Harvest Risk Assessment for Polar Bears in the Chukchi Sea

Report to the Commissioners of the U.S.-Russia Polar Bear Agreement

Eric V. Regehr[1*], Lori Polasek[2], Andrew Von Duyke[3], James M. Wilder[4], and Ryan R. Wilson[4]

[1]Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington 98105, USA

[2]Division of Wildlife Conservation, Alaska Department of Fish and Game, Juneau, Alaska 99802, USA

[3]Department of Wildlife Management, North Slope Borough, Utqiagvik, Alaska 99723, USA

[4]Marine Mammals Management, U.S. Fish and Wildlife Service, Anchorage, Alaska 99503, USA

*Corresponding author: Eric V. Regehr, E-mail: eregehr@uw.edu

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Executive Summary

In this report we summarize the results of a quantitative harvest risk assessment using modern methods (Regehr et al. 2017b) together with the first quantitative estimates of abundance and vital rates for Chukchi Sea (CS) polar bears (Regehr et al. in review). The final results of this assessment are a series of potential harvest strategies for the CS polar bear subpopulation. It is intended that these results, along with other sources of information and considerations such as the level of subsistence need, help inform the determination of sustainable harvest level.

Polar bears (*Ursus maritimus*) in the CS region are managed under the *Agreement between the Government of the United States of America and the Government of the Russian Federation on the Conservation and Management of the Alaska-Chukotka Polar Bear Population* (hereafter, "Agreement"; United States T. Doc. 107-10), a bilateral treaty signed in 2000. In addition to providing for the protection and conservation of polar bears and their habitats, the Agreement recognizes the nutritional and cultural importance of subsistence harvest and includes provisions for a legal and monitored harvest by Native people in Alaska and Chukotka. Furthermore, the Agreement indicates that harvest should not exceed the "sustainable harvest level" (SHL), defined as "a harvest level which does not exceed net annual recruitment to the population and maintains the population at or near its current level, taking into account all forms of removal, and considers the status and trend of the population…". Under the Agreement, a four-member commission consisting of two representatives from each country (hereafter, "Commission") is responsible for determining SHL. The Commission is advised by a Scientific Working Group (SWG) whose responsibilities include evaluating SHL based on reliable biological information, including scientific data and the traditional knowledge of Native people (i.e., Traditional Ecological Knowledge; TEK). In 2010 the Commission adopted a SHL of up to 58 bears/year, with a 2:1 male-to-female harvest sex ratio, to be shared equally between the U.S. and Russia. The Commission has reaffirmed this SHL each year from 2010 to 2017 on the recommendation of the SWG. Because the SHL adopted in 2010 was based on data that were not current and included large uncertainty, in 2016 the Commission tasked the SWG with re-evaluating SHL when new biological information became available.

The first quantitative estimates of abundance, survival rates, and reproductive rates for CS polar bears were recently obtained from capture-recapture research conducted in American territory, 2008 – 2016 (Regehr et al. in review). This analysis used a Bayesian approach to parameter estimation that incorporated informative priors on survival that were informed by scientific studies and TEK. Abundance, referenced to the area within the boundary for the CS polar bear subpopulation as recognized by the Polar Bear Specialist Group (PBSG) of the International Union for the Conservation of Nature, was approximately 2,937 bears (95% Credible Interval [CRI] = 1,552 – 5,944). Reproductive rates (e.g., breeding probability and litter size) were average-to-high compared to 12 other polar bear subpopulations with available data. The estimated vital rates corresponded to a subpopulation that was likely stable or slightly declining during the period 2008 – 2016, although interpretation was complicated by several factors including potential negative bias in estimates of survival.

Estimates of reproductive rates from Regehr et al. (in review) suggest that the CS polar bear subpopulation was productive during the period 2008 – 2016, which is consistent with other lines of evidence. For example, recent scientific studies have indicated that nutritional condition and reproduction of the CS subpopulation are good despite sea-ice loss, and that an index of recruitment has remained stable since research studies in the 1980s and 1990s. A recent pilot TEK study intended to inform polar bear management models (Braund et al. 2018), and other TEK assessments, suggest that polar bears are healthy in northwestern Alaska. Finally, the CS is one of the most biologically productive regions of the Arctic, and ice-dependent seal populations appear productive.

