerability vectors for females (stages 1–6) and males (stages 7–10) were [0.93, 1.17, 1.10, 1.00, 0.00, 0.00] and [1.25, 1.34, 1.01, 1.00], respectively. During population projections for KB, we used the same harvest vulnerability vectors as were estimated for BB, because harvest data for the KB subpopulation were sparse and the two subpopulations are subject to similar harvest management regimes (Chapter 8 in SWG 2016).

At the beginning of each population projection (i.e., $t = 1$), the harvest level was calculated using the mean values of the vital rates and N as estimated from recent subpopulation surveys (section State-dependent management approach). This ensured that starting harvest levels reflected current data for the BB and KB subpopulations. At the beginning of each subsequent management interval, the harvest level was calculated using estimates of vital rates and N derived from simulated population assessments. Conceptually, the simulated population assessments represent new subpopulation surveys, performed in the future, to obtain updated data that can be used for management. The simulated population assessments included sampling uncertainty, for which the level and correlation structure were based on recent CR studies (SWG 2016). In other words, each successive simulated population assessment produced demographic parameters of similar precision to the most recent genetic CR studies for the BB and KB subpopulations (SWG 2016). Exceptions were made for some simulations, which included a modified level of precision in simulated population assessments (section Population projections).

This allowed us to evaluate the effects on harvest management of future survey methods that provide more precise or less precise estimates of N and the vital rates (section Simulations).

State-dependent management approach

We used a state-dependent management approach to calculate harvest level (Regehr et al. 2017) as a function of N and the intrinsic population growth rate (r , which depends on the vital rates) as follows:

$$H^{female}(t) = F_O \times \tilde{r}_{MNPL}(t) \times 0.5 \times \tilde{N}(t) \quad [\text{eqn 1}]$$

and

$$H^{male}(t) = H^{female}(t) \times SR \quad [\text{eqn 2}]$$

where H^{female} is the number of females that can be removed annually;

F_O is a factor that directly adjusts the harvest rate to reflect management objectives and the risk tolerance of managers with respect to harvest;

\tilde{r}_{MNPL} is an estimate of the intrinsic population growth rate from subpopulation studies, referenced to population density at MNPL and selected as the 50th percentile of its sampling distribution;

0.5 is a factor to calculate female removals assuming an equal sex ratio in the subpopulation, which serves to protect against excessive female removals when the male segment of a subpopulation is depleted;

\tilde{N} is an estimate of N from subpopulation studies and selected as the 50th percentile of its sampling distribution;

H^{male} is the number of males that can be removed annually; and

SR is a factor that specifies the male-to-female ratio in removals.

To implement this state-dependent approach, managers must choose input values of the parameters F_O and SR . The parameter F_O directly influences the harvest rate: higher values lead

to a higher harvest, which can eventually increase the risk of negative population outcomes (e.g., depletion). The parameter SR determines the sex ratio of the harvest.

In our analyses, values of F_O and SR remain constant for the duration of population projections, so that each harvest strategy had a consistent definition. In practice these parameters could be adjusted over time in response to changing biological or management conditions. In contrast, in our analyses the biological parameters in equations 1 and 2 (i.e., the true values of r_{MNPL} and N , as well as their estimated values \tilde{r}_{MNPL} and \tilde{N}) varied during population projections (e.g., N declined over time due to declining K). The notation for time (t) in equations 1 and 2 indicates that the estimated parameters \tilde{r}_{MNPL} and \tilde{N} are updated periodically, as determined by the management interval. Equations 1 and 2 are written in terms of harvest level for convenience; the harvest rate (in this instance, referenced to the number of independent bears in the subpopulation) for females is the right side of equation 1 before multiplying by \tilde{N} .

Management Objectives

We evaluated harvest relative to three management objectives provided by the JC (section Introduction; Table BB1).

Management Objective 1 was to maintain N above 90% of its starting value. Although we report results for this objective for both subpopulations, it was of limited value for BB because our analyses included projected trends in K that made it unlikely to meet Management Objective 1 even with no harvest (section Carrying capacity and environmental variation).

For Management Objective 2, we interpreted the language “...ensure a maximum sustainable yield” (JC 2016) as a desire to maintain a subpopulation size above MNPL relative to a potentially changing K (Management Objective 2 in Table BB1). To evaluate this objective we used a single value of MNPL corresponding to a subpopulation density $(N/K) = 0.70$, which is similar to the mean estimate of density at MNPL across a wide range of vital rates (Regehr et al. 2017). Using a single value of MNPL across all population projections, had the benefit of providing a consistent point of reference for management decisions.

Management Objective 3 was specific to BB, and reflected the goal of a managed reduction in total subpopulation size to 2,000 bears in 10–15 years. This corresponds to a reduction of approximately 30% relative to the mean estimate of 2,826 for the period 2012–2013

(SWG 2016). In Table BB1, we express this objective as a desire to maintain a subpopulation size above 70% of its starting value (Table BB1), noting that Joint Commission (2017) indicated that Management Objective 3 should also consider “...not achieving an abundance below the level that would produce maximum sustainable yield” as well as “...a potentially changing environmental carrying capacity”. We interpret this as meaning that, to achieve Management Objective 3, the conditions for both Management Objectives 2 and 3 must be met.

In Table BB1 there are two versions of each Management Objective, reflecting “low” and “medium” levels of risk tolerance for not meeting the objective (section Introduction). We interpreted Management Objectives 1 and 2 as mid- to long-term objectives, and therefore evaluated them at the final time step $t = 36$ years, corresponding to approximately three polar bear generations in the future (section Population projections). Management Objective 3 was a short-term objective and was evaluated at $t = 15$. When reporting which harvest strategies met the management objectives, we included an additional condition requiring that the increased probability of a subpopulation being extirpated ($P_{extirpation}$) due to harvest, compared to an identical projection without harvest, not to exceed 0.05. In other words, this condition sought to ensure that harvest alone would not result in more than a 1-in-20 chance of extirpation. Applying this condition and Management Objective 2 together, over a sufficiently long time period, is consistent with the definition of “sustainable harvest” suggested by Regehr et al. (2107). Harvest strategies that met Management Objectives 1 and 2 generally were not associated with a high probability of extirpation, which meant that the condition on $P_{extirpation}$ had only a minor influence on the results. The exception was for some harvest strategies associated with Management Objective 3 (section Results).

Vital rates

We parameterized the matrix-based projection model using estimates of vital rates for the BB and KB subpopulations from recent genetic CR studies (SWG 2016). The published vital rates were adapted to the matrix-based projection model using methods described in Appendix S1 of Regehr et al. (2017).

For both the BB and KB subpopulations, litter production rate (equivalent to the parameter β_4 in Figure 1, for bears age ≥ 5 years) was not reported in SWG (2016) due to uncertainty in the age of bears that were observed from the air but not physically captured, and

therefore did not provide a tooth for subsequent age determination. Also, there was uncertainty in the sex of some animals for which genetic samples were not obtained. We used simulation methods to estimate reproductive parameters for each subpopulation in a manner that accounted for this uncertainty. First, we created 10,000 bootstrap datasets by resampling, with replacement, from the 2010s field data. In each bootstrap dataset, animals with known reproductive status (i.e., adult females with dependent young), or of known age (from counts of cementum annuli) and known sex (from genetic analysis of tissue samples), were deterministically assigned to a life cycle stage. For animals of known sex but unknown age, a value for numeric age was sampled from a multinomial distribution created for bears of the same field-estimated age class. The multinomial distribution used probabilities calculated from Table B3 in SWG (2016), which compares sex and age classes as estimated from the air, with known sex and age for bears observed in BB and KB during the period 2011–2014. For animals of unknown sex, a similar procedure was used that considered both sex and age, with probabilities calculated from Table B2 in SWG (2016). For each bootstrap dataset, we estimated mean litter production rate as the number of females with C0 (stage 5) in year $t + 1$ divided by the product of adult female survival and the number of females available to breed (stage 4) in year t , taking into account annual sample sizes (Taylor et al. 1987b). The number of bears in each stage was calculated directly from the field data because CR modeling did not identify differences in recapture probabilities among female bears (Chapters 5 and 10 in SWG 2016). Standard error in the reproductive parameters was estimated as the standard deviation of point estimates from the 10,000 bootstrap datasets.

Baffin Bay

During recent subpopulation studies for BB, there was uncertainty and concern about bias in estimates of survival probability, particularly during the period 2011–2013 (Chapter 5 in SWG 2016). Therefore, we considered three alternative scenarios for the vital rates of BB polar bears, which represented a potential range of conditions (i.e., from low to high) for the current status of the subpopulation. We performed population projections using the vital rates for all three scenarios (section Simulations) and attempt to provide guidance about which results are most applicable to management.

Reproductive parameters

All three scenarios of the vital rates for the BB subpopulation used reproductive parameters estimated from CR studies 2011–2013, based on field data described in Chapter 6 of SWG (2016), and using the methods described above. To calculate litter production rate we used $S = 0.95$, the estimate of total survival for females ≥ 2 years during the period 1998–2010 (Table 5.8 in SWG 2016). The resulting litter production rate for bears age ≥ 5 years (β_4) was 0.93, which suggests relatively high mating success and cub production. Other reproductive parameters were similar to values presented in Chapter 6 of SWG (2016), with minor differences in the point estimates and variances due to the simulation methods used here (Table BB1). The parameter β_4 is the most important breeding parameter in the matrix-based projection model (Hunter et al 2007). Due to the lack of age data for most observations in BB during the period 2011–2013, we were unable to estimate litter production rate for 4-year-old bears (β_3) with an acceptable degree of accuracy, and therefore used the value 0.10 for this parameter from Taylor et al. 2005. We set the value for β_5 to 0, because females that are observed with C0 in the autumn of year t are not able to subsequently lose their cubs, re-breed, and be observed with a new litter of C0 in year $t + 1$.

Scenarios for survival

We evaluated three scenarios for survival rates of BB polar bears, representing alternative hypotheses for the current status of the subpopulation. Scenario 1 used estimates of natural (i.e., unharvested) survival (S^*) for the period 2011–2013 (page 261 in SWG 2016). Scenario 1 represents the hypothesis that estimates of S^* for 2011–2013 are accurate, in contrast to the higher estimates for BB polar bears during the period 1998–2010 and the higher mean estimates for most other subpopulations (Appendix S1 in Regehr et al. 2017). This scenario suggests a relatively poor status for the BB subpopulation (section Results).

For Scenario 2, we calculated S^* from estimates of total survival (i.e., including harvest) and harvest reporting probabilities for the period 1998–2010 (Table 5.8 in SWG 2016), using the equations for natural survival on page 257 of SWG (2016). Scenario 2 represents the hypothesis that the 1998–2010 estimates of S^* for BB are accurate, whereas the 2011–2013 estimates were negatively biased. SWG (2016) proposed that such bias may occur due to heterogeneity in

recapture probability, non-random patterns of temporary emigration, of other factors. Terminal bias (i.e., bias at the end of a time series) in survival estimates commonly occurs in CR studies of long-lived, mobile animals (Peñaloza et al. 2014). Similar to our rationale in using Scenario 2, other studies have elected not to use terminal estimates S^* in population viability analyses due to concerns about bias (e.g., Langtimm 2009).

Scenario 3 used hypothetical survival rates representing an “average” polar bear subpopulation. To derive mean estimates of S^* for Scenario 3, we started with the estimates of S^* from Scenario 1 for female bears, and set estimates of S^* for male bears equal to 99% of these values. This reflects observations from other case studies that natural survival is generally similar for females and males (Table S1 in Regehr et al. 2017). Next, we increased all estimates of S^* in equal increments, until they produced an intrinsic population growth rate (r) of 0.05 under deterministic and asymptotic population dynamics. The value $r = 0.05$ is the mean estimate across case studies for polar bears as reviewed in Appendix S2 of Regehr et al. (2017). For Scenario 3, we used an amount of sampling uncertainty equivalent to data precision level 3 in Regehr et al. (2017). This represents the 50th percentile of estimated sampling uncertainty in case studies for polar bears, and is therefore typical of recent studies for the species (Appendix S4 in Regehr et al. 2017). Scenario 3 provides a benchmark for comparison with scenarios 1 and 2; it does not represent a data-based hypothesis for the current status of the BB subpopulation.

Estimates of S^* corresponding to the three scenarios of the vital rates are presented in Table BB3. For each scenario, we used the matrix-based projection model to calculate basic demographic parameters under asymptotic population dynamics (Table BB4). These parameters provide a general sense of the capacity for subpopulation growth under each scenario, but do not fully describe how the subpopulations behaved in the demographic model, because the model includes multiple types of stochasticity and can produce transient dynamics.

Kane Basin

During recent subpopulation studies estimates of S^* were derived from CR and harvest data collected during the period 1992–2014 (Chapter 10 in SWG 2016). Due to sparse data, SWG (2016) did not consider estimation models that allowed for temporal variation in survival. This presents a challenge for harvest assessment because all available estimates of S^* represent average values over a 23-year period, and do not reflect potential changes in survival in recent

years. Furthermore, exploratory population reconstruction using the time-constant estimates of S^* and observed harvest patterns, resulted in a declining subpopulation trend over the period 1998–2014 (section Population initialization). This is inconsistent with estimated increases in abundance of the KB subpopulation from CR modeling, from 224 (SE = 40) for the period 1995–1997, to 357 (SE = 92) for the period 2013–2014 (Chapter 10 in SWG 2016). SWG (2016) provide several caveats for the estimated increase in abundance, including potentially inconsistent sampling frames between the 1990s and 2010s. However, other lines of evidence from subpopulation ecology and Traditional Ecological Knowledge also suggest that the KB subpopulation is currently healthy and has been stable or increasing in recent years (SWG 2016). We considered two alternative scenarios of the vital rates for the KB subpopulation to reflect uncertainty in current subpopulation status.

Reproductive parameters

The two scenarios of the vital rates for KB used reproductive parameters estimated from CR studies 2012–2014, based on field data described in Chapter 21 of SWG (2016) and using the methods described above. To calculate litter production rate we used $S = 0.95$, the estimate of total survival for females ≥ 3 years during the period 1992–2014 (Table 10.3 in SWG 2016). The resulting litter production rate for bears age ≥ 5 years (β_4) was 0.71 (Table KB1). Because we were unable to estimate litter production rate for 4-year-old bears (β_3) using data from genetic sampling conducted 2012–2014, we set this parameter to 0 based on the finding by Taylor et al. (2008) that 4-year-old bears did not reproduce. We set the value for β_5 to 0.10 based on Regehr et al. (2010), which is the only study to directly estimate the probability that a female observed with C0 in the spring of year t , conditional on losing her cubs, will re-breed and produce a new litter of C0 in the spring of year $t + 1$. This likely had a minor effect on results, due to the relative unimportance of β_5 to population growth (Hunter et al. 2007).

Scenarios for survival

We evaluated two scenarios for survival rates of KB polar bears. Scenario 1 used unmodified estimates of S^* as reported on page 496 of SWG (2016). Scenario 1 represents the hypothesis that time-constant estimates of S^* are accurate and represent the current status of the

KB subpopulation, despite being too low to reproduce the estimated increase in abundance over the period 1998–2014 (section Population initialization). Scenario 1 suggests a relatively poor status for the KB subpopulation (section Results).

For Scenario 2, we modified values of S^* for some sex and age classes until the vital rates were sufficiently high to reproduce the estimated increase in abundance over the period 1998–2014. Specifically, for female and male polar bears age ≤ 2 years, we created 10 equal-increment values of S^* from a minimum corresponding to the point estimate for that sex and age class, to a maximum corresponding to the estimate of S^* for bears age ≥ 3 years of the same sex. This approach retained the lower values of unharvested survival for males compared to females, a pattern that was apparent for both the BB and KB subpopulations (SWG 2016). We chose to modify values of S^* for bears ≤ 2 years, rather than for adults, because CR and dead-recovery sample sizes were small for younger bears (Table 10.1 in SWG 2016), which resulted in high sampling uncertainty and increased potential for bias (Pollock et al. 1990). We performed population reconstructions for each set of equal-increment values of S^* , to determine the magnitude of increases in S^* necessary to achieve a 50% probability of reproducing the estimated increase in abundance of the KB subpopulation (section Population initialization). Thus, Scenario 2 represents the hypothesis that estimates of N for the KB subpopulation are accurate and provide a valid basis for inference about the subpopulation's capacity to grow and support harvest. Uncertainty in estimates of S^* for Scenario 2 was calculated from the relative standard deviations for Scenario 1, which meant that even though estimates of S^* for bears ≤ 2 years were increased under Scenario 2, the corresponding level of data precision was not improved.

Estimates of S^* corresponding to the two scenarios of the vital rates are presented in Table KB2. Basic demographic parameters, calculated under asymptotic population dynamics, are presented in Table KB3.

Population projections

We performed population projections to evaluate the dynamics of the BB and KB polar bear subpopulations and to investigate the effects of different harvest strategies. For a given projection, the main biological inputs were: a starting value of N (expressed as a number of independent bears); mean values from a scenario of the vital rates, referenced to MNPL;

estimates of sampling variation, process variation, and the correlation structure of the vital rates; a starting stage distribution; a starting subpopulation density, expressed as the ratio N/K ; stage-specific mee values; and a stochastic projection of the dimensionless metric κ , representing future variation in K . The main management inputs were: a value of F_0 for use in Equation 1 to calculate harvest rate; a value of SR for use in Equation 2 to calculate harvest level; stage-specific harvest vulnerability vectors for females and males; a value for the management interval; and $rsd.mod$, the modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty, which was applied to future subpopulation assessments (section Abbreviations, Acronyms, etc.).

Populations were projected 35 years into the future (i.e., from $t = 1, 2, \dots 36$), which is equivalent to approximately three polar bear generations (Regehr et al. 2016). At each time step $t = 2, 3, \dots k$, the following operations were performed. First, subpopulations were projected forward 1 year using a stage-structured matrix model: $\mathbf{n}(t+1) = \mathbf{A}(t) \times \mathbf{n}(t)$, where $\mathbf{n}(t)$ is a stage distribution vector representing the number of animals in each life cycle stage at time step t , and $\mathbf{A}(t)$ is a 10×10 projection matrix (Caswell 2001). Entries in $\mathbf{A}(t)$ were defined in terms of vital rates in the life cycle graph (Figure 1). Demographic stochasticity was not included, because it is considered relatively unimportant at subpopulation sizes typical of polar bears (White 2000). Second, harvest was allocated among stages using a multinomial distribution with the probability for each stage calculated as the product of its proportional stage distribution and harvest vulnerability vector. For some projections, selective harvest led to the depletion of bears in one or more stages. If the specified harvest level exceeded the number of bears in a stage, the excess harvest was applied to adult bears of the same sex (i.e., stages 4 or 10). If the specified harvest exceeded the total number of one sex, the excess harvest was applied to adult bears of the other sex. Third, subpopulation density was calculated by summing mee values across animals in the subpopulation, then dividing by the total mee values available at carrying capacity. The survival and reproductive rates corresponding to this density were determined from the density-dependent curves, with modifications applied to the parameter β_4 based on the Allee submodel. Fourth, these vital rates were subject to density-independent stochastic variation. Finally, the resulting vital rates were used to construct a projection matrix for the next time step $\mathbf{A}(t+1)$.

During population projections, we defined persistence as maintaining a subpopulation size greater than a pre-determined quasi-extinction threshold. We used a threshold of 100

independent bears for the BB subpopulation, which is similar to values that have been used for brown bears (Wielgus 2002). We used a threshold of 25 independent bears for KB, because it is a smaller subpopulation and 25 bears was likely high enough to avoid negative small-population dynamics resulting from demographic stochasticity (Morris and Doak 2002). We note that Regehr et al. (2017) used higher quasi-extinction thresholds, calculated as 15% of starting N . We did not follow that approach because our analyses incorporated an Allee submodel, which provided a mechanistic description of small-population dynamics that have been suggested as important for polar bears (Molnár et al. 2014). During projections, subpopulations that crossed below the quasi-extinction threshold were considered extirpated and could not recover.

Population initialization

For both BB and KB we performed exploratory population reconstruction, which consisted of retrospective projections that used historic biological and management conditions. This helped to evaluate the vital rates, establish reasonable initial conditions for the main population projections (e.g., a subpopulation composition that was consistent with the history of sex-selective harvest), and reduce transient dynamics in early years of projections (Caswell 2001).