Sea-ice loss due to climate change has been recognized as the primary threat to polar bears, and the CS region is experiencing rapid sea-ice loss that is projected to continue. Satellite telemetry data indicate that twice as many female bears are spending the summer on shore, and are remaining there 30 days longer, compared to two decades ago. As sea-ice loss continues, it is uncertain how much additional time polar bears in the CS subpopulation can spend in poor foraging habitats (e.g., on shore) without experiencing negative nutritional and demographic effects. Because of concerns about sea-ice loss for the circumpolar population of polar bears, signatories to the *1973 Agreement on the Conservation of Polar Bears* (hereafter, “Polar Bear Range States”) have recommended considering the effects of climate change when evaluating management actions for polar bears.

In this report we used estimates of subpopulation abundance and vital rates from Regehr et al. (in review), together with a modeling and management approach that accounts for changing conditions (Regehr et al. 2017b), to perform a quantitative harvest risk assessment. We examined harvest strategies that follow a “state-dependent” approach, which is similar to the “adaptive management” approach recommended by the Polar Bear Range States. A state-dependent harvest management approach means that harvest levels do not remain constant into the future, but rather are updated periodically using new data from scientific studies and TEK on the current status (i.e., “state”) of the subpopulation. This is an effective way to reduce the risk of overharvest while maintaining opportunities for use. The harvest risk assessment used a matrix projection model with several improvements compared to previous models for polar bears, including that it permits the effects of habitat loss to be modeled, and it provides a direct linkage between research and management, which allows consideration of how the frequency and intensity of future subpopulation studies affect the sustainability of harvest.

We evaluated the biological effects of a wide range of harvest strategies reflecting practical elements of polar bear harvest that can be managed, including the harvest rate, harvest level (measured in number of bears), harvest sex ratio, level of precision in subpopulation data, and management interval (i.e., the number of years elapsed between changes to the harvest level based on updated biological information). We attempted to examine a range of harvest levels that are likely to encompass subsistence need in Alaska and Chukotka based on harvest records for recent decades, although specific numbers for subsistence need were not available. We examined each potential harvest strategy relative to two management objectives based on the definition of SHL in the Agreement. Management Objective 1 sought to maintain the size of a harvested subpopulation above maximum net productivity level (*MNPL*), the subpopulation size that produces maximum sustainable yield, which for polar bears occurs at approximately 70% of environmental carrying capacity. Management Objective 1 recognizes that carrying capacity can change over time, which can result in changes to *MNPL* (e.g., if carrying capacity declines due to continued sea-ice loss, *MNPL* will decline, and the harvest level that meets Management Objective 1 will decline as well). We also considered Management Objective 2, which represented an alternative interpretation of SHL, and was defined relative to a static abundance level that did not consider subpopulation status or trend. Our analyses indicated that this objective was sensitive to untestable assumptions and, under some conditions, could lead to either overharvest or cessation of biologically sustainable harvest. Therefore, although results are presented for both management objectives, we focused on Management Objective 1 as more the useful tool for investigating SHL.

The harvest risk assessment accounted for major sources of uncertainty and variation, including statistical uncertainty in estimates of abundance and vital rates, potential bias in estimates of survival, interannual variation in environmental conditions, positive and negative density dependence, and uncertainty in how carrying capacity for polar bears might be affected by climate change. As a consequence of these uncertainties, we did not report a specific value of SHL that is guaranteed to be sustainable. Rather, we reported harvest strategies that met management objectives corresponding to different degrees of “risk tolerance”, where risk tolerance refers to the acceptable probability of failing to meet management objectives. Specifically, we reported strategies that had a 10, 30, or 50% chance of failing to meet objectives (alternatively, a 90, 70, or 50% chance of successfully meeting objectives). Some of the harvest strategies that were evaluated corresponded to plausible values of SHL, as discussed below.