Baffin Bay

We performed population reconstruction for the period 1998–2010 using vital rates from Scenario 2. We did not include 2011–2013 in the reconstruction due to concerns about bias in the survival estimates for those years (SWG 2016). For the population reconstruction, the mean value of starting N was set to 1,968 independent bears. This was calculated from the estimated total subpopulation size (i.e., including C0 and C1) of 2,826 for the period 2011–2013 (Chapter 5 in SWG 2016). We used this starting value because of potential bias in the 1993–1997 estimate of N due to limited geographic sampling in the 1990s (Chapters 3 and 6 in SWG 2016). Methods to convert from total subpopulation size, to the number of independent bears, are described below. Starting N/K (i.e., at $t = 1$) was set to 0.67, which corresponded to MNPL as estimated from the density-dependent curves of the vital rates for Scenario 2. Harvest was implemented at

a fixed level of 162 independent bears per year, which was the mean reported harvest for the BB subpopulation during the period 1998–2010 (Table 8.4 in SWG 2016).

We used a male-to-female sex ratio in the harvest (SR) of 1.25 for population reconstruction. This value was derived by averaging Canadian and Greenlandic harvest sex ratios, weighted by the total reported harvest in each country. The Canadian sex ratio was calculated directly from hunter-reported sex as it agreed with the genetically-determined sex, which indicated that 0.34 of harvested bears were female (Chapter 8 in SWG 2016). The Greenlandic sex ratio was estimated separately for this analysis, due to apparent discrepancies between hunter-reported sex and genetically-determined sex (Chapter 8 in SWG 2016). Specifically, we used the genetic sex data from tissue samples collected from 77 polar bears harvested in Greenland during the period 2011–2013, to estimate that 0.53 of the reported harvest was female. Lacking genetic sex data for other years, we assumed that this proportion was representative of the Greenlandic harvest 1998–2010. Harvest was implemented using the stage-specific harvest vulnerability vectors for the BB subpopulation. For population reconstruction, we used a deterministic proxy metric for K that was based directly on the observed time series of ice-covered days 1998–2010. Other specifications for population reconstruction were the same as for the full suite of projections (section Simulations).

The reconstructed subpopulation, using vital rates from Scenario 2 and a fixed-level harvest of 162 bears per year, exhibited a relatively stable trajectory during the period 1998–2010. The observed population growth rate was 1.01 (SE = 0.10) per year as calculated using the methods of Humbert et al. (2009). The ending proportion of females in the subpopulation was 0.69. For comparison, the mean proportion of females in the BB subpopulation during the period 2011–2013 was 0.66, as calculated using sex- and age-specific estimates of abundance for bears age ≥ 2 years from the most-supported CR model (Chapter 5 in SWG 2016). The similarity between the proportions 0.69 and 0.66, and the ability of population reconstruction to produce plausible population dynamics (i.e., a stable subpopulation under the observed harvest), provide a degree of confidence in the vital rates of Scenario 2.

To obtain a starting stage distribution for the full suite of population projections, we adjusted the final stage distribution from the population reconstruction until the proportion of females was 0.66, keeping the within-sex stage distributions constant. This produced the 10-stage distribution vector [0.07, 0.05, 0.05, 0.17, 0.18, 0.14, 0.07, 0.05, 0.05, 0.17]. When

combined with estimates of C0 and C1 litter size for Scenario 2, this produced a ratio of independent bears to total bears of 0.70. Therefore, all projections for the BB subpopulation started with a mean value of $N_{t=1} = 2,826 \times 0.70 \approx 1,968$ independent bears, where 2,826 is the estimated total subpopulation size for 2011–2013 from SWG (2016). To reduce transient dynamics, all projections started at a subpopulation density $N/K = 0.81$, the median estimated density at the final year of population reconstruction.

Kane Basin

We performed population reconstruction for the period 1998–2014, to evaluate the vital rates from Scenario 1 and to identify values of S^* for Scenario 2 (section Vital rates). For the population reconstruction, the mean value of starting N was set to 153 independent bears. This was calculated from the estimated total subpopulation size of 224 for the period 1995–1997 (Chapter 10 in SWG 2016). Methods to convert from total subpopulation size, to the number of independent bears, are described below. Starting N/K was set to 0.73, which corresponded to MNPL as estimated from the density-dependent curves of the vital rates for Scenario 1. Harvest was implemented at a fixed level of 8 independent bears per year, which is the mean harvest reported for the KB subpopulation during the period 1998–2013 (Tables 8.2 and 8.5 in SWG 2016).

We used $SR = 0.94$ for population reconstruction. This value was derived by averaging Canadian and Greenlandic harvest sex ratios, weighted by the total reported harvest in each country. The Canadian sex ratio was calculated directly from hunter-reported sex, which indicated that 0.33 of harvested bears were female (Chapter 8 in SWG 2016). The Greenlandic sex ratio was based on genetically-determined sex for bears harvested from the KB subpopulation during the period 2011–2014, which indicated that 0.53 of harvested bears were female (Chapter 8 in SWG 2016). Lacking genetic sex data for other years, we assumed that this proportion was representative of the Greenlandic harvest 1998–2014. Harvest was implemented using the stage-specific harvest vulnerability vectors that were calculated for the BB subpopulation.

For KB population reconstruction, we used a deterministic proxy metric for K with interannual variation based on the observed time series of ice-covered days 1998–2014, but with

an increasing trend of approximately 3% per year. We subjectively included this trend in K , rather than using observed values of the sea-ice metric, because an increasing trend would be necessary to allow N to increase from 224 bears in 1995–1997 to 357 bears in 2012–2014 (i.e., $N_{t=17} / N_{t=1} \approx 1.6$; Chapter 10 in SWG 2016), conditional on vital rates that were sufficiently high to produce such an increase. Other specifications for population reconstruction were the same as for the full suite of projections (section Simulations).

An initial KB population reconstruction used vital rates from Scenario 1 and a fixed-level harvest of 8 bears per year. This resulted in a declining trajectory during the period 1998–2014, with an observed population growth rate of 0.98 (SE = 0.40) per year. The large variance in the observed growth rate was due primarily to high sampling uncertainty in vital rates for the KB subpopulation (Chapter 10 in SWG 2016). The fact that the growth rate was negative, despite an increasing proxy for K , suggests that a subpopulation with vital rates similar to Scenario 1 would be unlikely to support a harvest of 8 bears per year, even in the absence of density-dependent regulation.

Subsequent KB population reconstructions used the same conditions as described above, but with the estimates of S^* from Scenario 1 modified to include incremental increases in survival for bears age ≤ 2 years (section Vital rates). We found that an average proportional increase in S^* of 38% (i.e., $S^*_{modified} = 1.38 \times S^*_{original}$) produced an increasing trajectory during the period 1998–2014, with an observed population growth rate of 1.03 (SE = 0.33). This corresponded to a median increase in abundance of $N_{t=17} / N_{t=1} = 1.59$ (SE = 0.71), which is similar to the estimated increase in abundance for the KB subpopulation from 1995–1997 to 2012–2014. Therefore, Scenario 2 of the vital rates for the KB subpopulation included these modified estimates of S^* for bears ≤ 2 years (section Results).

The reconstructed subpopulation, using vital rates from Scenario 2 and a fixed-level harvest of 8 bears per year, produced an ending proportion of females in the subpopulation of 0.70. For comparison, the mean proportion of females in the KB subpopulation during the period 2012–2014 was 0.71, as calculated from sex- and age-specific estimates of abundance for bears ≥ 2 years from the most-supported CR model (Chapter 10 in SWG 2016). To obtain a starting stage distribution for the full suite of projections, we adjusted the final stage distribution from the population reconstruction until the proportion of females was 0.71, keeping the within-sex stage distributions constant. This produced the 10-stage distribution vector [0.06, 0.06, 0.05, 0.24,

0.16, 0.14, 0.05, 0.04, 0.03, 0.17]. When combined with estimates of C0 and C1 litter size for Scenario 2, this leads to a ratio of independent bears to total bears of 0.68. Therefore, all projections for the KB subpopulation started with a mean value of $N_{t=1} = 357 \times 0.68 \approx 244$ independent bears, where 357 is the estimated total subpopulation size for 2012–2014 from SWG (2016). To reduce transient dynamics, all projections started at a subpopulation density $N/K = 0.69$, the median estimated density at the final year of population reconstruction.

Simulations

We define a “simulation” as multiple replicates of a population projection, where each replicate has the same mean biological inputs and the same management inputs (section Population projections). For each simulation, we used a parametric bootstrap procedure that generated 250 correlated random samples of the input vital rates and starting value of N , for the purpose of representing sampling variation in the vital rates (White 2000). We subjectively included sampling variation as 75% of total uncertainty (i.e., temporal variation plus sampling uncertainty) following the example of Taylor et al. (2002). Samples of the vital rates were generated using either a multivariate beta distribution or a stretched beta distribution (Morris and Doak 2002), as described in Appendix S3 of Regehr et al. (2017). When vital rates were near the boundary conditions [0,1] and variances were large, shape parameters for the beta distribution occasionally could not be determined. When this occurred, we generated a sample for the vital rate in question using a truncated normal distribution. The correlation structure for sampling variation in the vital rates was informed by the most-supported CR model for the BB subpopulation (Table 5.7 in SWG 2016). Specifically, we used a correlation coefficient of 1 within the following sets of parameters, and a correlation coefficient of 0 between the sets: $[\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6]$, $[\sigma_7, \sigma_8, \sigma_9, \sigma_{10}]$, $[\sigma_{L0}, \sigma_{L1}]$, $[\beta_3, \beta_4, \beta_5]$, and $[N]$. This correlation structure was also used for simulated population assessments, based on the assumption that future estimation methods would be broadly similar to SWG (2016).

For each random sample of the vital rates and starting N , we ran 50 projections, each with a different stochastic projection of κ (section Carrying capacity and environmental variation). Also, the projections included stochastic, density-independent variation at each time step. Therefore, for each simulation the resulting $250 \times 50 = 12,500$ replicate projections reflected

both sampling and environmental variation. Although 12,500 is a relatively small number of replicates for population viability analysis (White 2000), this number was computationally feasible (section Software) and gave reproducible results at the levels of precision we report.

For each subpopulation, we performed simulations designed to evaluate a range of biological conditions and harvest strategies relevant to polar bear management (see below). For each simulation, we report the probability of meeting management objectives, calculated as the number of replicates that met the corresponding population condition (Table BB1) divided by the total number of replicates. At specific time steps, we also report $P_{extirpation}$, defined as the proportion of replicates for which N declined below the quasi-extinction threshold at any time step prior to time step $t = k$; and the probability of male depletion ($P_{male.dep}$), defined as the proportion of replicates for which the number of adult males (stage 10) was below 50% of the quasi-extinction threshold at $t = k$. The metric $P_{male.dep}$ is relevant because lower values of S^* for males compared to females, combined with sex-selective harvest, led to severe depletion of adult male bears under some conditions. Finally, we report the median change in subpopulation size ($N_{t=k} / N_{t=1}$), the median subpopulation density ($N_{t=k} / K_{t=k}$), and the mean realized harvest level ($H_{t=k}$). These values were calculated over all replicates, including those that led to extirpation. The metric H is relevant because some simulations included declining N (to declining K or to high harvest) and declining r (due to Allee effects caused by male depletion), which led to declining values of H over time under state-dependent approach.

Baffin Bay

We performed a primary set of simulations for the BB subpopulation to evaluate sustainable harvest for the three scenarios of the vital rates. All primary simulations used a management interval of 15 years and $rsd.mod = 1$. For each scenario, we performed simulations over 36 annual time steps for all combinations of the following inputs:

1. Five, 11, and 8 values of the management factor F_O for Scenarios 1, 2, and 3, respectively. These values of F_O corresponded to starting harvest levels that differed by 20 bears per year, and encompassed the estimates of maximum sustainable yield for each scenario based on asymptotic dynamics and non-selective harvest (section Results).

2. Three values of sex ratio in the harvest, corresponding to $SR = 1.0$, 1.25 , and 2.0 . The value of $SR = 1.25$ represents the current status quo for the BB subpopulation under the assumptions made during population reconstruction (section Population initialization). We included $SR = 2$ because it is a common management objective for polar bears (Taylor et al. 2008b). We included $SR = 1$ to evaluate non-sex selective harvest, which might be a strategy for managed population reduction.

We performed a secondary set of simulations using the vital rates for Scenario 2 only, which we considered the most likely representation of the current status of the BB subpopulation. The objectives were to evaluate the effects of changes in the management interval and the precision of data obtained from future subpopulation assessments. All secondary simulations used $SR = 1.25$. We performed simulations over 36 annual time steps for all combinations of the following inputs:

1. Nine values of the management factor F_O , corresponding to starting harvest levels that differed by 10 bears per year, and encompassed the range of harvest that met management objectives for Scenario 2 during primary simulations.
2. Three values for the management interval corresponding to 10, 15, and 20 years.
3. Three levels of precision in subpopulation data, corresponding to $rsd.mod = 0.5$, 1.0 , and 1.5 .

We also performed several *post hoc* simulations that were focused on the issue of managed population reduction.

Kane Basin

We performed a primary set of simulations for the KB subpopulation to evaluate sustainable harvest for the two scenarios of the vital rates. All primary simulations used a management interval of 15 years and $rsd.mod = 1$. For each scenario, we performed simulations over 36 annual time steps for all combinations of the following inputs:

1. Five and 9 values of the management factor F_O for Scenarios 1 and 2, respectively. These values of F_O corresponded to starting harvest levels that differed by 2 bears per year, and encompassed the estimates of maximum sustainable yield for each scenario based on asymptotic dynamics and non-selective harvest (section Results).

2. Two values of sex ratio in the harvest, corresponding to $SR = 0.94$ and 2.0. The value of $SR = 0.94$ represents the current *status quo* for the KB subpopulation under the assumptions made during population reconstruction (section Population initialization).

We performed a secondary set of simulations using the vital rates for Scenario 2 only, to evaluate the effects of changes in the management interval and the precision of data obtained from future subpopulation assessments. Scenario 2 was more useful for this investigation because, unlike Scenario 1, it led to non-zero harvest levels that met management objectives. All secondary simulations used $SR = 0.94$. We performed simulations over 36 annual time steps for all combinations of the following inputs:

1. Nine values of the management factor F_O , corresponding to starting harvest levels that differed by 1 bear per year, and encompassed the range of harvest that met management objectives for Scenario 2 during the primary simulations.
2. Three values for the management interval corresponding to 10, 15, and 20 years.
3. Three levels of precision in subpopulation data, corresponding to $rsd.mod = 0.5, 1.0,$ and 1.5.

Finally, we performed several *post hoc* simulations focused on the ramifications of high uncertainty in estimates of S^* for bears age ≤ 2 years.

Software

Computations were performed in the R computing language (version R 3.4.0; The R Project for Statistical Computing; <http://www.r-project.org>). Simulations were run the Amazon Elastic Compute Cloud (<http://aws.amazon.com/ec2/>) using an Amazon Machine Image for RStudio Server (RStudio 2016) developed by L. Aslett (http://www.louisaslett.com/RStudio_AMI/). Each simulation took approximately 60 minutes using a Memory Optimized r4.xlarge computing instance.

Results

Baffin Bay

Primary simulations

We performed a primary set of simulations to evaluate population dynamics and sustainable harvest, for three scenarios of the vital rates, over a period of three polar bear generations during which K declined. Projections used a 15-year management interval, a baseline level of data precision (i.e., $rsd.mod = 1.0$) based on recent subpopulation surveys (SWG 2016), and a mean starting subpopulation size $N_{t=1} = 1,968$ (SE = 236) independent bears with a stage distribution and subpopulation density determined from population reconstruction (section Population initialization). Tables BB5–BB7 present the highest harvest strategies that met management objectives for each scenario of the vital rates (see below). The harvest rate (h) in these tables is presented as the percentage of total subpopulation size (i.e., subpopulation size including C0s and C1s) that is removed each year as independent bears, because this definition of h is commonly used in polar bear management. Strategies with lower values of F_O than appear in Tables BB5–BB7, but otherwise similar inputs (e.g., the same harvest sex ratio), also met management objectives. Some of the harvest strategies in Tables BB5–BB7 could result in the depletion of adult male bears; probabilities of extirpation, compared to projections with no harvest, that approach the upper limit of 0.05; or declines in the calculated harvest level over time. Detailed results from the primary simulations are presented in Appendix S1.

Scenario 1

Scenario 1 of the vital rates resulted in an asymptotic intrinsic growth rate at MNPL (r_{MNPL}) of 0.03 (Table BB4), suggesting a limited capacity for growth and low resilience relative to other polar bear subpopulations (Regehr et al. 2017). Statistical uncertainty in estimates of S^* for the period 2011–2013 (Table BB3) contributed to high uncertainty in the estimate of r_{MNPL} , with approximately 26% of its sampling distribution below 0 (i.e., corresponding to a negative intrinsic growth rate). Management Objective 1 was not achievable even in the absence of harvest, due to the combined effects of low r , declining K , and high uncertainty in the vital rates (Table BB5). Management Objective 2 could be met using $F_O = 0$ to 0.41, depending on the

value of SR and risk tolerance. This corresponds to a starting harvest rate $h_{t=1} = 0$ to 0.7%, and a starting harvest level $H_{t=1} = 0$ to 20 bears per year. Upper limits on F_O that met Management Objective 3 were 0 to 1.22, depending on SR and risk tolerance. However, due in part to high uncertainty in the vital rates, harvest strategies at the upper end of this range simultaneously increased $P_{extirpation}$ toward the upper condition of 0.05 at $t = 15$, while being unlikely to reduce the median subpopulation size by 30% (Table S.BB1). A subpopulation similar to Scenario 1 would have little capacity to support harvest, and would risk a 2 to 3% chance of extirpation at $t = 36$ in the absence of harvest (Table S.BB1).

Scenario 2

Scenario 2 resulted in $r_{MNPL} = 0.08$ (Table BB4), suggesting a strong capacity for growth and relatively high resilience. Due to declining K , Management Objective 1 was either not achievable or only achievable with no harvest (Table BB6). Management Objective 2 could be met using $F_O = 0.43$ to 1.03, depending on SR and risk tolerance. This corresponds to a starting harvest rate $h_{t=1} = 3.6$ to 5.7%, and a starting harvest level $H_{t=1} = 100$ to 160 bears per year. At the upper end of this range, a harvest strategy using $F_O = 0.92$ and the *status quo* value of $SR = 1.25$ corresponds to $h_{t=1} = 5.7\%$ and $H_{t=1} = 160$ bears per year, which is similar to harvest of the BB subpopulation in recent decades (Chapter 8 in SWG 2016). A sample of replicates from population projections can help visualize the effects of this harvest strategy on subpopulation trajectories. Figure BB3 shows that the median subpopulation size declines in parallel with (but not faster than) declining K , which is a consequence of a state-dependent management approach that meets Management Objective 2. The color-coding in Figure BB3 identifies the potential for male depletion or subpopulation extirpation in later years (Table S.BB2). For replicates that experienced male depletion, reproductive rates declined due to Allee effects in the mating system. This reduced the subpopulation's capacity for growth and resulted in lower calculated harvest levels under the state-dependent approach. Figure BB4 illustrates these effects, for the same harvest strategy that was shown in Figure BB3. Other harvest strategies that were more selective for males (i.e., $SR = 2$), including some strategies that met Management Objective 2 (Table BB6), had higher probabilities of causing male depletion (e.g., up to 0.25 at $t = 36$; Table S.BB2). Evaluation of Management Objective 3 is presented with results from the secondary simulations (see below).