Harvest strategies were evaluated by modeling polar bear populations 35 years into the future, which corresponds to approximately three polar bear generations. This time frame is common for population projections and allowed assessment of relatively long-term sustainability. Future carrying capacity was modeled according to three alternative methods to project the number of “ice-covered days” in the CS region, calculated from satellite data of sea-ice extent: (i) a decline of 5.6% per decade, reflecting the observed trend in sea ice from 1979 to 2016; (ii) a decline of 9.0% per decade, reflecting the more rapid declining trend in sea ice from 2000 to 2016; and (iii) a stable trend for 17 years, followed by a declining trend of 9.0%

per decade. The third method reflected the hypothesis that carrying capacity for the CS subpopulation, which is likely a function of multiple factors including biological productivity and prey availability, will remain stable for a number of years prior to declining due to sea-ice loss. At each annual time step, the modeled subpopulations were subject to harvest according to a specified strategy. We recorded the probabilities of meeting the two management objectives described above, as well as other outcomes such as trends in subpopulation size, trends in harvest level, and the probability of negative outcomes including extirpation and the depletion of adult male bears.

We performed population projections for two scenarios of the vital rates due to potential bias in estimates of survival. Scenario 1 used vital rates directly from Regehr et al. (in review) and likely represented a lower bound for the current status of CS polar bears. Scenario 2 used survival rates that were adjusted to result in a subpopulation growth rate that is average for polar bears, based on case studies throughout the Arctic. We suggest that Scenario 2 was likely a more accurate representation of the CS subpopulation in recent decades based on evidence of subpopulation productivity (see above), and the fact that negative bias in estimates of survival from capture-recapture studies with a sampling design similar to the CS study is a well-documented problem. Nonetheless, lacking direct quantitative evidence for the higher subpopulation growth rates of Scenario 2, and recognizing concerns about the future effects of sea-ice loss, we considered Scenario 2 as an upper bound for the status of the CS subpopulation. Thus, when interpreting results from the harvest risk assessment, we focused on harvest strategies that would likely be sustainable if the status of the CS subpopulation was between scenarios 1 and 2 (see below).

As expected, harvest strategies that met management objectives were higher for Scenario 2 than for Scenario 1. Expressed differently, for a given harvest strategy, estimated risk was lower for Scenario 2 than for Scenario 1. For example, we can examine a harvest strategy similar to the current value of SHL as determined by the Commission, with a present-day harvest level of 58 bears/year, a 2:1 male-to-female harvest sex ratio, and the assumption that harvest levels will be updated every 10 years using new subpopulation data with similar precision to Regehr et al. (in review). For this harvest strategy, the probabilities of meeting

Management Objective 1 would be approximately 0.67 and 0.97 under Scenario 1 and Scenario 2 of the vital rates, respectively. Both scenarios had negligible probabilities of extirpation or depletion of adult male bears (which can happen under excessive levels of sex-selective harvest). These findings suggest that the CS subpopulation can likely support a higher harvest than 58 bears/year.

The three alternative assumptions about future carrying capacity did not have a large effect on the present-day harvest levels that met management objectives, although sustainable harvest declined faster over time for the more pessimistic projections for carrying capacity. Harvest strategies that included shorter management intervals, and more precise estimates of abundance and vital rates, substantially reduced harvest risk under most conditions. These findings can be used in cost-benefit analyses, for example when deciding whether to spend additional research money to obtain better abundance estimates. Sustainable harvest levels were moderately higher for harvest strategies that selected for male bears (e.g., a 2:1 male-to-female harvest sex ratio). This effect was partially offset by the fact that our projection model included Allee effects in the mating system, which reduced reproductive rates when adult male numbers were low. Nonetheless, we emphasize that male-selective harvest is an important conservation tool due to the higher reproductive value of female bears. Results also suggested that a multiyear quota system for polar bear harvest, endorsed by the Commission in 2012, is a sound method to accommodate interannual variation in the availability of bears to hunters, without increasing harvest risk. Finally, our modeling demonstrated that ineffective harvest management, represented as a combination of under-reporting and failure to follow a state-dependent harvest management approach (i.e., implementing a fixed-level harvest under which harvest levels are not updated periodically), can substantially increase the risks of negative subpopulation outcomes including depletion or extirpation.