Scenario 3

Scenario 3 was based on hypothetical vital rates that resulted in $r_{MNPL} = 0.05$ (Table BB4), representing a subpopulation with average capacity for growth and resilience. This scenario provided a benchmark for comparison with the data-based Scenarios 1 and 2. Similar to Scenario 2, Management Objective 1 was either not achievable or only achievable with no harvest, due to declining K (Table BB7). Management Objective 2 could be met using $F_O = 0.53$ to 0.89, depending on SR and risk tolerance. This corresponds to a starting harvest rate $h_{t=1} = 2.1$ to 3.6%, and a starting harvest level $H_{t=1} = 60$ to 100 bears per year. Harvest strategies under Scenario 3 that used $SR = 2$ were less likely to cause male depletion than similar strategies under Scenario 2 (Table S.BB3), because under Scenario 3 values of S^* were similar for adult females and adult males. Upper limits on F_O that met Management Objective 3 were 0.66 to 1.40, depending on SR and risk tolerance. In some cases, the condition requiring that $P_{extirpation} < 0.05$ at $t = 15$, compared to a similar projection without harvest, was the limiting factor for Management Objective 3. In other words, a harvest strategy could achieve an acceptable level of risk with respect to the population condition $N_{t=15} > (0.7 \times N_{t=1})$ but also result in $P_{extirpation} > 0.05$. Harvest strategies that met Management Objective 3, in terms of both $N_{t=15} > (0.7 \times N_{t=1})$ and the condition on $P_{extirpation}$, were unlikely to reduce the subpopulation size by 30% (Table S.BB3). These findings suggest that a managed population reduction of 30% is unlikely to be achieved, within the guidelines for risk tolerance provided by the JC, when using a 15-year management interval for a subpopulation with vital rates and a level of data precision similar to Scenario 3.

Secondary simulations

We performed a secondary set of simulations for Scenario 2 to evaluate the effects of management interval and data precision. Table BB8 shows the highest harvest strategies that met Management Objective 2b as a function of these factors, illustrating the potential impact of different management conditions. For example, $h_{t=1}$ is 54% higher for a 10-year management interval and $rsd.mod = 0.5$ (which corresponds to a relative standard deviation of 0.01 in σ_4 due to sampling uncertainty), compared to a 20-year management interval and $rsd.mod = 1.5$ (which

corresponds to a relative standard deviation of 0.03 in σ_4). Table S.BB4 provides detailed results for the simulations summarized in Table BB8. In Table S.BB4, results for the expected value of $H_{t=36}$ require additional explanation. It appears counterintuitive that $H_{t=36}$ is higher for a 20-year management interval than for a 15-year management interval. This occurs because the harvest strategies in Table S.BB4 are fairly aggressive, and can result in moderate degrees of male depletion and reduced capacity for growth at $t = 36$. Using a 15-yr management interval, these negative effects result in a reduced harvest level at the second subpopulation assessment, which occurs at $t = 32$. In contrast, using a 20-year management interval, the second subpopulation assessment does not occur until $t = 42$, which is beyond the duration of projections. The ramifications are that using a 20-year management interval (i) leads to higher probabilities of extirpation at $t = 36$, and (ii) would be expected to result in large reductions to the calculated harvest level at $t = 42$.

We used results from the secondary set of simulations to evaluate Management Objective 3, because the primary simulations suggested that achieving a subpopulation reduction, within the specified risk tolerance, would require a short management interval and improved data precision. In the secondary simulations, the harvest strategy with the highest harvest and best management conditions was $F_O = 1.15$, a 10-year management interval, and $rsd.mod = 0.5$. This corresponded to $h_{t=1} = 7.1\%$ and $H_{t=1} = 200$. For this strategy, the median value of $N_{t=15} / N_{t=1}$ was 0.86 at $t = 15$ (i.e., a median reduction of 14% in starting subpopulation size; Table S.BB4). Although this strategy met Management Objective 3b as stated in Table BB1, it did not reduce the subpopulation by 30%. Also, it led to a 0.38 probability that subpopulation size was below MNPL at $t = 15$, which exceeded the risk tolerance for the condition on maximum sustainable yield that was associated with Management Objective 3 (section Management Objectives).

Post hoc simulations

We performed two *post hoc* simulations to inform future considerations for managed population reduction. First, we identified a state-dependent harvest strategy (BB_S1) that came as close as possible to achieving a subpopulation reduction of 30% in 15 years, while meeting the population condition for Management Objective 3b as stated in Table BB1, but without the additional condition related to maximum sustainable yield. Harvest strategy BB_S1 used $F_O = 1.58$, $SR = 1.0$, a 5-year management interval, and $rsd.mod = 0.5$. Use of $SR = 1$ promoted

subpopulation reduction by removing more females, compared to a sex-selective harvest. This strategy corresponded to $h_{t=1} = 8.7\%$ and $H_{t=1} = 245$. At $t = 15$, the median value of $N_{t=15} / N_{t=1}$ was 0.75 (i.e., a median reduction of 25% in starting subpopulation size) and Management Objective 3b was met (Table S.BB5). The mean harvest level declined at each management interval, concurrent with declining subpopulation size (e.g., $H_{t=15} = 180$ bears per year; Table S.BB5). Conceptually, BB_S1 represents a near-optimal harvest strategy that would require nearly continuous surveys and rapid management response.

For comparison with BB_S1, we evaluated a second harvest strategy (BB_S2) that used the same starting harvest level, but did not follow a state-dependent approach and used the *status quo* value $SR = 1.25$. Strategy BB_S2 applied a fixed-level harvest of 250 bear per year, for a period of 15 years, without new subpopulation assessments or changes to management during this period. At $t = 15$, the median value of $N_{t=15} / N_{t=1}$ was 0.55, indicating that the subpopulation was depleted beyond the desired 30% reduction. Also, strategy BB_S2 did not meet Management Objective 3 and resulted in a 0.30 probability of male depletion and a 0.23 probability of subpopulation extirpation at $t = 15$ (Table S.BB5).

Kane Basin

Primary simulations

We performed a primary set of simulations to evaluate population dynamics and sustainable harvest, for two scenarios of the vital rates, over a period of three polar bear generations during which K remained stable. Projections used a 15-year management interval, the baseline level of data precision (i.e., $rsd.mod = 1.0$), and a mean starting subpopulation size $N_{t=1} = 244$ (SE = 41) independent bears with a stage distribution and subpopulation density determined from population reconstruction (section Population initialization). Tables KB4–KB6 present the highest harvest strategies that met management objectives for each scenario of the vital rates. Strategies with lower values of F_O , but otherwise similar inputs, also met management objectives. Some of the harvest strategies in Tables KB4–KB6 could result in the depletion of adult male bears or increased probabilities of extirpation, compared to projections with no harvest, that approached the upper limit of 0.05. Detailed results for the primary simulations are presented in Appendix S1.

Scenario 1

Scenario 1 of the vital rates resulted in $r_{MNPL} = 0.01$ (Table KB3), suggesting a very limited capacity for growth and low resilience. Statistical uncertainty in estimates of S^* for the period 2012–2014 (Table KB2), especially for bears ≤ 2 years, contributed to high uncertainty in the estimate of r_{MNPL} , with approximately 29% of its sampling distribution below 0 (i.e., corresponding to a negative intrinsic growth rate). Due to low values of r and high uncertainty in the vital rates, most management objectives could not be met even with no harvest (Table KB4). This is illustrated by Figure KB1, which shows a sample of replicates from population projections with $F_O = 0$ (i.e., no harvest). Although the median N increases gradually over time, the subpopulation trajectories are highly variable. The color-coding in Figure KB1 indicates that male depletion is possible due to lower estimates of S^* for males compared to females (e.g., $P_{male.dep} = 0.10$ at $t = 15$; Table S.KB1). A subpopulation with vital rates similar to Scenario 1 would have little guarantee of supporting harvest, and would face a 2 to 4% chance of extirpation at $t = 36$ in the absence of harvest (Table S.KB1). The ramifications of high uncertainty in vital rates for the KB subpopulation were evaluated in the secondary and *post hoc* simulations (see below).

Scenario 2

Scenario 2 resulted in $r_{MNPL} = 0.05$ (Table KB3), suggesting a medium capacity for growth and resilience. Management Objectives 1a and 2a (i.e., the version of the objectives with low risk tolerance for not achieving the population condition; Table BB1) could not be met with no harvest, due to variability in subpopulation trajectories arising from uncertainty in the vital rates (Table S.KB2). Management Objective 1b could be met using $F_O = 0.31$ to 0.48, depending on the value of SR (Table KB5). This corresponds to a starting harvest rate $h_{t=1} = 1.7\%$ and a starting harvest level $H_{t=1} = 6$ bears per year, which is similar to recent harvest of the KB subpopulation (SWG 2016). Management Objective 2b could be met using $F_O = 0.21$ to 0.31, depending on the value of SR . This corresponds to a starting harvest rate $h_{t=1} = 1.1\%$ and a starting harvest level $H_{t=1} = 4$ bears per year. The harvest strategy that meets Management Objective 2 is lower than the strategy that meets Management Objective 1, because projections

for the KB subpopulation included a stable trend in K (i.e., $K_{t=36} \approx K_{t=1}$). Therefore, at $t = 36$, Management Objective 1 requires a subpopulation size that is greater than $0.9 \times N_{t=1} = 0.90 \times (0.69 \times K_{t=1}) \approx 0.62 \times K_{t=1}$; whereas Management Objective 2 requires a subpopulation size that is greater than $0.70 \times K_{t=36} \approx 0.70 \times K_{t=1}$ (i.e., a lower subpopulation size). Harvest strategies that met Management Objectives 1 and 2 were associated with increases in median N of up to 21% at $t = 36$ (Table S.KB2). This indicates that uncertainty in the vital rates, rather than the mean values of the rates, was a limiting factor in meeting management objectives. At $t = 36$, the harvest strategies in Table KB5 were associated with probabilities of causing male depletion of up to 0.27, due in part to lower S^* of males; and increased probabilities of extirpation, compared to projections with no harvest, of up to 0.03 (Table S.KB2).

Secondary simulations

We performed secondary simulations for Scenario 2 to evaluate the effects of management interval and data precision. Table KB6 shows the highest harvest strategies that met Management Objective 1b as a function of these factors, indicating the potential impact of different management conditions on harvest strategies for the KB subpopulation. For example, the highest harvest strategy under improved management conditions (i.e., a 10-year management interval and $rsd.mod = 0.5$) corresponded to $h_{t=1} = 2.2\%$ and $H_{t=1} = 8$. This harvest rate is 57% higher than the rate for a 20-year management interval and $rsd.mod = 1.5$.

In contrast to the BB subpopulation, the highest starting harvest level for the KB subpopulation, under improved management conditions, was lower than the expected value of maximum sustainable yield based on asymptotic population dynamics (i.e., 13 bears per year; Table KB3). This finding is largely due to high uncertainty in estimates of S^* for bears age ≤ 2 years (Table KB3). The reason is that improved data precision (i.e., $rsd.mod = 0.5$) only reduced sampling variation for simulated population assessments that occur in the future. Therefore, all subpopulation trajectories were highly variable during the first management interval (i.e., for the first 10, 15, or 20 years) due to high uncertainty in the baseline vital rates for Scenario 2. Because we only evaluated strategies with time-constant values of F_0 , the range of harvest strategies that met management objectives was constrained by high uncertainty in the currently-available data for the KB subpopulation. A consequence of this effect is that, for some harvest

strategies, the calculated harvest level increased after the first management interval, and remained 1-2 bears higher than the starting value at $t = 15$ and 36 (Table S.KB3).

Post hoc simulations

We performed two *post hoc* simulations to explore the ramifications of high uncertainty in estimates of S^* for bears age ≤ 2 years. First, we reduced sampling variation in these estimates by 75%, which resulted in levels of uncertainty similar to bears age ≥ 3 years (e.g., the reduced relative standard deviation due to sampling uncertainty was 0.04 for the vital rate σ_1 , which is equivalent to the un-modified value for σ_4). Conceptually, this permitted exploration of how a higher level of confidence in estimates of S^* for bears age ≤ 2 years might affect sustainable harvest. After reducing the uncertainty in estimates of S^* , we performed simulations under conditions similar to current harvest practices for the KB subpopulation (i.e., $SR = 0.94$, a 15-year management interval, and $rsd.mod = 1.0$) and identified the highest strategy that met Management Objective 1b. The resulting strategy (KB_S1) corresponded to $F_O = 0.80$, $h_{t=1} = 2.8\%$, and $H_{t=1} = 10$ bears per year (Table S.KB4). Interpretation of these results requires caution, because there was not an analytical basis for reducing uncertainty in estimates of S^* for bears age ≤ 2 years. Nonetheless, this *post hoc* simulation can provide guidance on what a sustainable harvest strategy might be, if it was assumed with an increased degree of confidence that survival rates of bears age ≤ 2 years have been sufficiently high to produce the estimated increase in abundance for the KB subpopulation.

Second, we explored uncertainty in estimates of S^* for bears age ≤ 2 years using a different approach. For all other simulations in this report, total uncertainty in the vital rates was partitioned as 75% sampling variation and 25% process variation, following the example of Taylor et al. (2002). Because time-constant estimates of S^* for KB bears were referenced to a 23-year period from 1992–2014, this partitioning may not be accurate for younger animals, which often exhibit higher interannual variation in survival compared to adults (Eberhardt 2002). We were not able to perform an analysis of variance components in S^* (e.g., Cooch and White 2016) due to sparse data. Therefore, for bears age ≤ 2 years, we subjectively repartitioned total uncertainty as 25% sampling variation and 75% process variation. After making this change, we performed simulations under conditions similar to current harvest practices for the KB subpopulation (i.e., $SR = 0.94$, a 15-year management interval, and $rsd.mod = 1.0$) and identified

the highest harvest strategy that met Management Objective 1b. The resulting strategy (KB_S2) corresponded to $F_O = 0.64$, $h_{t=1} = 2.2\%$, and $H_{t=1} = 8$ bears per year (Table S.KB4).

Discussion

We used subpopulation data from SWG (2016) in a demographic model adapted from Regehr et al. (2017) to evaluate a suite of potential harvest strategies for the BB and KB polar bear subpopulations, relative to management objectives and risk tolerances provided by the JC.

Demographic and management model

Additional details of the demographic model are presented in Regehr et al. (2015, 2017), including caveats and topics for future work. In this report we integrated the demographic model with a mechanistic submodel of Allee effects in the mating system (Molnár et al. 2008, 2014). In simulations for both the BB and KB subpopulations, lower estimates of S^* for males than females, combined with a sex-selective harvest, produced stage distributions that were skewed toward females. If the demographic model did not incorporate Allee effects, such subpopulations could exhibit unrealistically high values of r (i.e., in excess of the theoretical r_{max} under asymptotic population dynamics) because most adults were female and litter production rates could potentially remain high even in the near-absence of adult males. This effect could be compounded by the fact that the model tracked subpopulation density in terms of metabolic energetic equivalents, which allowed a given resource base to support a larger number of females compared to males (section Density dependence). We suggest that deriving parameters of the Allee submodel for the BB and KB subpopulations, and validating model-based predictions against field data, are areas for future work.

The demographic model differed from RISKMAN (Taylor et al. 2001) in several ways, including its ability to model temporal changes in vital rates and K . Also, we used a correlation structure for sampling variation that was informed by the CR models used to estimate vital rates (Chapter 6 in SWG 2016), whereas RISKMAN assumes sampling errors are independent (Taylor et al. 2006). This can influence PVA results, with correlated vital rates generally resulting in more variable subpopulation trajectories and higher risks of negative outcomes. To illustrate, we used the demographic model to calculate an unharvested, asymptotic population growth rate (λ)

using vital rates for the BB subpopulation as reported in Taylor et al. (2005). Our estimate of $\lambda = 1.053$ (SE = 0.022) was similar to the geometric mean estimate of unharvested $\lambda = 1.055$ (SE = 0.011) in Taylor et al. (2005), but our estimated standard error was twice as large. We suggest that our approach is more consistent with recommended practices in population viability analysis (Morris and Doak 2002).

Application of the demographic model required several key assumptions. First, to create density-dependent curves of the vital rates it was necessary to specify a subpopulation density (N/K) at which the vital rates were estimated. In practice, it is not possible to directly estimate K for wildlife populations (e.g., Gerrodette and Demaster 1990). Therefore, we inferred that N/K corresponded to a subpopulation size in the vicinity of MNPL, based on evidence that harvest in recent decades had been near maximum sustainable yield (Regehr et al. 2017). If actual N/K corresponded to a subpopulation size below MNPL, our estimates of intrinsic growth rate (r) could be positively biased. That is, the value of r corresponding to the vital rates would be closer to r_{max} , whereas we assumed it was equivalent to r_{MNPL} . If actual values of N/K corresponded to a subpopulation size significantly above MNPL, bias would be in the opposite direction. Second, we initialized population projections at time step $t = 1$ at a subpopulation size close to MNPL. This assumed that the BB and KB subpopulations are currently not experiencing strong density-dependent suppression of demographic parameters, which could be inaccurate for BB given evidence of range contraction (Chapter 4 in SWG 2016) and links between sea-ice and nutritional condition and reproductive rates (Chapters 6 and 7 in SWG 2016). Although we placed low confidence in the low estimates of S^* for the BB subpopulation from 2011–2013 (Scenario 1; see below), it is possible these estimates partially reflected negative effects of sea-ice loss. In combination, the short duration of recent subpopulation assessments in BB and KB, statistical uncertainty and potential bias in demographic parameters, and interannual variation, precluded direct estimation of subpopulation density. Our modeling approach did not make purposefully conservative assumptions about current density effects, especially for the BB subpopulation, and therefore could have understated the current and future effects of sea-ice loss. We recommend that future predictive modeling include sensitivity analyses with respect to key assumptions (e.g., Zabel et al. 2006).

Polar bears are distributed throughout the circumpolar Arctic in 19 subpopulations (PBSG 2010). Their life history is dependent on sea ice (Laidre and Regehr 2017), which is used

as a platform from which to hunt their primary prey, ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*). Earlier sea-ice breakup and reductions in optimal ice habitat have been linked to reductions in polar bear body condition, survival, reproduction, and abundance in some subpopulations (Stirling et al. 1999; Regehr et al. 2007, 2010; Rode et al. 2012; Bromaghin et al. 2015; Lunn et al. 2016; Obbard et al. 2016). Additional studies have documented use of less optimal sea ice habitat in several polar bear subpopulations (e.g. Durner et al. 2009, Wilson et al. 2014, Laidre et al. 2015, McCall et al. 2015). Our population projections for the BB and KB subpopulations included environmental variation primarily through the proxy metric for K , which was calculated from remote-sensing data for sea ice. Sea-ice metrics from other case studies for polar bears are reviewed by Stern and Laidre (2016). We did not consider rapid, non-linear declines in K or potentially catastrophic ecological or demographic effects due to climate change (e.g., Derocher et al. 2013), although the modeling framework could readily be adapted to include such effects. If subpopulations experience negative density-dependent effects that are larger or more abrupt than represented by the proxy metric for K , or negative density-independent effects that occur rapidly with respect to the management interval (i.e., so that multiple years elapse before such effects are detected), the harvest strategies identified in this report might cease to meet management objectives, resulting in increased risk of negative outcomes. Following a state-dependent management approach with a relatively short management interval (e.g., 10–15 years) can mitigate such risks, because reductions in N and the vital rates, whatever their cause, could be detected in future subpopulation surveys, and harvest strategies adjusted accordingly. Population dynamics and harvest strategies for declining populations are reviewed in detail in USFWS (2016).

Management objectives

We evaluated Management Objectives 1 and 2 at $t = 36$, corresponding to three polar bear generations (Regehr et al. 2016) in the future, a common time reference for population projections (e.g., IUCN 2017). We also report results at $t = 15$ years to provide insight into near-term population dynamics and identify potential metrics for monitoring (e.g., the proportion of females, see below).

Management Objective 1, which desired to achieve $N \geq 90\%$ of its current value, is more relevant to harvest assessments when habitat is stable or increasing. Under conditions of

declining K , it is not possible to meet Management Objective 1 over the long term, even in the absence of harvest. For example, population projections for BB only met Management Objective 1b under cessation of harvest, which resulted in transient subpopulation increases as N approached K , followed by declines as N/K reached 1 (Tables BB6 and S.BB2).

Management Objective 2, which desired to keep $N \geq \text{MNPL}$ with respect to a changing K , is more relevant to harvest assessments when habitat is declining. The goal is to maintain a constant ratio of N/K , such that subpopulation size and carrying capacity decline in parallel. If N remains far enough below K due to harvest (e.g., at MNPL), density effects are alleviated and there is a harvestable surplus. Under a harvest strategy that fulfills these conditions, long-term declines in N are driven primarily by declines in K . Regehr et al. (2017) proposed that such strategies are possible for polar bears, as long as habitat loss affects subpopulations primarily through density-dependent mechanisms (e.g., increased crowding and competition for limited resources), or if a state-dependent management approach is followed and the management interval is short enough to respond to density-independent reductions in r (e.g., reduced reproductive success because bears have insufficient time to hunt seals on the sea ice, regardless of density). Figure BB3 shows sample replicates from population projections that illustrate this concept, except toward the end of the projections when the probability of severe male depletion increases and causes reproductive failure (see below).