Determination of SHL is a decision for the Commission based on risk tolerances relative to meeting biological management objectives, meeting subsistence need, and other considerations. We evaluated a wide range of harvest strategies in the context of a sensitivity analysis, some of which were unlikely to be viable management options (e.g., some strategies were overly conservative, while others resulted in overharvest). To orient managers toward a useful range of harvest strategies, we concurrently compared results from Scenario 2 and Scenario 1, which corresponded to higher and lower representations of the demographic status of the CS subpopulation. For example, under Scenario 2 the harvest strategy that met Management Objective 1 at low risk tolerance (i.e., allowing up to a 10% chance of not meeting the objective) corresponded to a present-day harvest level of 86 bears/year at a 2:1 male-to-female harvest sex ratio, assuming a 10-year management interval and levels of precision in future subpopulation data similar to Regehr et al. (in review). For comparison, under Scenario 1 this harvest strategy would have a 60% chance of failing to meet Management Objective 1. Other outcomes under Scenario 1 included a 1% chance of extirpation and a 5% chance of depleting adult male bears after 35 years. Although this harvest strategy might exceed managers' risk tolerance, in the event that Scenario 1 was a more accurate representation of the demographic status of the CS subpopulation, it would be unlikely to cause severe negative effects in coming decades. Furthermore, under a state-dependent approach, this harvest strategy would be updated in the future if new subpopulation data indicated that changes were required to ensure sustainability.

Our modeling results suggested that plausible lower and upper bounds on SHL might be identified by examining harvest strategies that met Management Objective 1 at medium risk tolerance for the two scenarios of the vital rates. This would result in a range of present-day harvest levels from approximately 50 to 120 bears/year. Within this range, the risk of negative subpopulation outcomes due to harvest increases with higher harvest levels, and the risk of unnecessarily limiting subsistence opportunities increases with lower harvest levels. Recognizing that the Commission may consider multiple factors when determining SHL, results for harvest strategies throughout this range were included in the main report. It may be possible to focus on a narrower portion of this range by considering the assumptions and results of the harvest risk assessment in aggregate. Specifically, harvest strategies with a present-day harvest level in the vicinity of 80 to 90 bears/year, at a 2:1 male-to-female sex ratio, would likely meet the definition of SHL in the Agreement at a moderate degree of risk tolerance with respect to the biological effects of harvest. These findings assume that a functional management system will be implemented and that harvest levels will be updated every 10 years (or more frequently) using new subpopulation data.

The potential values of SHL discussed above can be evaluated relative to a harvest strategy that has been applied to other polar bear subpopulations throughout the Arctic under favorable environmental conditions, generally without negative effects: a 4.5% harvest rate, defined as the fraction of total subpopulation size removed by humans each year, at a 2:1 male-to-female harvest sex ratio. For the CS subpopulation, present-day harvest levels of 50, 85, and 120 bears/year would correspond to total harvest rates of approximately 1.6% (95% CRI = 0.8% – 3.2%), 2.7% (95% CRI = 1.4% – 5.5%), and 3.8% (95% CRI = 2.2% – 7.8%), respectively. All of these rates are likely lower than 4.5%, despite the fact that several lines of evidence suggest the CS subpopulation has been productive in recent decades. This is because our modeling and management approach considered the relatively low precision of estimates of abundance and vital rates for the CS subpopulation (Regehr et al. in review), the likely-but-unquantified bias in estimates of survival, and the potential negative effects of sea-ice loss due to climate change.