Management Objective 3 desired to achieve, but not exceed, a 30% reduction in N in 10–15 years, while maintaining subpopulation size above the level necessary to achieve maximum sustainable yield (i.e., above MNPL). Simultaneously meeting these two population conditions is likely not possible. That is because MNPL for polar bears occurs at approximately $N/K = 0.70$ (Regehr et al. 2017). Unless a subpopulation started at $N/K = 1$, a 30% reduction in N would necessarily result in a density $N/K < 0.70$ (i.e., below the subpopulation size that would produce maximum sustainable yield).

Harvest and subpopulation sex ratio

For both subpopulations, we performed projections with multiple values of sex ratio in the harvest (SR). Male-biased harvest is a common wildlife management and conservation tool (e.g., Mysterud 2011). For polar bears, seeking to harvest at $SR = 2$ (i.e., a 2:1 male-to-female ratio) is intended to protect adult females (Taylor et al. 2008b), which have the highest

reproductive value (Hunter et al. 2007). For the BB and KB subpopulations, harvest data from recent decades suggested that $SR = 1.25$ and 0.94 , respectively. These estimates were based on hunter-reported sex in Canada, which genetic testing suggests is highly accurate; and genetic sex determination of harvest samples from Greenland in the 2010s, which was assumed to represent the long-term sex ratio in the Greenlandic harvest due to apparent inaccuracies in hunter-reported sex (Chapter 8 in SWG 2016). For most of our simulations, harvest strategies that used $SR = 2$, instead of the lower *status quo* values of SR , did not result in higher harvest rates that met management objectives. This should not be interpreted as evidence against the conservation value of sex-selective harvest. Rather, it is a consequence of lower estimates of S^* for males than females in both subpopulations which, in conjunction with a sex-selective harvest, often led to the depletion of males. This had negative effects on reproduction via Allee effects in the mating system, translating into lower realized values of r and lower sustainable harvest. Taylor et al. (2008b) suggested that a 2:1 male-to-female harvest designed to achieve maximum sustainable yield, is unlikely to reduce the abundance or mean age of male bears to the point of reducing mating success. However, that analysis used equal survival rates for males and females, and the harvest rate was calculated relative to a different interpretation of maximum sustainable yield than is used here. Accurate monitoring of the sex ratio in the harvest, as well as the sex composition of the subpopulation and the litter production rate, are necessary to determine the extent to which reduction of male bears might affect the productivity of the BB and KB subpopulations. We suggest that it is important to investigate the analytical and biological reasons for lower estimates of S^* for male bears. Our finding that females comprise approximately 70% of independent bears in both subpopulations, despite harvest that may not be strongly selective for males, suggests that there is a biological basis for this finding, which could signal an emerging conservation concern and have demographic consequences not considered in our analyses.

We estimated stage-specific harvest vulnerability vectors for females and male using age data from the BB subpopulation (section Population initialization). Results suggested a slight preferential selection for juvenile bears of both sexes, compared to their representation in the subpopulation. For example, male two-year-olds (stage 7) were 25% more likely to be harvested compared to what would be expected based on their relative abundance. Strong selection against adult female bears with dependent young (stages 5 and 6) was consistent with the protection of

family groups in BB (Chapter 8 in SWG 2016). All population projections assumed that harvest vulnerability will remain constant in the future. If this is not the case (e.g., if selection becomes stronger for adults and weaker for subadults), the harvest strategies that meet management objectives might change.

Baffin Bay

We suggest that demographic modeling results for both subpopulations should be interpreted within the context of other available information. Sea-ice habitat in the BB region significantly declined between the previous subpopulation assessment in the 1990s and the recent reassessment in the 2010s (Chapter 4 in SWG 2106). The length of summer (i.e., the number of days from sea-ice retreat in spring to sea-ice advance in fall) increased by 12 days/decade since 1979. The mean sea-ice concentration during June–October decreased by 4% per decade. The general pattern of melt occurs about 3–4 weeks earlier in the 2010s than in 1990s. In general, BB has incurred large changes in the sea-ice regime experienced by polar bears and this has resulted in habitat loss (Stern and Laidre 2016; SWG 2016), which has translated to biological changes in the subpopulation. BB bears used significantly lower sea-ice concentrations in winter and spring in the 2010s than the 1990s (SWG 2016). Adult female bears are significantly closer to land in all months than in the 1990s, except at the end of breakup (June–July) when they stay on offshore sea ice as long as possible, likely to maximize feeding. Arrival dates on Baffin Island in summer are one month earlier in the 2010s than in the 1990s, and therefore the amount of time bears spent on land has increased by 20–30 days since the 1990s. There is a significantly shorter maternity den duration in the 2010s and maternity dens occur at higher elevations and steeper slopes than maternity dens in the 1990s, likely due to reduced snow cover (Escajeda et al. 2017).

Body condition declined in BB between 1993 and 2013, and declines were in close association with the duration of the ice-free period and spring sea ice transition dates. Reproductive metrics indicate that, from 1993 to 2013, an annual index of C0 recruitment declined concurrent with a trend towards earlier spring sea-ice break-up (SWG 2016). There has also been a significant reduction in the size of the 2010s BB 95% kernel range (i.e., a measure of the area used by bears fitted with radiocollars) in all months and seasons compared to the range in the 1990s. The most marked reduction is a 60% decline in subpopulation range size in summer. With respect to movements across subpopulation boundaries, BB bears in the 2010s

were significantly less likely to leave BB than in the 1990s. In particular, there was a reduction in the number of collared bears moving into Davis Strait and Lancaster Sound, apparently due to reduced winter sea-ice coverage. This suggests the BB subpopulation has become more discrete, with less exchange between it and other subpopulations.

For the BB subpopulation, litter production rate for females age ≥ 5 years (β_4) was estimated to be 0.93 (SE = 0.08) from field data collected 2011–2013. Taking into account statistical uncertainty, this value is similar to the values of 0.88 for bears age 5 years, and 1.00 for bears age ≥ 6 years, reported for BB by Taylor et al. (2005); and higher than the mean value of 0.80 for bears age ≥ 6 years across 11 other subpopulations (range = 0.44 to 0.98; Table S1 in Regehr et al. 2017). Relatively high litter production is consistent with our modeling assumption that, despite evidence for ecological change, the BB subpopulation is currently not experiencing strong density-dependent limitation in demographic parameters. We estimated β_4 directly from the sample of observed bears (section Methods), which was assumed to reflect the subpopulation because CR modeling did not identify differences in recapture probabilities (Chapter 5 in SWG 2016). However, during the autumn single adult females were more likely to be inland or at high elevations (SWG 2016), which could have led to heterogeneity in recapture probabilities that was not detected in the modeling process. If this was the case, single adult females could have been under-represented in the observation sample, which could lead to positive bias in estimates of β_4 because the number of single adult females appears in the denominator of the equation for litter production rate.

The three scenarios of the vital rates for BB corresponded to significant differences in subpopulation status (Table BB4) and therefore in harvest strategies. We placed less confidence in Scenario 1, because estimates of S^* for the period 2011–2103 were based primarily on three years of sampling, and bias in survival during the terminal years of a CR study is common when there is un-modeled heterogeneity in recapture probabilities or non-random temporary emigration from the sampling area (Peñaloza et al. 2014). Estimates of S^* for Scenario 2 were referenced to 1998–2010, a longer period that was bracketed by intensive sampling in the 1990s and 2010s, and throughout which research marks were returned in the harvest. Furthermore, population reconstruction suggested that a subpopulation with the vital rates from Scenario 2 could exhibit a stable trajectory over the period 1998–2010, when subject to the observed harvest of approximately 162 bears per year and observed variation in sea-ice conditions. We started the

population reconstruction in 1998 at an assumed abundance of 2,826 (i.e., the estimate for the period 2011–2013), because SWG (2016) indicated that lower estimates of N from the 1990s included an unknown level of negative bias, and that trends in the size of the BB subpopulation could not be reliably determined. Our finding that the vital rates of Scenario 2 were capable of maintaining a stable subpopulation does not constitute evidence that this occurred. We did not complete a comprehensive suite of population reconstructions, and other combinations of factors (e.g., higher starting N and lower vital rates) might reproduce equally plausible histories. Nonetheless, the vital rates of Scenario 2 appear consistent with available information on the history of the BB subpopulation, to the extent this can be determined given uncertainties and potential biases in the data. Also, population reconstruction from 1998–2010 led to an ending proportion of females in the subpopulation that was similar to the value estimated from sex- and age-specific abundance estimates for the period 2011–2013.

For the reasons discussed above, we considered Scenario 2 to be the more likely representation of the current status of the BB subpopulation. Harvest strategies in Table BB6 that met Management Objective 2 are likely to satisfy the definition of sustainable harvest proposed by Regehr et al. (2017), which requires maintaining a subpopulation size above MNPL with respect to a changing K , and limiting the negative effects of harvest on persistence. For harvest strategies using the *status quo* value of $SR = 1.25$ and a 15-year management interval, the upper limits on present-day harvest rate ($h_{t=1}$) were 4.3 and 5.7% for “low” and “medium” risk tolerances, as stated by the JC. This corresponds to present-day harvest levels of up to 120 and 160 bears per year, respectively, which would be applied for a period of 15 years and then updated. This range encompasses current TAH of 132 for the BB subpopulation (SWG 2016). The sustainability of these harvest strategies is conditional on the input data and assumptions of our modeling approach, including (1) that Scenario 2, the most optimistic scenario of the vital rates, is an accurate representation of the current and future status of the BB subpopulation; and (2) adherence to a state-dependent management approach over the next 35 years, with a 15-year management interval and future subpopulation assessments that provide a level of precision similar to the 1998–2010 estimates of S^* (SWG 2016). The harvest strategy corresponding to “low” risk tolerance (i.e., $h_{t=1} = 4.3\%$) is associated with lower probabilities of male depletion and extirpation in later years of the projection. For the BB subpopulation, nearly all harvest strategies can be expected to require reductions in the harvest level over time, due primarily to

declining K , but also potentially due to harvest if there are inaccuracies in the input data or our modeling approach. It is also possible that the harvest rate will decline over time due to Allee effects in the mating system or to density-independent reductions in r that were not considered in our analyses.

We included Scenario 3 of the vital rates, to provide a means of comparison with an “average” polar bear subpopulation. Table BB7 indicates that, using the *status quo* $SR = 1.25$ and a 15-year management interval, harvest strategies with $h_{t=1} = 3.6\%$ could meet Management Objective 2 at the “medium” level of risk tolerance. This corresponds to a present-day harvest level of up to 100 bears per year. The upper limit on $h_{t=1}$ was also 3.6% for a harvest strategy with $SR = 2$, which is lower than the historic standard 4.5% harvest rate when using a 2:1 male-to-female sex ratio, for subpopulations experiencing positive environmental conditions (Taylor et al. 1987a). This difference is partially due to our inclusion of a declining trend in K for the BB subpopulation. It also suggests that our demographic modeling approach, when used in conjunction with Management Objective 2 and a “medium” risk tolerance as stated by the JC, may be slightly more conservative than previous predictive modeling for polar bears.

For the BB subpopulation, the challenges of meeting Management Objective 3, as it was stated by the JC, were presented above. To inform future discussion of subpopulation reduction, we identified a harvest strategy that resulted in a 25% reduction in starting subpopulation size over 15 years, while remaining with the stated risk tolerance for not exceeding a 30% reduction (Management strategy BB_S1 in Table S.BB5). This strategy required $SR = 1$, a 5-year management interval, and improved precision in the vital rates estimated from future subpopulation surveys. The starting harvest rate was 8.7%, corresponding to a present-day harvest level of 245 bears per year. It is unlikely that the near-optimal management conditions required by this strategy are feasible in practice, suggesting that either the management objectives or risk tolerances associated with a managed subpopulation reduction require reconsideration. Another practical challenge of managed reduction is that harvest must be rapidly reduced from very high levels in early years, to much lower levels once the target subpopulation size has been achieved. The risks of not reducing harvest in this manner were demonstrated by harvest strategy BB_S2, which maintained a fixed-level harvest of 245 bears per year for 15 years, without new subpopulation assessments or adjustments to the harvest. That strategy resulted high probabilities of extirpation (Table S.BB5), emphasizing the critical importance of

monitoring and responsive management under aggressive harvest regimens.

Kane Basin

The annual cycle of sea-ice habitat in KB has shifted from a largely year-round ice platform (>30% coverage in summer) to a cycle that resembles the seasonal ice ecoregion (Amstrup et al. 2008) with complete melt-out in summer (<5% coverage; SWG 2016). The KB subpopulation has responded to changing sea-ice conditions with broad movement and habitat use patterns that are more similar to those of bears in seasonal sea-ice ecoregions (e.g., expanded seasonal home ranges). Apparent improvement in body condition in the 2010s, and no evidence of changes in reproductive performance in KB between the 1990s and 2010s, may reflect natural variation or a response to long-term changes in sea-ice dynamics in KB (SWG 2016). These observed changes reflect general differences in habitat use of bears occupying the archipelago vs. seasonal ice ecoregions: bears inhabiting seasonal ice regions have larger and more variable home ranges as they temporally track sea ice, whereas bears in archipelago regions have smaller home ranges with less variation.

For the KB subpopulation, litter production rate for females age ≥ 5 years (β_4) was estimated to be 0.71 (SE = 0.16) from field data collected 2012–2014. Considering statistical uncertainty, this suggests reproductive success similar to, or slightly lower than, other subpopulations (Table S1 in Regehr et al. 2017). The two scenarios of the vital rates for KB corresponded to significant differences in subpopulation status (Table KB3) and therefore in harvest strategies. Scenario 1 was characterized by low capacity for growth and high uncertainty ($\lambda = 0.01$ [SE = 0.04]), due largely to low and uncertain estimates of S^* for bears age ≤ 2 years (Table KB2). We placed less confidence in Scenario 1 because survival estimates of young bears were based on very small sample sizes during the period 2012–2014 (e.g., < 4 C0 marked per year). Furthermore, population reconstruction suggested that a subpopulation with vital rates from Scenario 1 would exhibit a declining trend from 1998–2014, when subject to the observed harvest of approximately 8 bears per year and an increasing trend in K . This is inconsistent with the estimated increase in abundance from 224 in the 1990s to 357 in the 2010s (Chapter 10 in SWG 2016), and with other evidence for productivity of the KB subpopulation (Chapters 9, 12, and 13 in SWG 2016).

Scenario 2 for KB included modified values of S^* for bears age ≤ 2 years, as necessary to reproduce the estimated subpopulation trend between the 1990s and 2010s, keeping other vital rates (e.g., adult survival) identical to Scenario 1. Vital rates in Scenario 2 retained the same amount of sampling variation as Scenario 1. Therefore, trajectories during population reconstruction were highly variable, corresponding to an 80% probability that the ending subpopulation size was at least one bear larger than the starting subpopulation size (i.e., that $N_{2014} > N_{1998}$). This stochastic representation of the history of the KB subpopulation was slightly more pessimistic (i.e., more likely to correspond to a declining subpopulation) compared to findings in SWG (2016), which suggested that the probability of a positive subpopulation change between the 1990s and 2010s was 95%. For Scenario 2, the modified estimates of S^* for bears age ≤ 2 years (Table KB2) were lower than the corresponding estimates for BB (noting that survival has a different time reference for the two subpopulation based on spring vs. autumn sampling), and within the range of juvenile survival estimates for other subpopulations with spring sampling (Table S1 in Regehr et al. 2017). The estimate of $\lambda = 1.05$ for Scenario 2 was equivalent to the mean estimate of unharvested population growth rate for other subpopulations (Regehr et al. 2017). Considering other lines of evidence for increasing productivity in the KB region, we suggest that Scenario 2 is a plausible representation of the current demographic status of this subpopulation.

For Scenario 2 of the vital rates and using the *status quo* value of $SR = 0.94$ and a 15-year management interval, the highest harvest strategy that met Management Objective 1 at “medium” risk tolerance corresponded to $h_{t=1} = 1.7\%$ and $H_{t=1} = 6$ bears per year. This finding is conditional on the input data and assumptions of the modeling approach, including (1) that Scenario 2 is an accurate representation of the KB subpopulation; (2) that K will remain stable for the next 35 years; and (3) adherence to a state-dependent management approach over the next 35 years, with a 15-year management interval and future subpopulation assessments that provide a level of precision similar to the estimates of S^* in SWG (2016). Sustainable harvest strategies for KB exhibited slight increases in mean harvest level over time (Table S.KB2), due in part to stability in K . If increasing biological productivity in the KB region leads to increasing trends over time in K and the intrinsic population growth rate, sustainable harvest levels would be expected to increase as well.

The relatively low estimate of sustainable harvest for KB was largely due to high uncertainty in vital rates, particularly estimates of S^* for bears age ≤ 2 years. This is evidenced by comparing a harvest level of up to 6 bears per year, calculated from the stochastic model projections (see above), with the estimated maximum sustainable yield of 13 bears per year based on asymptotic population dynamics (Table KB3). To investigate further, we performed two *post hoc* simulations with alternative assumptions for sampling uncertainty. The first simulation, which reduced uncertainty in estimates of S^* for bears ≤ 2 years to match the level of uncertainty in other survival estimates, resulted in a sustainable harvest of up to 2.8% (10 bears per year) under Management Objective 1 with “medium” risk tolerance, when using a 15-year management interval. The second simulation, which reallocated total uncertainty between sampling and process variation, resulted in a sustainable harvest of up to 2.2% (8 bears per year) under the same management conditions. These simulations were relevant because it is difficult to obtain precise and accurate estimates of vital rates for small and remote subpopulations such as KB. Without such estimates, the options available to managers include (1) inferring subpopulation status and sustainable harvest based on data other than the estimated vital rates (e.g., by modifying some estimates of S^* based on other information, similar to Scenario 2 and the *post hoc* simulations); or (2) adopting a conservative harvest strategy (e.g., Taylor et al. 2002).

Considering all available ecological and demographic data for the KB subpopulation, we suggest that present-day harvest rates up to approximately 2.8% (10 bears per year) are unlikely to cause negative population outcomes, if coupled with effective monitoring under a state-dependent approach. Use of a 10-year management interval would reduce the risks of harvest associated with high uncertainty in the currently available vital rates. If the challenges of studying the KB subpopulation lead to continued difficulty in obtaining accurate and precise estimates of vital rates, despite increased survey efforts, supplementary monitoring that is more frequent but less intensive may be valuable. We suggest developing a suite of ecological and demographic indicators to monitor subpopulation status, including accurate information on the level and composition of the harvest, marine productivity, habitat use and availability, reproductive rates, and estimates or indices of subpopulation size (via aerial survey or CR).

Monitoring

All of the harvest strategies considered in this report require the existence of a coupled research-management system under which both the sustainable harvest rate and the harvest level are adjusted periodically, based on new scientific information from subpopulation surveys and other sources. For both subpopulations, shorter management intervals and more precise estimates of N and vital rates, can substantially reduce the risk of negative population outcomes associated with a given harvest strategy. Results from the secondary simulations can help managers balance trade-offs between monitoring frequency and intensity (and therefore cost), the sustainable harvest rate, and harvest risks (Tables BB8 and KB6).

In our simulations, the management interval corresponded to the exact number of years between changes to the harvest level. For example, during population projections a 15-year management interval meant that new simulated population assessments were completed, and changes to the harvest level implemented, every 15 years. In practice, time lags in the coupled research-management system will likely result in departures from this simplified representation. For example, even if on-the-ground changes to TAH are implemented every 15 years, each change might be based on data from subpopulation surveys that were completed 2–3 years earlier. Application of the findings in this report should consider major differences, if they exist, between the definition of the management interval in practice and the definition used here.

Periodically obtaining new estimates of N and the vital rates (which determine r) is a central feature of a state-dependent management approach (Regehr et al. 2017). These parameters can be difficult and expensive to collect for wildlife populations (e.g., Williams et al. 2002), although both field methods (e.g., genetic CR; SWG 2016) and analytical approaches (e.g., Bayesian implementation of multistate models; Lunn et al. 2016) continue to evolve. Our analyses highlight the challenges of using estimated demographic parameters in harvest assessments for polar bears, even when the parameters were obtained from well-designed CR studies (SWG 2016). We sought to address these challenges primarily through consideration of multiple scenarios of the vital rates, which were developed based on (i) the estimated vital rates, referenced to different time periods; (ii) insights into the magnitude and directionality of potential bias (e.g., Schaub et al. 2004; Peñaloza et al. 2014); (iii) population reconstruction; and (iv) comparison with other case studies for polar bears. Although the magnitude of bias is generally lower in estimates of survival from CR studies compared to estimates of abundance

(Williams et al. 2002), the ramifications of relatively small bias in survival (e.g., 1–2%) can be profound when survival rates are used for population projections (e.g., Regehr et al. 2009). Skalski et al. (2012) recommend that biological realism should serve as a fundamental check for estimated demographic parameters and trends, and that auxiliary information should be used whenever possible to validate the results from predictive modeling. Peacock et al. (2011) recommend that management decisions for polar bears also include assessments of changes in body condition, habitat, population, and genetic delineation, and simultaneous surveys on Traditional Ecological Knowledge and human dimensions. Most of these subjects were successfully addressed during recent studies in BB and KB (SWG 2016). In this report, analyses relied heavily on estimates of subpopulation abundance and vital rates from SWG (2016), with limited interpretation of these estimates for the purpose of developing alternative scenarios and *post hoc* simulations.

Detailed recommendations on how to improve future estimates of N and r for the BB and KB subpopulations are beyond the scope of this report. Analyses to optimize the design of CR studies are being conducted under implementation of the Circumpolar Action Plan for polar bears (Polar Bear Range States 2015). For BB and KB, we suggest considering CR studies with a modified sampling scheme (e.g., sampling every other year for a period of six years, rather than sampling annually for three years), which could be combined with ongoing, less-intensive monitoring (see below). Also, we suggest that future study plans consider collecting and analyzing multiple types of data under the framework of an integrated population model (e.g., Frederiksen et al. 2014). Integrated population models can offer benefits for precision, accuracy, and the number of relevant parameters that can be estimated. For example, Regehr et al. (In preparation) concurrently analyzed radiotelemetry and CR data, which allowed direct estimation of temporary emigration and likely reduced bias in estimates of survival. Integrated population models can lead to increased consistency among demographic parameters (e.g., such that estimates of survival from studies of individually-marked animals, are consistent with estimates of subpopulation trend from aerial surveys). Finally, these models could allow integration of multiple types of research data with information from the harvest, local observations, and Traditional Ecological Knowledge. This has the potential to provide an improved assessment of overall subpopulation status that represents multiple perspectives.

Together with the conclusions and recommendations in SWG (2016), our analyses

highlight important ecological and demographic indices for monitoring the BB and KB subpopulations. Accurate knowledge of the number, and sex and age composition, of human-caused removals is critical to understanding the effects of harvest on a subpopulation. Incomplete harvest reporting can lead to subpopulation depletion and other undesired outcomes, including negative bias in estimates of S^* that result in pessimistic population projections and lower estimates of sustainable harvest. We recommend that all harvested bears for the BB and KB subpopulations be genetically monitored, to detect recoveries of animals that were genetically marked during research. When used in CR models, accurate recovery data provide important information on survival and can reduce bias compared to studies with live recaptures only (Kendall et al. 2013). Furthermore, a systematic analysis of the sex and age composition of all harvest data (i.e., not only from research-marked bears) could provide complementary estimates of harvest rate and other demographic parameters (Skalski et al. 2005). Although such analyses can be limited by low statistical power and untestable assumptions, these problems are reduced if sample sizes are large (e.g., for the BB subpopulation) and recent data are available from a comprehensive subpopulation assessment. We suggest that systematic analysis of harvest data can be a useful monitoring tool between subpopulation surveys.

Nutritional condition and reproductive rates should be monitored as key indicators of subpopulation productivity (e.g., Vongraven et al. 2012). Changes in these parameters may precede or occur at the same time as other demographic changes (e.g., declining survival). Estimated relationships between time series of reproductive rates (or any other vital rate) and environmental conditions can be used in population projections to evaluate the future effects of habitat loss (e.g., Hunter et al. 2010). When such relationships are available, this represents an empirical alternative to our approach of projecting future trends in K that operated on vital rates through the density-dependent functions.

For a subpopulation that is harvested near maximum sustainable yield, and therefore in theory should function at a density well below carrying capacity (e.g., $N/K = 0.70$), declining nutritional condition and reproductive rates may signal negative density-independent effects. Density-independent limitation can result in lower values of r_{MNPL} , thus reducing the sustainable harvest rate that is calculated from equations 1 and 2. Under strong density-independent limitation, continued harvest without adjustment could lead to predominately additive mortality, with the potential to accelerate subpopulation declines compared to what would be expected

under sea-ice loss only (USFWS 2016). Given that there is uncertainty about the extent to which sea-ice loss affects polar bears via density-dependent vs. density-independent mechanisms (e.g., Rode et al. 2012; Lunn et al. 2016), a high priority should be placed on monitoring spatial and temporal changes in habitat availability (e.g., as estimated from remote-sensing data of sea ice; Stern and Laidre 2016) along with indices of nutritional status and reproduction. SWG (2016) presented multiple reproductive indices for the BB and KB subpopulations, and we suggest that the number of yearlings per adult female may be particularly useful because it integrates litter production rate and juvenile survival (Rode et al. 2014; Regehr et al. 2015). Furthermore, concurrent monitoring of reproduction and the proportion of females in the subpopulation, is important to detect potential declines in subpopulation productivity due low male survival, skewed sex ratios in the subpopulation, and potential Allee effects in the mating system. Our analyses highlight these issues as potential conservation concerns for both the BB and KB subpopulations.

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Abbreviations, Acronyms, Symbols, and Definitions

Adult – A polar bear age ≥ 5 years.

Allee effect – In this report, Allee effects refer to changes in reproductive rates due to density effects in the mating system. Declining reproductive rates can occur if adult males are depleted relative to adult females, or if overall subpopulation density is low during the spring on-ice breeding season.

Capture-recapture (CR) – A type of research study in which animals are individually marked, often through biopsy darting to obtain a genetic sample, or chemical immobilization to apply a physical mark (e.g., ear tags and lip tattoos). Over multiple years, data on individually marked animals can be used to estimate abundance and vital rates.

Carrying capacity (K) – The maximum number of individuals in a subpopulation that can be supported by the environment. This limit reflects the availability of food, habitat, and other resources. In this report, K is measured in the number of independent bears. Within the demographic model K is converted to metabolic energetic equivalents for the purpose of tracking subpopulation density over time.

Coefficient of variation (CV) – Ratio of the standard deviation to the mean of a statistical distribution of values. The CV reflects the level of uncertainty in an estimate, compared to the value of the estimate.

Confidence interval (CI) – A range of values that describes the uncertainty surrounding an estimate. Estimates of abundance and vital rates are often accompanied by a 95% CI.

Cub-of-the-year (C0) – A polar bear cub less than one year of age. In the polar bear life cycle it is assumed that C0 are born on 01 January of each year.

Density dependence – Demographic processes that change the birth or death rates as subpopulation density (i.e., the number of individuals per unit of habitat) changes.

Dependent young – A polar bear age ≤ 2 years that is accompanied by its mother.

Extirpation – The functional extinction of a subpopulation, which occurs in the population projections when a subpopulation size falls below the quasi-extinction threshold. In our analyses, extirpation is an irreversible condition that cannot be recovered from once the quasi-extinction threshold is crossed.

Harvest – In this report, harvest refers to all types of human-caused removals (i.e., subsistence harvest, sport hunting, removal of problem bears, defense kills, etc.).

Harvest level (H) – The number of independent bears removed each year through harvest.

Harvest rate (h) – Percentage of the total subpopulation size (i.e., the number of all bears, including dependent young) that is removed as independent bears each year through harvest.

Harvest strategy – A particular set of management and research conditions that define how harvest is conducted within the context of a state-dependent management approach. A

harvest strategy is specified by inputs to equations 1 and 2, which determine the level and sex ratio of the harvest; as well as by the management interval and the level of precision in subpopulation data.

Independent bears – Polar bears age ≥ 2 years that are not with their mothers. Includes all polar bears in a subpopulation except for yearlings, cubs-of-the-year, and dependent two-year olds.

Intrinsic population growth rate (r) – The intrinsic population growth rate in the absence of human-caused removals. The maximum intrinsic growth rate (r_{max}) occurs at a low density relative to carrying capacity. The intrinsic growth rate at a density referenced to maximum net productivity level is denoted r_{MNPL} . Both r_{max} and r_{MNPL} are unharvested, potential growth rates that provide measures of the resilience of a subpopulation.

κ – A dimensionless metric representing proportional changes in carrying capacity (K), calculated from the number of ice-covered days per year. During projections, carrying capacity at year t , calculated as $K(t) = K(t = 1) * \kappa(t)$, operated on vital rates through the density-dependent relationships.

Litter production rate (β_4) – The proportion of adult females that are available to breed in year t , which produce a litter of cubs-of-the-year in year $t+1$.

Management interval (*mgmt.interval*) – Duration (in years) of the interval between successive changes to the harvest level based on new data from completed subpopulation surveys. For example, under a 10-year management interval, a harvest level would be calculated in year $t = 1$ and then applied each year $t = 1, 2, \dots, 10$. During the later years of this period, a subpopulation survey would be completed to provide updated estimates of abundance and the vital rates. A new harvest level would be calculated using these data equations 1 and 2, and the new harvest level would be applied in each year $t = 11, 12, \dots, 20$.

Management Objective – An overall goal for management of a subpopulation, as stated by the responsible management agencies. In this report, management objectives are presented as a desired population condition (e.g., maintaining a relatively stable subpopulation size) along with a risk tolerance for not meeting the population condition.

Maximum net productivity level (MNPL) – The subpopulation size that results in the greatest net annual increment in subpopulation numbers resulting from reproduction minus losses due to natural mortality. The value of MNPL depends on how density dependence

operates in a subpopulation. Regehr et al. (2017) suggested that for polar bears MNPL occurs at approximately 70% of the maximum number of animals the environment can support on average (i.e., $MNPL \approx 0.70 \times K$).

Metabolic energetic equivalent value (*mee*) – The energetic requirements of an individual bear, expressed relative to the energetic requirements of an average adult female. Larger bears (e.g., adult males) have higher *mee* values than smaller bears (e.g., subadult females), and therefore occupy more “energetic space” and make a greater individual contribution to density effects.

P_{extirpation} – The probability of extirpation for a subpopulation.

P_{male.dep} – The probability of severe male depletion, defined as the number of adult males in a subpopulation (stage 10 in Figure 1) falling below 50% of the quasi-extinction threshold.

P_{Objective} – The probability of meeting the population condition corresponding to a Management Objective as defined in Table BB1.

Population growth rate (λ) – The rate of change of subpopulation size, measured in numbers of individuals per unit time.

Population projection – A simulated process in which the matrix-based model is used to project the size and composition of a subpopulation forward over a certain number of annual time steps. Each projection was defined by a specific set of biological and management conditions.

Population reconstruction – In this report, population reconstruction refers to retrospective population projections that used historic biological and management conditions. Population reconstruction was used to explore the past performance of the BB and KB subpopulations.

Quasi-extinction threshold – The size below which a subpopulation is considered to be extirpated. Population viability analyses often use quasi-extinction thresholds that are larger than one animal, because at very low numbers there can be negative small-population dynamics that reduce viability and accelerate extirpation. In this report, the quasi-extinction thresholds were 100 and 25 independent bears for the BB and KB subpopulations, respectively.

Risk tolerance – The attitude toward risk of the responsible management agencies. In this report, risk tolerance is expressed as the required probability of meeting the population

condition associated with a Management Objective (e.g., the required probability, as stated by managers, of maintaining subpopulation size above a desired level).

rsd.mod – A modifier on the baseline relative standard deviation (SD) of the vital rates due to sampling uncertainty. Using different values of *rsd.mod* in population projections, allowed evaluation of the effects of different levels of precision in the data obtained from future subpopulation surveys. For example, a projection with *rsd.mod* = 0.5 meant that simulated population assessments would produce estimates of the vital rates and subpopulation size with approximately 50% less sampling variation, compared to the actual amount of sampling variation for the corresponding scenario of the vital rates.

Scenario of the vital rates – A specific set of vital rates assumed to represent the current status of a subpopulation. In this report, multiple scenarios of the vital rates were considered because of uncertainty and potential bias in estimates of certain demographic parameters from CR studies for both the BB and KB subpopulations (SWG 2016).

Stage – Stages in the life cycle graph representing bears of different sex, age, and reproductive status (Figure 1).

Standard deviation (SD) – A statistical measure that quantifies the amount of variation of a set of numbers around the mean (i.e., average) value. A low standard deviation means that most numbers are very close to the mean.

Standard error (SE) – A statistical measure that quantifies the amount of variation associated with an estimated parameter. The standard error is the standard deviation of a parameter's sampling distribution (i.e., its probability distribution, as estimated from a random sample of data).

Sex ratio (SR) – A factor that specifies the male-to-female ratio in the harvest. For example, *SR* = 2 is equivalent to a 2:1 male-to-female sex ratio.

Simulated population assessments – Simulated subpopulation surveys that were performed during population projections, on a schedule according to the management interval. The simulated population assessments provided updated estimates of subpopulation size and vital rates, which were used in equations 1 and 2 to calculate an updated harvest level, which was applied for the subsequent management interval.

State-dependent management – An approach under which management actions are based on the current state (status) of the subpopulation. In this report, state-dependent management

refers to a coupled research-management system under which both the harvest rate and the harvest level are adjusted periodically, based on new scientific information from subpopulation surveys.

Subadult – Independent polar bear aged 2–4 years

Subpopulation – One of the 19 polar bear subpopulations recognized by the International Union for the Conservation of Nature (in the present case the Baffin Bay and Kane Basin subpopulations).

Subpopulation size (N) – The number of bears in a subpopulation.

t – Annual time step in a subpopulation projection. Quantities labeled with a subscript t are referenced to a specific time step. For example, $H_{t=1}$ is a harvest level at year 15.

Vital rates – Demographic parameters such as reproductive rates and survival rates, which define transitions in the life cycle graph (Figure 1) and determine the composition and growth of a subpopulation.

Yearling (C1) – A polar bear cub between one and two years of age.

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Tables and Figures

Table BB1. Potential Management Objectives for the Baffin Bay (1-3) and Kane Basin (1-2) polar bear subpopulations. Population size (N) and carrying capacity (K) are measured in the number of independent bears and referenced to an annual time step (t) during population projections.

Management Objective	Population condition	Required probability of meeting objective
1a	$N_{t=36} > (0.9 \times N_{t=1})$	≥ 0.90
1b	$N_{t=36} > (0.9 \times N_{t=1})$	≥ 0.70
2a	$N_{t=36} > (0.7 \times K_{t=36})$	≥ 0.90
2b	$N_{t=36} > (0.7 \times K_{t=36})$	≥ 0.70
3a	$N_{t=15} > (0.7 \times N_{t=1})$	≥ 0.90
3b	$N_{t=15} > (0.7 \times N_{t=1})$	≥ 0.30

Table BB2. Reproductive parameters for the Baffin Bay polar bear subpopulation estimated from field data collected 2011-2013. Dependent young are cubs-of-the-year (C0) and yearlings (C1). Adult females are ≥ 5 years. The mean and standard error (SE) we calculated using simulations methods described in the main text.

Parameter	Mean	SE
Litter production rate for adult females (β_4)	0.93	0.08
C0 per adult female	0.58	0.04
Proportion of adult females with C0	0.38	0.02
C0 litter size	1.55	0.04
C1 per adult female	0.35	0.03
Proportion of adult females with C1	0.24	0.02
C1 litter size	1.47	0.05

Table BB3. Estimates (mean and standard error [SE]) of unharvested survival (S^*) for three scenarios of the vital rates for the Baffin Bay polar bear subpopulation. The scenarios are described in the main text.

†The life cycle graph (Figure 1) does not include separate stages for cubs-of-the-year (C0) and yearlings (C1), but survival rates for these age classes contribute to transition probabilities between reproductive stages for adult females.

Sex	Age class	Stage	Scenario 1		Scenario 2		Scenario 3	
			Mean	SE	Mean	SE	Mean	SE
female	C0	†	0.88	0.06	0.88	0.06	0.88	0.06
female	C1	†	0.89	0.06	0.89	0.06	0.89	0.06
female	2-4 year	1-3	0.91	0.05	0.96	0.02	0.93	0.05
female	≥5 year	4-6	0.91	0.05	0.96	0.02	0.93	0.05
male	C0	†	0.88	0.06	0.88	0.06	0.88	0.06
male	C1	†	0.89	0.06	0.89	0.06	0.89	0.06
male	2-4 year	7-9	0.83	0.06	0.91	0.02	0.92	0.06
male	≥5 year	10	0.83	0.06	0.91	0.02	0.92	0.06

Table BB4. Demographic parameters (mean and standard error [SE]) for the Baffin Bay polar bear subpopulation, corresponding to the three scenarios of the vital rates, based on asymptotic population dynamics. The parameters are: unharvested population growth rate (λ); subpopulation density (i.e., N/K) corresponding to maximum net productivity level (MNPL); intrinsic population growth rate at MNPL (r_{MNPL}); intrinsic population growth rate at low population density (r_{max}); and maximum sustainable yield (MSY) measured in numbers of independent bears under non-selective harvest.

Sex	Scenario 1		Scenario 2		Scenario 3	
	Mean	SE	Mean	SE	Mean	SE
λ	1.03	0.05	1.08	0.04	1.05	0.03
MNPL	0.72	0.04	0.67	0.03	0.70	0.03
r_{MNPL}	0.03	0.06	0.08	0.03	0.05	0.03
r_{max}	0.03	0.06	0.10	0.04	0.06	0.04
MSY	49	67	156	50	100	59

Table BB5. Summary of primary simulations for the Baffin Bay polar bear subpopulation, using Scenario 1 of the vital rates. For each row in the table, parameters are shown for the maximum starting (i.e., $t = 1$) harvest strategy that meets the corresponding Management Objective (Table BB1). F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with a 15-year management interval and baseline data precision (i.e., $rsd.mod = 1$). *NA* indicates that a Management Objective was not met with no harvest.

Management Objective	<i>SR</i> = 1.0			<i>SR</i> = 1.25			<i>SR</i> = 2.0		
	F_O	$H_{t=1}$	$h_{t=1}$	F_O	$H_{t=1}$	$h_{t=1}$	F_O	$H_{t=1}$	$h_{t=1}$
1a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
1b	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
2a	0.00	0	0.0%	0.00	0	0.0%	0.00	0	0.0%
2b	0.41	20	0.7%	0.36	20	0.7%	0.27	20	0.7%
3a	0.00	0	0.0%	0.00	0	0.0%	0.00	0	0.0%
3b	1.22	60	2.1%	1.08	60	2.1%	1.08	80	2.8%

Table BB6. Summary of primary simulations for the Baffin Bay polar bear subpopulation, using Scenario 2 of the vital rates. For each row in the table, parameters are shown for the maximum starting (i.e., $t = 1$) harvest strategy that meets the corresponding Management Objective (Table BB1). F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with a 15-year management interval and baseline data precision (i.e., $rsd.mod = 1$). *NA* indicates that a Management Objective was not met with no harvest.

Management Objective	<i>SR</i> = 1.0			<i>SR</i> = 1.25			<i>SR</i> = 2.0		
	F_O	$H_{t=1}$	$h_{t=1}$	F_O	$H_{t=1}$	$h_{t=1}$	F_O	$H_{t=1}$	$h_{t=1}$
1a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
1b	0.00	0	0.0%	0.00	0	0.0%	0.00	0	0.0%
2a	0.78	120	4.3%	0.69	120	4.3%	0.43	100	3.6%
2b	1.03	160	5.7%	0.92	160	5.7%	0.60	140	5.0%
3a	1.03	160	5.7%	0.92	160	5.7%	0.60	140	5.0%
3b	1.16	180	6.4%	1.15	200	7.1%	0.78	180	6.4%

Table BB7. Summary of primary simulations for the Baffin Bay polar bear subpopulation, using Scenario 3 of the vital rates. For each row in the table, parameters are shown for the maximum starting (i.e., $t = 1$) harvest strategy that meets the corresponding Management Objective (Table BB1). F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with a 15-year management interval and baseline data precision (i.e., $rsd.mod = 1$). *NA* indicates that a Management Objective was not met with no harvest.