We have attempted to provide the Commission with the most accurate and reliable information possible. The harvest risk assessment did not include purposefully conservative assumptions, and the findings in this report have important caveats. First, all of the harvest strategies evaluated require the existence of a coupled research-management system under which both the harvest rate and harvest level are adjusted periodically, based on new biological information from scientific subpopulation assessments, TEK, or other sources. The consequences of not meeting these requirements (i.e., not following a state-dependent harvest management approach) can be severe. Second, the harvest strategies discussed above include a 2:1 male-to-female harvest sex ratio, a 10-year management interval, and future levels of precision in subpopulation data similar to Regehr et al. (in review). The main report provides information that could be used to adjust harvest strategies to accommodate other biological or management conditions (e.g., a longer management interval), or other risk tolerances. Also, it is possible that the Commission will consider additional factors influencing sustainability that were beyond the scope of our analyses. Third, our modeling did not consider more rapid declines in carrying capacity than 9.0% per decade, density-independent declines in subpopulation growth rate, or potential catastrophic events (e.g., large-scale mortality due to an oil spill). If the CS subpopulation experiences these things, the harvest strategies in this report might cease to meet management objectives and result in higher risks of negative outcomes.

Findings in this report apply to the CS subpopulation as recognized by the PBSG, which has a smaller area than the “Alaska-Chukotka population” of polar bears as recognized under the Agreement. This is because polar bears studied during research conducted 2008 – 2016 in American territory primarily used the area within the CS subpopulation boundary. Comparable research was not conducted in Russian territory to provide information on polar bears that used the far western portion of the Alaska-Chukotka population range. Consequently, the newly available estimates of abundance and vital rates from Regehr et al. (in review), and the harvest risk assessment using these data, apply to the CS subpopulation boundary only. The main report discusses additional uncertainties associated with the demographic status of polar bears in the larger area Alaska-Chukotka population range, and suggests how results from the harvest risk assessment might be adapted to that area.

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Introduction

Management and conservation of polar bears (*Ursus maritimus*) in the Chukchi Sea (CS) occurs under the *Agreement between the Government of the United States of America and the Government of the Russian Federation on the Conservation and Management of the Alaska-Chukotka Polar Bear Population* (hereafter, "Agreement"; United States T. Doc. 107-10). The Agreement includes provisions to ensure that subsistence harvest, which has nutritional and cultural importance (Voorhees et al. 2014, Kochnev and Zdor 2016, Schliebe et al. 2016), is sustainably managed. Specifically, the Agreement stipulates that reliable biological information, including scientific data and the traditional knowledge of Native people, should be used to determine the sustainable harvest level (SHL); and that annual take limits, as determined by a four-member commission established under the Agreement (hereafter, "Commission"), should not exceed SHL.

The CS region has experienced rapid sea-ice loss in recent decades (Stern and Laidre 2016), which is projected to continue (Douglas 2010). Nevertheless, recent scientific studies have suggested positive nutritional condition and reproduction for CS bears (Rode et al. 2014), which is consistent with earlier assessments of Traditional Ecological Knowledge (TEK; Voorhees et al. 2014) and a recent pilot study documenting local observations and TEK in northwestern Alaska (Braund et al. 2018). It is not known how long positive indicators will continue to be observed, however, because ongoing sea-ice loss is expected to reduce on-ice hunting opportunities for polar bears to the point that body condition, reproduction, and survival will be eventually affected (e.g., Lunn et al. 2016). Consistent with this expectation, CS polar bears spend 30 days longer on land during the summer, in response to sea-ice loss, compared to the 1980s and 1990s (Rode et al. 2015). Understanding the future effects of sea-ice loss on the CS subpopulation will require additional research, as a growing number of case studies suggest that multiple interacting factors influence when and how sea-ice loss affects polar bear demography (e.g., Bromaghin et al. 2015, Scientific Working Group to the Canada-Greenland Joint Commission on Polar Bear 2016).

Until recently, abundance and vital rates (e.g., reproduction, survival) for CS bears have not been estimated using quantitative methods, and the Polar Bear Specialist Group (PBSG) of the International Union for the Conservation of Nature recently classified abundance and trend of the CS subpopulation as unknown (Durner et al. 2018). To address this lack of information, the U.S. Fish and Wildlife Service (USFWS) and partners performed live-capture research on the sea ice west of Alaska in 2008 – 2011, 2013, and 2015 – 2016. Capture-recapture, radiotelemetry, and count data from this research study were recently analyzed using an integrated population model developed in a Bayesian framework specifically for the CS subpopulation (hereafter, “CS-IPM”; Regehr et al. in review). Results from the CS-IPM suggest that, during the period 2008 – 2016, reproductive rates for CS bears were average-to-high compared to 12 other polar bear subpopulations with available data as summarized in Regehr et al. (2017b). The number of yearlings (C1) per adult female, a key reproductive indicator, had not declined since the 1980s and 1990s. Estimated abundance during the spring, referenced to the area within the CS subpopulation boundary as recognized by the PBSG, was 2,937 bears (95% Credible Interval [CRI] = 1,552 – 5,944).