Management Objective	<i>SR</i> = 1.0			<i>SR</i> = 1.25			<i>SR</i> = 2.0		
	F_O	$H_{t=1}$	$h_{t=1}$	F_O	$H_{t=1}$	$h_{t=1}$	F_O	$H_{t=1}$	$h_{t=1}$
1a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
1b	0.00	0	0.0%	0.00	0	0.0%	0.00	0	0.0%
2a	0.60	60	2.1%	0.53	60	2.1%	0.53	80	2.8%
2b	0.80	80	2.8%	0.89	100	3.6%	0.66	100	3.6%
3a	1.00	100	3.6%	0.71	80	2.8%	0.66	100	3.6%
3b	1.40	140	5.0%	1.24	140	5.0%	0.93	140	5.0%

Table BB8. Summary of secondary simulations for the Baffin Bay polar bear subpopulation, using Scenario 2 of the vital rates. Rows are different levels of *rsd.mod*, a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty. Columns are different management intervals. Values in the cells represent the upper limits that meet Management Objective 2b (Table BB1); where F_0 is a factor to calculate the harvest rate, and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with $SR = 1.25$.

<i>rsd.mod</i>	Management interval (years)		
	10	15	20
(Results reported as values of F_0)			
0.5	1.15	0.98	0.86
1.0	1.03	0.92	0.80
1.5	0.92	0.80	0.75
(Results reported as values of $h_{t=1}$)			
0.5	7.1%	6.0%	5.3%
1.0	6.4%	5.7%	5.0%
1.5	5.7%	5.0%	4.6%

Table KB1. Reproductive parameters for the Kane Basin polar bear subpopulation estimated from field data collected 2012-2014. Dependent young are cubs-of-the-year (C0) and yearlings (C1). Adult females are ≥ 5 years. The mean and standard error (SE) we calculated using simulations methods described in the main text.

Parameter	Mean	SE
Litter production rate for adult females (β_4)	0.71	0.16
C0 per adult female	0.55	0.10
Proportion of adult females with C0	0.34	0.06
C0 litter size	1.64	0.10
C1 per adult female	0.22	0.06
Proportion of adult females with C1	0.17	0.04
C1 litter size	1.23	0.12

Table KB2. Estimates (mean and standard error [SE]) of unharvested survival (S^*) for two scenarios of the vital rates for the Kane Basin polar bear subpopulation. The scenarios are described in the main text.

†The life cycle graph (Figure 1) does not include separate stages for cubs-of-the-year (C0) and yearlings (C1), but survival rates for these age classes contribute to transition probabilities between reproductive stages for adult females.

Sex	Age class	Stage	Scenario 1		Scenario 2	
			Mean	SE	Mean	SE
female	C0	†	0.45	0.15	0.74	0.25
female	C1	†	0.74	0.15	0.87	0.15
female	2 year	1	0.74	0.15	0.87	0.15
female	3 year	2	0.97	0.04	0.97	0.04
female	4 year	3	0.97	0.04	0.97	0.04
female	≥5 year	4-6	0.97	0.04	0.97	0.04
male	C0	†	0.45	0.15	0.70	0.23
male	C1	†	0.54	0.17	0.74	0.23
male	2 year	7	0.54	0.17	0.74	0.23
male	3 year	8	0.90	0.06	0.90	0.06
male	4 year	9	0.90	0.06	0.90	0.06
male	≥5 year	10	0.90	0.06	0.90	0.06

Table KB3. Demographic parameters (mean and standard error [SE]) for the Kane Basin polar bear subpopulation, corresponding to the two scenarios of the vital rates, based on asymptotic population dynamics. The parameters are: unharvested population growth rate (λ); subpopulation density (i.e., N/K) corresponding to maximum net productivity level (MNPL); intrinsic population growth rate at MNPL (r_{MNPL}); intrinsic population growth rate at low population density (r_{max}); intrinsic population growth rate at low population density in the absence of human-caused removals (r_{max}); and maximum sustainable yield (MSY) measured in numbers of independent bears under non-selective harvest.

Sex	Scenario 1		Scenario 2	
	Mean	SE	Mean	SE
λ	1.01	0.04	1.05	0.06
MNPL	0.73	0.05	0.69	0.04
r_{MNPL}	0.01	0.04	0.05	0.06
r_{max}	0.02	0.05	0.07	0.06
MSY	3	6	13	13

Table KB4. Summary of primary simulations for the Kane Basin polar bear subpopulation, using Scenario 1 of the vital rates. For each row in the table, parameters are shown for the maximum starting (i.e., $t = 1$) harvest strategy that meets the corresponding Management Objective (Table BB1). F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with a 15-year management interval and baseline data precision (i.e., $rsd.mod = 1$). *NA* indicates that a Management Objective was not met with no harvest.

Management Objective	<i>SR</i> = 0.94			<i>SR</i> = 2.0		
	<i>F_O</i>	<i>H_{t=1}</i>	<i>h_{t=1}</i>	<i>F_O</i>	<i>H_{t=1}</i>	<i>h_{t=1}</i>
1a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
1b	0.00	0	0.0%	<i>NA</i>	<i>NA</i>	<i>NA</i>
2a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
2b	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>

Table KB5. Summary of primary simulations for the Kane Basin polar bear subpopulation, using Scenario 2 of the vital rates. For each row in the table, parameters are shown for the maximum starting (i.e., $t = 1$) harvest strategy that meets the corresponding Management Objective (Table BB1). F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with a 15-year management interval and baseline data precision (i.e., $rsd.mod = 1$). *NA* indicates that a Management Objective was not met with no harvest.

Management Objective	<i>SR</i> = 0.94			<i>SR</i> = 2.0		
	<i>F_O</i>	<i>H_{t=1}</i>	<i>h_{t=1}</i>	<i>F_O</i>	<i>H_{t=1}</i>	<i>h_{t=1}</i>
1a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
1b	0.48	6	1.7%	0.31	6	1.7%
2a	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>	<i>NA</i>
2b	0.32	4	1.1%	0.21	4	1.1%

Table KB6. Summary of secondary simulations for the Kane Basin polar bear subpopulation, using Scenario 2 of the vital rates. Rows are different levels of *rsd.mod*, a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty. Columns are different management intervals. Values in the cells represent the upper limits that meet Management Objective 1b (Table BB1); where F_0 is a factor to calculate the harvest rate, and $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears. All simulations followed a state-dependent management approach with $SR = 0.94$.

<i>rsd.mod</i>	Management interval (years)		
	10	15	20
(Results reported as values of F_0)			
0.5	0.64	0.64	0.56
1.0	0.56	0.48	0.48
1.5	0.56	0.40	0.40
(Results reported as values of $h_{t=1}$)			
0.5	2.2%	2.2%	2.0%
1.0	2.0%	1.7%	1.7%
1.5	2.0%	1.4%	1.4%

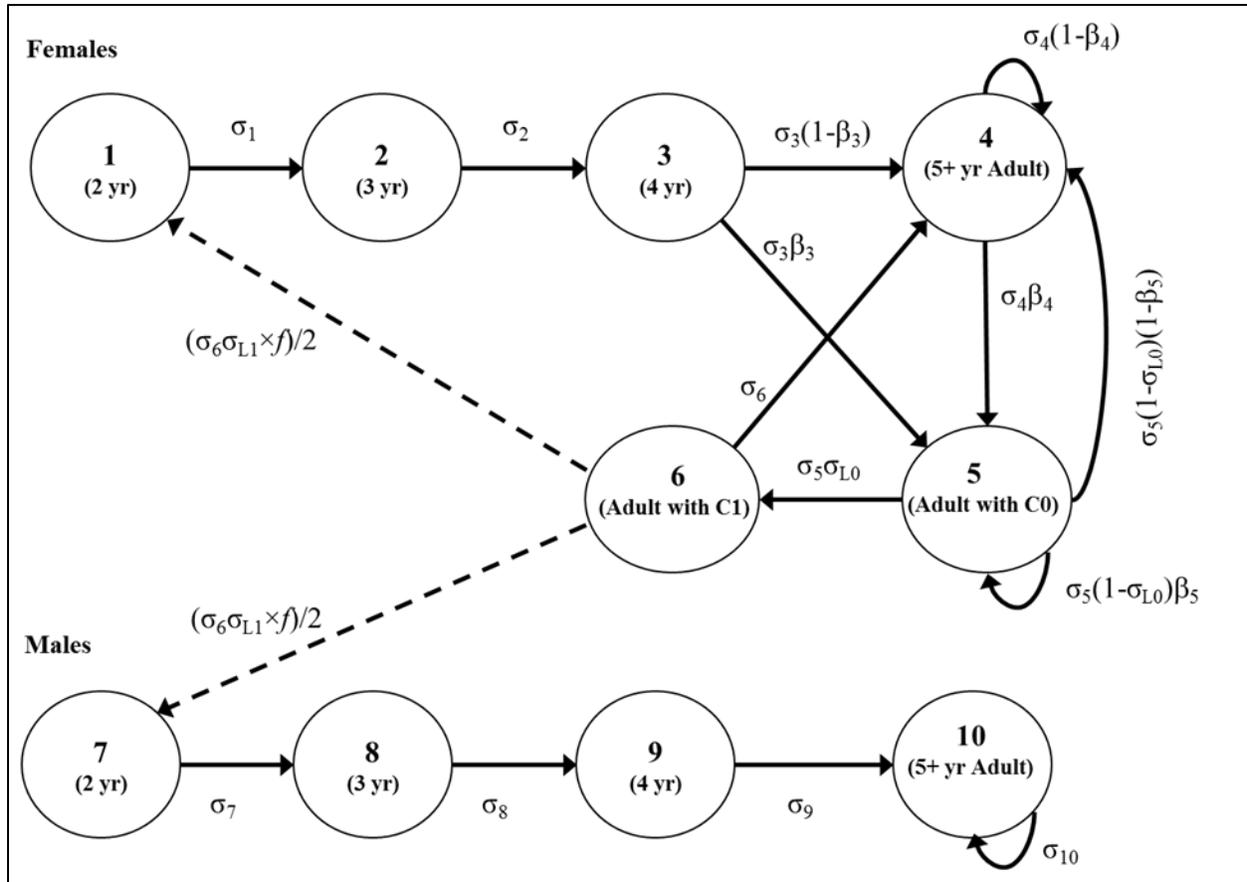


Figure BB1. The polar bear life cycle graph underlying the matrix-based projection model, reproduced from Figure 1 in Regehr et al. (2017). Stages 1–6 are females and stages 7–10 are males; σ_i is the annual probability of survival of an individual in stage i , σ_{L0} and σ_{L1} are the probabilities of at least one member of a cub-of-the-year (C0) or yearling (C1) litter surviving, f is the expected size of C1 litters that survive to 2 years, and β_i is the probability, conditional on survival, of an individual in stage i breeding, thereby producing a C0 litter with at least one member surviving. Solid lines are stage transitions and dashed lines are reproductive contributions.

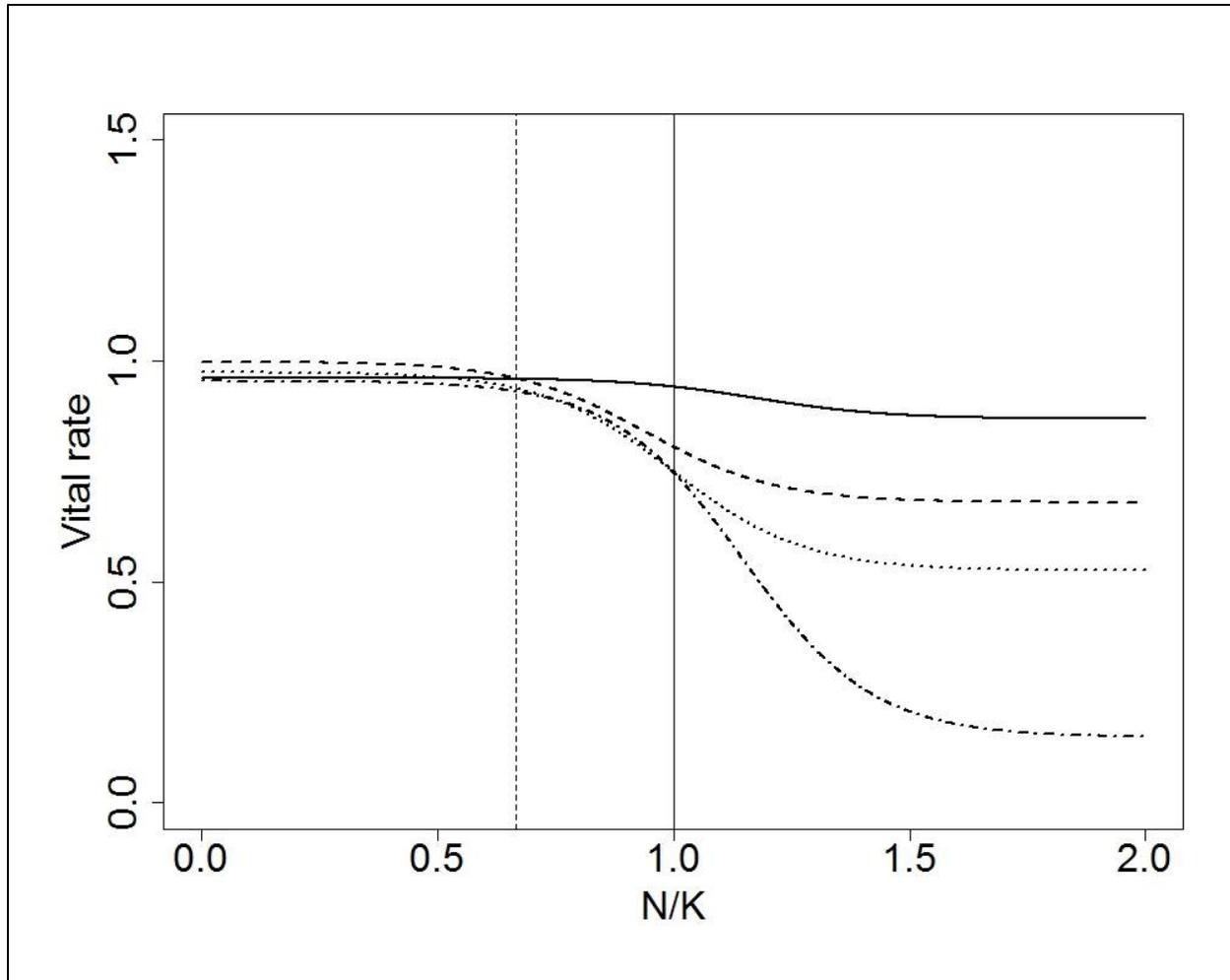


Figure BB2. Sample density-dependent curves of the vital rates for the Baffin Bay polar bear subpopulation for Scenario 2. Vital rates shown are survival probability for stage 4 (σ_4 , solid line), survival probability for stage 1 (σ_1 , dashed line), survival probability for cub-of-the-year litters (σ_{LO} , dotted line), and breeding probability for stage 4 (β_4 , dash-dot line). Density on the x-axis is expressed as the ratio of population size (N) to carrying capacity (K). The solid vertical line corresponds to $N/K = 1$ at carrying capacity. The vital rates at this density would result in a stable subpopulation (i.e., intrinsic population growth rate $[r] = 0$) assuming asymptotic dynamics. The dashed vertical line corresponds to maximum net productivity level (MNPL). The vital rates at a subpopulation size equivalent to MNPL are the mean parameter values for Scenario 2 (Tables BB2 and BB3).

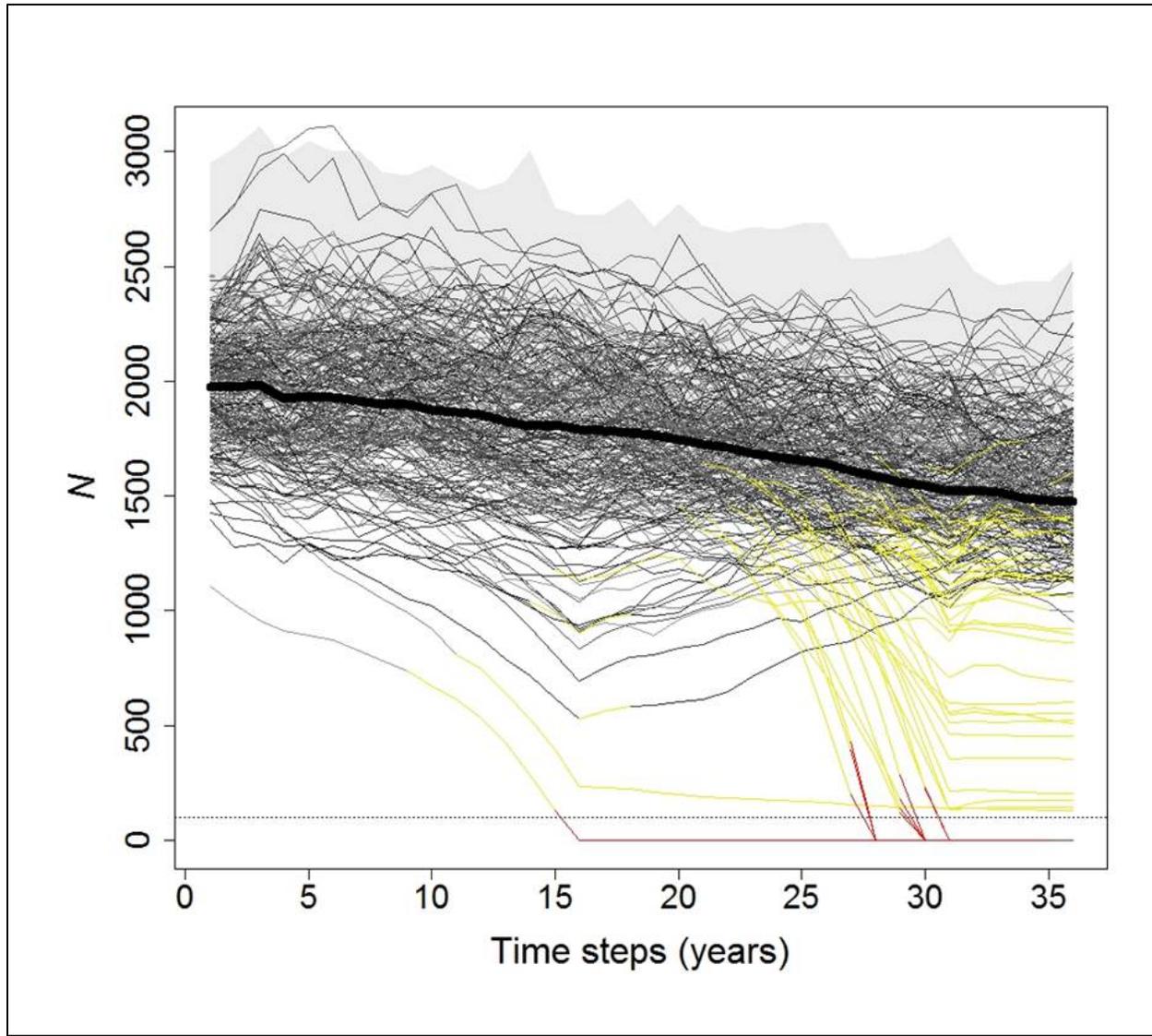


Figure BB3. Sample replicates (black lines) from population projections for the Baffin Bay subpopulation, using vital rates from Scenario 2. The grey shaded area in the background represents the upper 95% confidence interval for carrying capacity, measured in number of bears, which declined at a rate of approximately 5.5% per decade. The y-axis N is subpopulation size referenced to independent bears, and the heavy black line is median subpopulation size. Replicates are shaded yellow and red for time steps at which they experienced male depletion or extirpation, respectively. Projections are for a harvest strategy with $F_0 = 0.92$, $SR = 1.25$, a 15-year management interval, and $rsd.mod = 1.0$ (management inputs are defined in the main text). This harvest strategy equates to a starting (i.e., $t = 1$) harvest level of 160 bears per year.