In this report, our objective was to evaluate the population-level effects of different harvest strategies using the newly available estimates of abundance and vital rates from Regehr et al. (in review). Analyses were performed using a matrix projection model (Regehr et al. 2017b) that takes into account the interactive effects of human-caused removals and habitat loss, and allows assessment of how the frequency and precision of future subpopulation studies influence the risk associated with different harvest strategies. All analyses assume that a “state-dependent” harvest management approach will be followed. State-dependent management has many features in common with the “adaptive management” approach recommended by the signatories to the *1973 Agreement on the Conservation of Polar Bears* (Polar Bear Range States 2015). Under state-dependent harvest management, harvest levels do not remain constant into the future, but rather are updated periodically (e.g., every 10 years) using new estimates of abundance and vital rates from scientific studies or TEK. In this manner, harvest management depends on the current status (i.e., “state”) of a subpopulation, which may change over time, for example due to the effects of habitat loss. State-dependent harvest management can be an effective way to reduce the risk of overharvest while maintaining opportunities for use (e.g., Lyons et al. 2008). This is especially important given that sea-ice loss is affecting the ecology of CS polar bears (Rode et al. 2015, Ware et al. 2017) and may lead to negative demographic effects in the future.

Methods

Analyses in this report are referenced to a life cycle graph with stages representing the sex, age, and reproductive status of individual polar bears (Fig. 1). Estimation of abundance and vital rates using the CS-IPM is described in Regehr et al. (in review). The matrix projection model and state-dependent management framework are described in Regehr et al. (2015, 2017b). Unless otherwise noted, details of the current application follow from these sources. A complete list of abbreviations, parameters, and indexing definitions is provided in Table 1. Methods are organized into eight primary sections, which are summarized below to help orientation.

1. Description of the boundaries of the CS polar bear subpopulation, to which analyses in this report are referenced.
2. Description of the demographic parameters (i.e., estimates of abundance and vital rates) from the CS-IPM that were used in the harvest risk assessment.
3. Overview of the matrix model used to project simulated polar bear subpopulations forward in time, subject to different harvest strategies.
4. Presentation of alternative assumptions for future carrying capacity, which were used to investigate the interactive effects of human-caused removals and habitat loss due to climate change.
5. Details of the state-dependent harvest management approach that underpins the harvest strategies in this report.
6. Presentation of biological management objectives based on the definition of SHL in the Agreement.
7. Step-by-step description of population projections, including application of harvest to the subpopulation.

8. Description of the simulations (i.e., sets of population projections sharing common features) used to investigate the population-level effects of different harvest strategies.

1. Subpopulation boundaries

The harvest risk assessment applies to the CS polar bear subpopulation as recognized by the PBSG (Durner et al. 2018), because the CS-IPM estimated abundance and vital rates for the CS subpopulation (Regehr et al. in review). The CS subpopulation boundary extends from approximately Chaunskaya Bay in northern Chukotka to Icy Cape in western Alaska. When estimating abundance and vital rates using the CS-IPM, the southern extent of this boundary was modified to exclude regions that were not used by polar bears fitted with telemetry devices during American live-capture research conducted 2008 – 2016 (Wilson et al. 2014, 2016). The area within the CS subpopulation boundary is smaller than, and encompassed by, the area of the "Alaska-Chukotka population" of polar bears as recognized under the Agreement, which extends from approximately the Kolyma River in Russia, to Point Barrow in the U.S. Implications of referencing the harvest risk assessment to the CS subpopulation are addressed at the end of this report (see section "Extension of findings to the Alaska-Chukotka population" in Discussion).