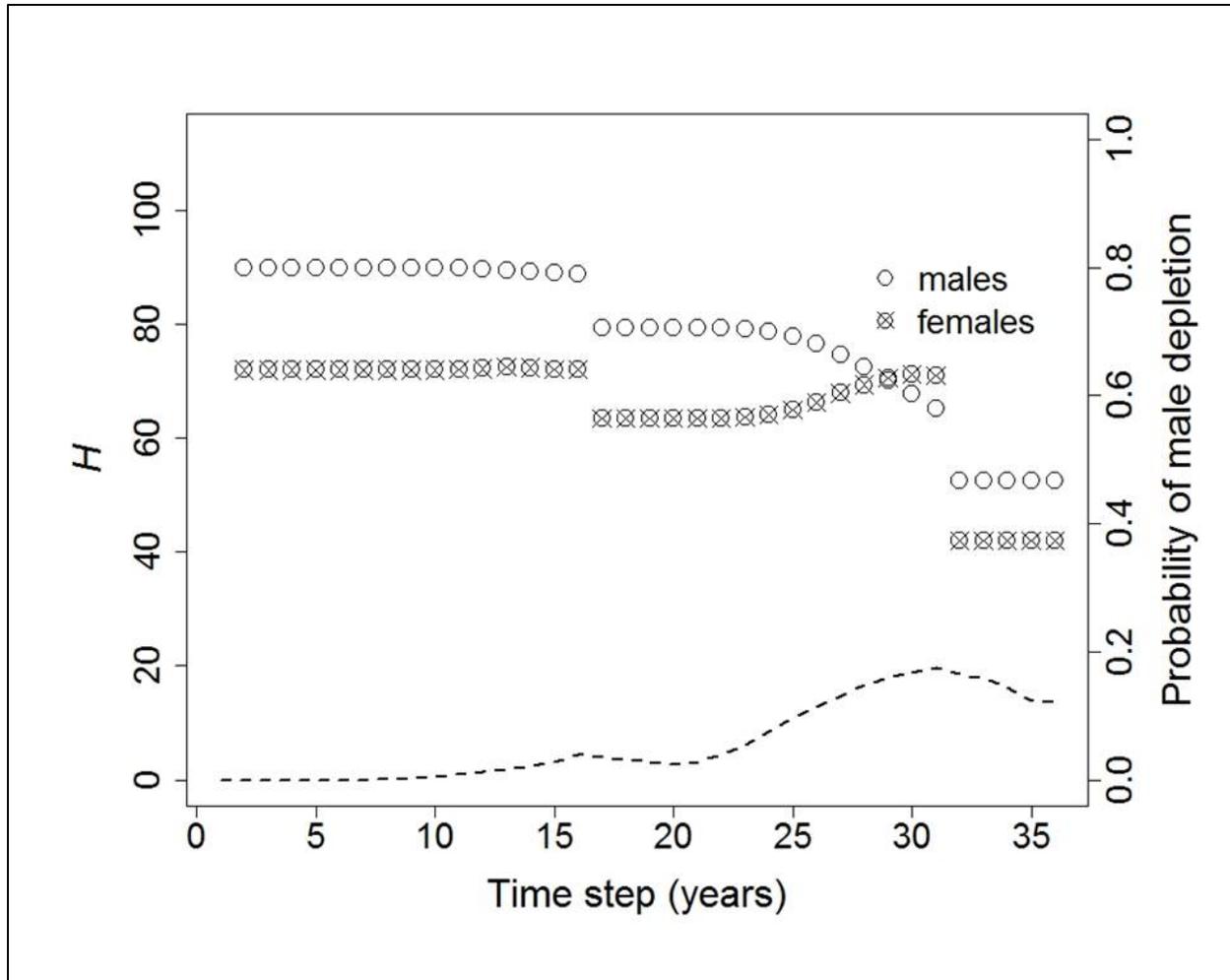


Figure BB4. Example results from population projections for the Baffin Bay polar bear subpopulation, using vital rates from Scenario 2. The left y-axis H is the harvest level, with the circles and cross-circles representing the average number of independent male and female polar bear removed per year, respectively, under a state-dependent management approach. The right y-axis is the probability of severe male depletion, values of which are plotted as the dashed line. Projections are for a harvest strategy with $F_0 = 0.92$, $SR = 1.25$, a 15-year management interval, and $rsd.mod = 1.0$ (i.e., the same harvest strategy as Figure BB3; management inputs are defined in the main text). This harvest strategy equates to a starting (i.e., $t = 1$) harvest level of 160 bears per year.

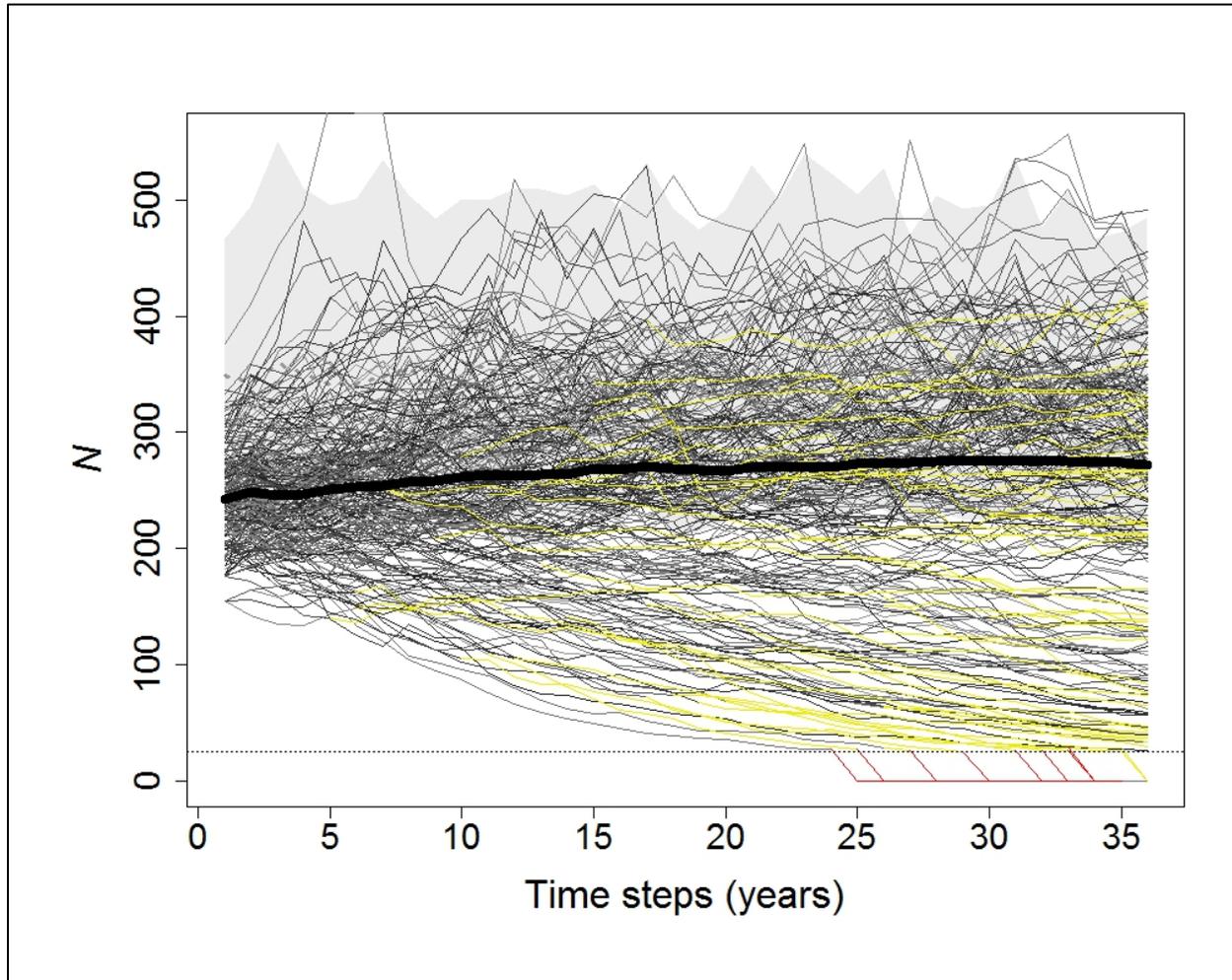


Figure KB1. Sample replicates (black lines) from population projections for the Kane Basin subpopulation, using vital rates from Scenario 1. The grey shaded area in the background represents the upper 95% confidence interval for carrying capacity, measured in number of bears, which declined at a rate of approximately 5.5% per decade. The y-axis N is subpopulation size referenced to independent bears, and the heavy black line is median subpopulation size. Replicates are shaded yellow and red for time steps at which they experienced severe male depletion or extirpation, respectively. Projections are for a subpopulation with no harvest.

Appendix S1.

Table S.BB1. Detailed results of primary simulations for the Baffin Bay polar bear subpopulation, using Scenario 1 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36. F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; $mgmt.interval$ is the management interval (years); $rsd.mod$ is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-3 (Table BB1). All results assume a state-dependent management approach.

	$t = 1$					$t = 1$					$t = 1$				
F_O	0.00	0.41	0.81	1.22	1.63	0.00	0.36	0.72	1.08	1.45	0.00	0.27	0.54	0.81	1.08
$h_{t=1}$	0.0%	0.7%	1.4%	2.1%	2.8%	0.0%	0.7%	1.4%	2.1%	2.8%	0.0%	0.7%	1.4%	2.1%	2.8%
$H_{t=1}$	0	20	40	60	80	0	20	40	60	80	0	20	40	60	80
SR	1.00	1.00	1.00	1.00	1.00	1.25	1.25	1.25	1.25	1.25	2.00	2.00	2.00	2.00	2.00
$mgmt.interval$	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
$rsd.mod$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	$t = 15$					$t = 15$					$t = 15$				
N_t/N_1	1.05	1.05	0.95	0.90	0.89	1.08	1.03	0.99	0.93	0.87	1.07	1.04	0.98	0.97	0.90
N_t/K_t	0.94	0.91	0.85	0.80	0.78	0.95	0.91	0.87	0.82	0.76	0.94	0.93	0.87	0.86	0.81
H_t	0	20	40	59	77	0	20	40	58	77	0	20	39	59	78
$P_{extirpation}$	0.00	0.00	0.01	0.03	0.04	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.01	0.01	0.02
$P_{male.dep}$	0.00	0.00	0.01	0.04	0.05	0.00	0.00	0.00	0.04	0.07	0.00	0.01	0.01	0.06	0.11
$P_{Objective1}$	0.78	0.73	0.66	0.58	0.53	0.81	0.78	0.69	0.60	0.51	0.81	0.79	0.69	0.68	0.57
$P_{Objective2}$	0.83	0.79	0.72	0.67	0.63	0.86	0.82	0.77	0.69	0.60	0.87	0.82	0.76	0.76	0.67
$P_{Objective3}$	0.86	0.83	0.77	0.71	0.69	0.89	0.86	0.82	0.74	0.66	0.91	0.85	0.80	0.81	0.73

Table S.BB1. Continued.

	<i>t</i> = 36					<i>t</i> = 36					<i>t</i> = 36				
<i>N_t/N₁</i>	0.88	0.83	0.65	0.42	0.37	0.90	0.82	0.69	0.45	0.30	0.89	0.83	0.63	0.39	0.25
<i>N_t/K_t</i>	0.93	0.85	0.68	0.45	0.38	0.94	0.87	0.72	0.47	0.32	0.94	0.88	0.66	0.41	0.27
<i>H_t</i>	0	27	39	41	46	0	28	39	40	38	0	27	31	35	33
<i>P_{extirpation}</i>	0.03	0.05	0.07	0.21	0.22	0.02	0.03	0.06	0.20	0.26	0.03	0.04	0.06	0.25	0.33
<i>P_{male.dep}</i>	0.01	0.04	0.11	0.18	0.20	0.02	0.03	0.12	0.20	0.22	0.01	0.05	0.23	0.26	0.25
<i>P_{Objective1}</i>	0.53	0.30	0.13	0.07	0.05	0.55	0.34	0.15	0.08	0.05	0.55	0.37	0.15	0.09	0.07
<i>P_{Objective2}</i>	0.78	0.72	0.49	0.31	0.26	0.81	0.77	0.53	0.33	0.24	0.81	0.77	0.48	0.33	0.26
<i>P_{Objective3}</i>	0.78	0.71	0.47	0.28	0.23	0.80	0.76	0.50	0.29	0.21	0.80	0.76	0.45	0.29	0.22

Table S.BB2. Detailed results of primary simulations for the Baffin Bay polar bear subpopulation, using Scenario 2 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36. F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; $mgmt.interval$ is the management interval (years); $rsd.mod$ is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-3 (Table BB1). All results assume a state-dependent management approach.

(a) male-to-female sex ratio in harvest (SR) = 1.0

	t = 1											
F_O	0.000	0.516	0.646	0.775	0.904	1.033	1.162	1.291	1.420	1.549	1.679	
$h_{t=1}$	0.0%	2.8%	3.6%	4.3%	5.0%	5.7%	6.4%	7.1%	7.8%	8.5%	9.2%	
$H_{t=1}$	0	80	100	120	140	160	180	200	220	240	260	
$mgmt.interval$	15	15	15	15	15	15	15	15	15	15	15	
$rsd.mod$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	t = 15											
N_t/N_1	1.14	1.03	1.01	0.97	0.95	0.87	0.85	0.77	0.73	0.57	0.47	
N_t/K_t	1.00	0.91	0.89	0.86	0.83	0.78	0.75	0.68	0.64	0.51	0.41	
H_t	0	82	102	122	142	162	180	198	220	220	225	
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.03	0.16	0.21	
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.10	0.12	0.21	0.26	
$P_{Objective1}$	1.00	0.98	0.92	0.83	0.68	0.45	0.31	0.17	0.09	0.04	0.03	
$P_{Objective2}$	1.00	1.00	0.99	0.95	0.91	0.79	0.66	0.45	0.34	0.19	0.14	
$P_{Objective3}$	1.00	1.00	1.00	0.97	0.96	0.90	0.80	0.62	0.55	0.36	0.27	
	t = 36											
N_t/N_1	0.96	0.86	0.84	0.80	0.78	0.72	0.69	0.62	0.57	0.39	0.20	
N_t/K_t	1.00	0.90	0.88	0.85	0.81	0.77	0.72	0.65	0.59	0.41	0.21	
H_t	0	72	86	97	104	105	107	105	108	94	90	
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.14	0.18	0.35	0.43	
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.02	0.04	0.05	0.08	0.11	0.13	0.13	
$P_{Objective1}$	0.75	0.32	0.22	0.13	0.08	0.05	0.03	0.02	0.02	0.01	0.00	
$P_{Objective2}$	1.00	1.00	0.99	0.95	0.84	0.71	0.55	0.40	0.30	0.18	0.11	
$P_{Objective3}$	1.00	0.99	0.97	0.91	0.80	0.66	0.50	0.33	0.24	0.14	0.08	

Table S.BB2. Continued**(b) male-to-female ratio in the harvest (SR) = 1.25**

	$t = 1$										
F_0	0.000	0.459	0.574	0.689	0.804	0.918	1.033	1.148	1.263	1.378	1.492
$h_{t=1}$	0.0%	2.8%	3.6%	4.3%	5.0%	5.7%	6.4%	7.1%	7.8%	8.5%	9.2%
$H_{t=1}$	0	80	100	120	140	160	180	200	220	240	260
<i>mgmt.interval</i>	15	15	15	15	15	15	15	15	15	15	15
<i>rsd.mod</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	$t = 15$										
N_t/N_1	1.12	1.06	1.00	0.96	0.96	0.92	0.88	0.80	0.75	0.59	0.41
N_t/K_t	1.01	0.92	0.89	0.87	0.85	0.82	0.78	0.71	0.66	0.53	0.37
H_t	0	81	101	122	142	161	181	198	211	212	205
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.07	0.18	0.28
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.14	0.23	0.34	0.39
$P_{Objective1}$	1.00	0.98	0.93	0.86	0.75	0.59	0.43	0.26	0.16	0.07	0.03
$P_{Objective2}$	1.00	0.99	0.98	0.96	0.93	0.85	0.73	0.55	0.42	0.25	0.12
$P_{Objective3}$	1.00	1.00	0.99	0.98	0.97	0.92	0.85	0.72	0.58	0.39	0.24
	$t = 36$										
N_t/N_1	0.94	0.88	0.85	0.81	0.78	0.75	0.71	0.65	0.56	0.37	0.14
N_t/K_t	1.00	0.91	0.89	0.87	0.82	0.79	0.74	0.68	0.58	0.39	0.15
H_t	0	71	81	89	93	94	98	100	99	96	93
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.02	0.04	0.11	0.16	0.25	0.36	0.45
$P_{male.dep}$	0.00	0.00	0.01	0.02	0.08	0.12	0.14	0.20	0.22	0.21	0.23
$P_{Objective1}$	0.76	0.39	0.28	0.21	0.13	0.09	0.06	0.04	0.03	0.02	0.01
$P_{Objective2}$	1.00	1.00	0.99	0.95	0.84	0.74	0.64	0.51	0.37	0.25	0.17
$P_{Objective3}$	1.00	0.99	0.97	0.93	0.81	0.69	0.57	0.42	0.29	0.18	0.12

Table S.BB2. Continued**(c) male-to-female ratio in the harvest (SR) = 2.00**

	<i>t</i> = 1										
<i>F_O</i>	0.000	0.344	0.430	0.516	0.603	0.689	0.775	0.861	0.947	1.033	1.119
<i>h_{t=1}</i>	0.0%	2.8%	3.6%	4.3%	5.0%	5.7%	6.4%	7.1%	7.8%	8.5%	9.2%
<i>H_{t=1}</i>	0	80	100	120	140	160	180	200	220	240	260
<i>mgmt.interval</i>	15	15	15	15	15	15	15	15	15	15	15
<i>rsd.mod</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	<i>t</i> = 15										
<i>N_t/N₁</i>	1.12	1.04	1.02	1.01	0.99	0.94	0.85	0.78	0.60	0.41	0.15
<i>N_t/K_t</i>	1.01	0.94	0.91	0.89	0.87	0.83	0.76	0.69	0.54	0.36	0.13
<i>H_t</i>	0	81	102	122	142	161	181	195	198	197	181
<i>P_{extirpation}</i>	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.08	0.16	0.26	0.42
<i>P_{male.dep}</i>	0.00	0.00	0.00	0.01	0.03	0.17	0.32	0.46	0.57	0.60	0.51
<i>P_{Objective1}</i>	1.00	1.00	0.96	0.92	0.81	0.63	0.39	0.24	0.09	0.06	0.02
<i>P_{Objective2}</i>	1.00	1.00	0.99	0.98	0.94	0.83	0.69	0.51	0.31	0.20	0.11
<i>P_{Objective3}</i>	1.00	1.00	1.00	1.00	0.97	0.89	0.79	0.61	0.41	0.27	0.15
	<i>t</i> = 36										
<i>N_t/N₁</i>	0.94	0.88	0.85	0.83	0.79	0.73	0.68	0.61	0.48	0.22	0.00
<i>N_t/K_t</i>	1.00	0.93	0.90	0.87	0.82	0.77	0.72	0.64	0.51	0.23	0.00
<i>H_t</i>	0	64	66	68	67	73	87	94	101	92	77
<i>P_{extirpation}</i>	0.00	0.00	0.00	0.01	0.05	0.09	0.14	0.19	0.27	0.40	0.55
<i>P_{male.dep}</i>	0.00	0.02	0.08	0.17	0.25	0.29	0.34	0.34	0.33	0.34	0.27
<i>P_{Objective1}</i>	0.76	0.47	0.37	0.28	0.20	0.14	0.10	0.06	0.04	0.02	0.01
<i>P_{Objective2}</i>	1.00	0.99	0.93	0.85	0.74	0.66	0.60	0.47	0.36	0.21	0.11
<i>P_{Objective3}</i>	1.00	0.98	0.92	0.83	0.72	0.62	0.53	0.39	0.28	0.15	0.08

Table S.BB3. Detailed results of primary simulations for the Baffin Bay polar bear subpopulation, using Scenario 3 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36 . F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; $mgmt.interval$ is the management interval (years); $rsd.mod$ is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-3 (Table BB1). All results assume a state-dependent management approach.

(a) male-to-female ratio in the harvest (SR) = 1.0

	$t = 1$							
F_O	0.000	0.598	0.797	0.996	1.196	1.395	1.594	1.793
$h_{t=1}$	0.0%	2.1%	2.8%	3.6%	4.3%	5.0%	5.7%	6.4%
$H_{t=1}$	0	60	80	100	120	140	160	180
$mgmt.interval$	15	15	15	15	15	15	15	15
$rsd.mod$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	$t = 15$							
N_t/N_1	1.14	1.05	1.00	0.98	0.94	0.87	0.82	0.73
N_t/K_t	1.02	0.93	0.90	0.87	0.83	0.78	0.72	0.66
H_t	0	60	80	100	119	136	153	172
$P_{extirpation}$	0.00	0.00	0.00	0.01	0.01	0.04	0.06	0.06
$P_{male.dep}$	0.00	0.00	0.00	0.01	0.01	0.01	0.05	0.06
$P_{Objective1}$	0.97	0.94	0.88	0.80	0.68	0.48	0.35	0.21
$P_{Objective2}$	0.99	0.97	0.94	0.89	0.84	0.73	0.60	0.48
$P_{Objective3}$	1.00	0.98	0.97	0.92	0.89	0.81	0.70	0.59
	$t = 36$							
N_t/N_1	0.94	0.84	0.79	0.73	0.68	0.64	0.61	0.57
N_t/K_t	0.99	0.88	0.83	0.77	0.72	0.68	0.64	0.60
H_t	0	51	66	76	79	80	82	80
$P_{extirpation}$	0.00	0.00	0.00	0.02	0.04	0.07	0.12	0.15
$P_{male.dep}$	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02
$P_{Objective1}$	0.72	0.26	0.17	0.11	0.07	0.06	0.05	0.03
$P_{Objective2}$	0.97	0.94	0.86	0.68	0.54	0.46	0.41	0.36
$P_{Objective3}$	0.97	0.93	0.83	0.64	0.49	0.41	0.36	0.31

Table S.BB3. Continued**(b) male-to-female ratio in the harvest ($SR = 1.25$)**

	$t = 1$							
F_0	0.000	0.531	0.709	0.886	1.063	1.240	1.417	1.594
$h_{t=1}$	0.0%	2.1%	2.8%	3.6%	4.3%	5.0%	5.7%	6.4%
$H_{t=1}$	0	60	80	100	120	140	160	180
<i>mgmt.interval</i>	15	15	15	15	15	15	15	15
<i>rsd.mod</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	$t = 15$							
N_t/N_1	1.15	1.05	1.02	0.99	0.94	0.87	0.83	0.79
N_t/K_t	1.01	0.93	0.91	0.87	0.83	0.78	0.74	0.70
H_t	0	60	80	99	119	136	156	167
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.02	0.03	0.05	0.09
$P_{male.dep}$	0.00	0.01	0.00	0.00	0.03	0.04	0.07	0.06
$P_{Objective1}$	0.96	0.92	0.88	0.80	0.69	0.52	0.42	0.33
$P_{Objective2}$	0.97	0.94	0.92	0.86	0.82	0.71	0.64	0.56
$P_{Objective3}$	0.98	0.95	0.94	0.89	0.86	0.79	0.73	0.66
	$t = 36$							
N_t/N_1	0.95	0.85	0.82	0.77	0.73	0.69	0.66	0.67
N_t/K_t	0.99	0.89	0.86	0.80	0.76	0.73	0.70	0.70
H_t	0	52	63	74	79	82	86	89
$P_{extirpation}$	0.00	0.01	0.00	0.01	0.06	0.08	0.10	0.13
$P_{male.dep}$	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04
$P_{Objective1}$	0.70	0.33	0.23	0.17	0.12	0.09	0.07	0.06
$P_{Objective2}$	0.96	0.93	0.88	0.75	0.66	0.58	0.52	0.51
$P_{Objective3}$	0.96	0.92	0.86	0.72	0.62	0.53	0.47	0.45

Table S.BB3. Continued**(c) male-to-female ratio in the harvest (SR) = 2.00**

	$t = 1$							
F_O	0.000	0.399	0.531	0.664	0.797	0.930	1.063	1.196
$h_{t=1}$	0.0%	2.1%	2.8%	3.6%	4.3%	5.0%	5.7%	6.4%
$H_{t=1}$	0	60	80	100	120	140	160	180
<i>mgmt.interval</i>	15	15	15	15	15	15	15	15
<i>rsd.mod</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	$t = 15$							
N_t/N_1	1.14	1.07	1.05	1.02	0.98	0.94	0.91	0.84
N_t/K_t	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.7
H_t	0	60	80	99	118	136	153	171
$P_{extirpation}$	0.00	0.00	0.00	0.01	0.02	0.03	0.06	0.06
$P_{male.dep}$	0.00	0.00	0.00	0.03	0.04	0.07	0.12	0.17
$P_{Objective1}$	0.97	0.94	0.91	0.84	0.80	0.67	0.59	0.42
$P_{Objective2}$	0.99	0.96	0.95	0.89	0.86	0.80	0.72	0.60
$P_{Objective3}$	0.99	0.97	0.97	0.91	0.89	0.85	0.77	0.69
	$t = 36$							
N_t/N_1	0.93	0.89	0.86	0.82	0.77	0.74	0.72	0.71
N_t/K_t	0.98	0.93	0.91	0.86	0.81	0.79	0.76	0.74
H_t	0	50	65	68	73	75	79	80
$P_{extirpation}$	0.00	0.00	0.01	0.03	0.07	0.09	0.14	0.14
$P_{male.dep}$	0.00	0.00	0.02	0.05	0.09	0.13	0.13	0.14
$P_{Objective1}$	0.70	0.47	0.38	0.29	0.22	0.18	0.16	0.14
$P_{Objective2}$	0.96	0.96	0.94	0.82	0.74	0.68	0.62	0.59
$P_{Objective3}$	0.96	0.95	0.93	0.80	0.71	0.64	0.58	0.54

Table S.BB4. Detailed results of secondary simulations for the Baffin Bay polar bear subpopulation, using Scenario 2 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36 . Results are presented for the highest strategies that meet Management Objective 2b, for each unique combination of *mgmt.interval* and *rsd.mod*. F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; *mgmt.interval* is the management interval (years); *rsd.mod* is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-3 (Table BB1). All results assume a state-dependent management approach.

	$t = 1$									
F_O	1.148	0.976	0.861	1.033	0.918	0.804	0.918	0.804	0.746	
$h_{t=1}$	7.1%	6.0%	5.3%	6.4%	5.7%	5.0%	5.7%	5.0%	4.6%	
$H_{t=1}$	200	170	150	180	160	140	160	140	130	
SR	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	
<i>mgmt.interval</i>	10	15	20	10	15	20	10	15	20	
<i>rsd.mod</i>	0.50	0.50	0.50	1.00	1.00	1.00	1.50	1.50	1.50	
<hr/>										
	$t = 15$									
N_t/N_1	0.86	0.89	0.93	0.88	0.90	0.96	0.92	0.96	0.96	
N_t/K_t	0.76	0.78	0.82	0.78	0.81	0.85	0.81	0.84	0.85	
H_t	159	173	153	163	161	142	154	142	132	
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	
$P_{male.dep}$	0.03	0.02	0.01	0.01	0.03	0.00	0.01	0.01	0.00	
$P_{Objective1}$	0.25	0.47	0.62	0.41	0.55	0.77	0.55	0.75	0.79	
$P_{Objective2}$	0.62	0.77	0.87	0.75	0.80	0.93	0.85	0.92	0.93	
$P_{Objective3}$	0.89	0.88	0.95	0.92	0.89	0.98	0.96	0.96	0.97	
<hr/>										
	$t = 36$									
N_t/N_1	0.74	0.77	0.78	0.74	0.75	0.76	0.76	0.77	0.77	
N_t/K_t	0.77	0.80	0.81	0.77	0.79	0.79	0.79	0.80	0.81	
H_t	126	97	122	115	94	130	107	90	113	
$P_{extirpation}$	0.00	0.03	0.01	0.01	0.04	0.02	0.01	0.05	0.03	
$P_{male.dep}$	0.10	0.11	0.12	0.14	0.10	0.18	0.10	0.10	0.13	
$P_{Objective1}$	0.02	0.06	0.12	0.07	0.09	0.14	0.12	0.14	0.18	
$P_{Objective2}$	0.76	0.80	0.83	0.71	0.76	0.77	0.73	0.76	0.78	
$P_{Objective3}$	0.68	0.76	0.76	0.65	0.71	0.70	0.68	0.71	0.72	

Table S.BB5. Detailed results of *post hoc* simulations for the Baffin Bay polar bear subpopulation, using Scenario 2 of the vital rates. Each column corresponds to one simulation, with results reported at time step $t = 15$. Management strategies BB_S1 and BB_S2 are described in the main text. F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; *mgmt.interval* is the management interval (years); *rsd.mod* is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-3 (Table BB1).

	Management strategy	
	BB_S1	BB_S2
	$t = 1$	
F_O	1.58	-
$h_{t=1}$	8.7%	8.7%
$H_{t=1}$	245	245
SR	1.00	1.25
<i>mgmt.interval</i>	5	-
<i>rsd.mod</i>	0.50	-
	$t = 15$	
N/N_1	0.75	0.55
N/K_t	0.67	0.49
H_t	180	212
$P_{extirpation}$	0.00	0.23
$P_{male.dep}$	0.01	0.30
$P_{Objective1}$	0.05	0.07
$P_{Objective2}$	0.22	0.24
$P_{Objective3}$	0.73	0.36

Table S.KB1. Detailed results of primary simulations for the Kane Basin polar bear subpopulation, using Scenario 1 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36 . F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; $mgmt.interval$ is the management interval (years); $rsd.mod$ is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-2 (Table BB1). All results assume a state-dependent management approach.

	t = 1					t = 1				
F_O	0.000	0.645	1.289	1.934	2.579	0.000	0.417	0.834	1.251	1.668
$h_{t=1}$	0.0%	0.6%	1.1%	1.7%	2.2%	0.0%	0.6%	1.1%	1.7%	2.2%
$H_{t=1}$	0	2	4	6	8	0	2	4	6	8
SR	0.94	0.94	0.94	0.94	0.94	2.00	2.00	2.00	2.00	2.00
$mgmt.interval$	15	15	15	15	15	15	15	15	15	15
$rsd.mod$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	t = 15					t = 15				
N_t/N_1	1.10	1.02	0.90	0.79	0.79	1.09	1.02	0.98	0.83	0.75
N_t/K_t	0.78	0.72	0.64	0.56	0.56	0.76	0.70	0.69	0.58	0.53
H_t	0	2	4	6	7	0	2	4	6	7
$P_{extirpation}$	0.00	0.01	0.01	0.02	0.06	0.01	0.00	0.01	0.01	0.07
$P_{male.dep}$	0.10	0.16	0.26	0.34	0.37	0.10	0.15	0.34	0.39	0.46
$P_{Objective1}$	0.74	0.64	0.52	0.46	0.43	0.71	0.61	0.63	0.48	0.42
$P_{Objective2}$	0.59	0.46	0.37	0.33	0.30	0.56	0.45	0.45	0.34	0.28
	t = 36					t = 36				
N_t/N_1	1.12	0.82	0.44	0.28	0.22	1.12	0.79	0.54	0.29	0.24
N_t/K_t	0.80	0.59	0.31	0.20	0.16	0.79	0.55	0.38	0.21	0.17
H_t	0	3	4	4	4	0	3	3	3	3
$P_{extirpation}$	0.02	0.09	0.19	0.28	0.38	0.04	0.08	0.17	0.31	0.36
$P_{male.dep}$	0.20	0.36	0.45	0.47	0.43	0.27	0.45	0.59	0.50	0.51
$P_{Objective1}$	0.70	0.48	0.21	0.13	0.10	0.68	0.43	0.25	0.14	0.10
$P_{Objective2}$	0.64	0.33	0.14	0.08	0.07	0.61	0.31	0.16	0.09	0.06

Table S.KB2. Detailed results of primary simulations for the Kane Basin polar bear subpopulation, using Scenario 2 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36 . F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; $mgmt.interval$ is the management interval (years); $rsd.mod$ is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-2 (Table BB1). All results assume a state-dependent management approach.

	$t = 1$										$t = 1$									
F_O	0.000	0.159	0.319	0.478	0.638	0.797	0.956	1.116	1.275	0.000	0.103	0.206	0.309	0.412	0.516	0.619	0.722	0.825		
$h_{t=1}$	0.0%	0.6%	1.1%	1.7%	2.2%	2.8%	3.4%	3.9%	4.5%	0.0%	0.6%	1.1%	1.7%	2.2%	2.8%	3.4%	3.9%	4.5%		
$H_{t=1}$	0	2	4	6	8	10	12	14	16	0	2	4	6	8	10	12	14	16		
SR	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00		
$mgmt.interval$	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15		
$rsd.mod$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
	$t = 15$										$t = 15$									
N_t/N_1	1.28	1.31	1.26	1.28	1.19	1.16	1.10	1.06	0.99	1.34	1.28	1.26	1.23	1.20	1.16	1.13	1.08	1.01		
N_t/K_t	0.92	0.91	0.88	0.88	0.83	0.81	0.78	0.75	0.70	0.92	0.91	0.89	0.86	0.84	0.82	0.78	0.76	0.70		
H_t	0	2	4	6	8	10	11	13	13	0	2	4	6	8	9	11	13	13		
$P_{extirpation}$	0.00	0.00	0.02	0.02	0.04	0.03	0.04	0.09	0.18	0.00	0.00	0.00	0.02	0.03	0.04	0.06	0.09	0.18		
$P_{male.dep}$	0.06	0.10	0.13	0.12	0.16	0.20	0.24	0.26	0.18	0.05	0.08	0.14	0.15	0.23	0.28	0.31	0.32	0.36		
$P_{Objective1}$	0.85	0.85	0.78	0.78	0.73	0.74	0.69	0.63	0.57	0.86	0.85	0.78	0.78	0.72	0.73	0.70	0.63	0.57		
$P_{Objective2}$	0.77	0.77	0.72	0.69	0.64	0.64	0.58	0.53	0.48	0.79	0.78	0.71	0.70	0.64	0.65	0.61	0.54	0.49		
	$t = 36$										$t = 36$									
N_t/N_1	1.26	1.29	1.20	1.19	1.07	0.97	0.84	0.72	0.59	1.33	1.26	1.21	1.14	1.03	0.91	0.78	0.54	0.48		
N_t/K_t	0.92	0.90	0.85	0.83	0.75	0.68	0.60	0.52	0.42	0.93	0.90	0.87	0.81	0.73	0.65	0.55	0.39	0.34		
H_t	0	3	5	7	8	9	9	9	10	0	3	4	6	6	7	7	6	7		
$P_{extirpation}$	0.03	0.03	0.05	0.06	0.07	0.08	0.14	0.22	0.29	0.03	0.03	0.05	0.06	0.10	0.12	0.17	0.26	0.32		
$P_{male.dep}$	0.11	0.16	0.18	0.17	0.22	0.29	0.32	0.33	0.25	0.13	0.15	0.22	0.27	0.36	0.43	0.47	0.47	0.44		
$P_{Objective1}$	0.81	0.83	0.75	0.73	0.66	0.60	0.50	0.42	0.37	0.84	0.83	0.75	0.72	0.61	0.56	0.46	0.36	0.33		
$P_{Objective2}$	0.78	0.79	0.70	0.66	0.57	0.48	0.39	0.31	0.28	0.80	0.78	0.70	0.65	0.53	0.46	0.36	0.28	0.25		

Table S.KB3. Detailed results of secondary simulations for the Kane Basin polar bear subpopulation, using Scenario 2 of the vital rates. Each column corresponds to one simulation, with results reported at time steps $t = 15$ and 36 . Results are presented for the highest strategies that meet Management Objective 1b, for each unique combination of *mgmt.interval* and *rsd.mod*. F_O is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; *mgmt.interval* is the management interval (years); *rsd.mod* is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-2 (Table BB1). All results assume a state-dependent management approach.

	$t = 1$									
F_O	0.638	0.638	0.558	0.558	0.478	0.478	0.558	0.398	0.398	
$h_{t=1}$	2.2%	2.2%	2.0%	2.0%	1.7%	1.7%	2.0%	1.4%	1.4%	
$H_{t=1}$	8	8	7	7	6	6	7	5	5	
SR	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	
<i>mgmt.interval</i>	10	15	20	10	15	20	10	15	20	
<i>rsd.mod</i>	0.50	0.50	0.50	1.00	1.00	1.00	1.50	1.50	1.50	

	$t = 15$									
N_t/N_1	1.12	1.19	1.22	1.15	1.25	1.24	1.17	1.19	1.24	
N_t/K_t	0.80	0.82	0.86	0.82	0.89	0.88	0.84	0.84	0.87	
H_t	10	8	7	9	6	6	8	5	5	
$P_{extirpation}$	0.01	0.02	0.03	0.00	0.02	0.01	0.01	0.01	0.02	
$P_{male.dep}$	0.17	0.15	0.11	0.13	0.11	0.14	0.10	0.09	0.09	
$P_{Objective1}$	0.74	0.76	0.77	0.79	0.82	0.80	0.79	0.77	0.79	
$P_{Objective2}$	0.61	0.66	0.69	0.69	0.74	0.72	0.69	0.67	0.70	

	$t = 36$									
N_t/N_1	1.08	1.10	1.11	1.10	1.17	1.15	1.12	1.15	1.18	
N_t/K_t	0.78	0.77	0.79	0.80	0.84	0.82	0.81	0.82	0.84	
H_t	9	9	9	8	7	7	7	5	6	
$P_{extirpation}$	0.04	0.06	0.07	0.05	0.05	0.07	0.05	0.05	0.08	
$P_{male.dep}$	0.23	0.21	0.19	0.21	0.18	0.21	0.16	0.14	0.15	
$P_{Objective1}$	0.70	0.72	0.72	0.75	0.79	0.75	0.74	0.72	0.74	
$P_{Objective2}$	0.59	0.61	0.64	0.66	0.71	0.67	0.66	0.66	0.68	

Table S.KB4. Detailed results of *post hoc* simulations for the Kane Basin polar bear subpopulation, using Scenario 2 of the vital rates. Each column corresponds to one simulation, with results reported at time step $t = 15$ and $t = 36$. Harvest strategies KB_S1 and KB_S2 and the simulation conditions on which they are based, are described in the main text. F_o is a factor to calculate the harvest rate using equation (1); SR is a factor that specifies the male-to-female ratio in the harvest; $H_{t=1}$ is the starting harvest level measured in the number of independent bears per year; $h_{t=1}$ is the starting harvest rate, defined as the fraction of total population size (i.e., including dependent young) that is removed each year as independent bears; *mgmt.interval* is the management interval (years); *rsd.mod* is a modifier on the baseline relative standard deviation of the vital rates due to sampling uncertainty; N is population size referenced to independent bears; and K is carrying capacity expressed as numbers of bears. Results for $P_{condition}$ are the estimated probabilities of meeting population conditions corresponding to: extirpation, male depletion, and Management Objectives 1-2 (Table BB1). All results assume a state-dependent management approach.

	Management strategy	
	KB_S1	KB_S2
	$t = 1$	
F_o	0.80	0.60
$h_{t=1}$	2.8%	2.2%
$H_{t=1}$	10	8
SR	0.94	0.94
<i>mgmt.interval</i>	15	15
<i>rsd.mod</i>	1.00	1.00
	$t = 15$	
N_t/N_1	1.20	1.19
N_t/K_t	0.85	0.83
H_t	10	8
$P_{extirpation}$	0.02	0.00
$P_{male.dep}$	0.07	0.11
$P_{Objective1}$	0.82	0.79
$P_{Objective2}$	0.69	0.65
	$t = 36$	
N_t/N_1	1.09	1.08
N_t/K_t	0.80	0.77
H_t	10	8
$P_{extirpation}$	0.04	0.04
$P_{male.dep}$	0.21	0.18
$P_{Objective1}$	0.71	0.70
$P_{Objective2}$	0.56	0.55