2. Demographic parameters

Estimates of abundance and vital rates were available as 30,000 samples from the posterior distributions from the Bayesian CS-IPM, which preserved the covariance structure of estimated parameters (Regehr et al. in review). We evaluated the demographic status of CS bears by using the estimated vital rates to calculate asymptotic growth rates, stable stage distributions, and other characteristics of population dynamics (see section "3. Matrix projection model" in Methods; Caswell 2001). We report the median of most parameters estimated in the harvest risk assessment. For consistency with Regehr et al. (in review), we report the mode of parameter estimates obtained directly from the CS-IPM.

Values of total survival used in this report were estimated from the Bayesian CS-IPM using informative priors established from the distribution of point estimates of total survival obtained from case studies for 12 polar bear subpopulations (Regehr et al. in review). These priors did not reflect a specific hypothesized trend for the CS subpopulation (i.e., declining, stable, or increasing), buy they did reflect the relatively strong assumption that point estimates of survival from other case studies are unbiased and representative of the species (e.g., similar to expected values based on life history; Eberhardt 1990), and that survival rates for CS bears during the period 2008 – 2016 would likely be similar to these values. We suggest that this assumption is justified because several lines of evidence, obtained from scientific studies and TEK, suggest that the CS subpopulation was productive during the period 2008 – 2016 (see section "Scenario 2 of the vital rates" in Methods) and that harvest rates were likely low relative to some other harvested subpopulations (see section "Demographic parameters" in Results).

Harvest mortality

Estimates of survival for independent polar bears (i.e., bears ≥ 2 years) from the CS-IPM represented total apparent survival, defined as the probability of remaining alive, considering all sources of mortality, and not permanently emigrating from the study area. We adjusted estimates of total survival to exclude human-caused mortality, as follows:

$$\sigma = \sigma^{total}/(1 - H/N), \qquad \text{[eqn1]}$$

where σ is unharvested survival, σ^{total} is total survival, H is the number of bears removed by humans (i.e., the combination of subsistence harvest, removals of problem bears, defense kills, and other direct sources of human-caused mortality), and N is abundance. Thus, H/N is the harvest mortality rate. We performed these calculations for polar bears in different life-cycle stages (Fig. 1) using stage-specific harvest data (see below) and mean estimates of stage-specific abundance from the CS-IPM. Equation 1 assumed that human-caused mortality is additive within a given year, whereas the density-dependent functions in the matrix projection model allowed vital rates to respond in a compensatory manner to changes in density across years (see section "3. Matrix projection model" in Methods). It was necessary to parameterize the projection model using estimates of unharvested survival (i.e., instead of total survival) to evaluate the subpopulation's capacity to grow in the absence of harvest, and to evaluate the effects of harvest levels that differ from the actual harvest during the period 2008 – 2016 (e.g., Taylor et al. 2009).

To estimate unharvested survival using equation 1, harvest data for Alaska were obtained from the USFWS Marking, Tagging, and Reporting Program. Average annual harvest within the U.S. portion of the CS subpopulation was 23.1 bears/year for the period 2008 – 2015. To account for likely under-reporting in U.S. harvest (Schliebe et al. 2016) we increased this value by 15% (B. Benter, USFWS, *personal communication*), resulting in 27.2 bears/year as the American contribution to H. To estimate the life-cycle stage composition of the harvest we used hunter-reported sex (available for 84% of the harvest sample), hunter-reported age class (available for 90% of the harvest sample), and ages estimated from counting the cementum annuli in vestigial premolar teeth (Calvert and Ramsay 1998) of harvested bears that were submitted by hunters (available for 50% of the harvest sample). For the sample of bears with all three data types, we used age data to estimate the distribution of life-cycle stages (Fig. 1) corresponding to each combination of hunter-reported sex and hunter-reported age class. We then assumed that this distribution applied to bears that had sex and age-class data, but did not have age data. Bears without age-class data were assumed to be adults, and bears without sex data were assumed to have the same sex distribution as bears with sex data. Polar bear harvest in the U.S. portion of the CS subpopulation is described in detail in Schliebe et al. (2016).

Harvest data for Chukotka, obtained from an interview survey of hunters and community members conducted in 2011 – 2012 (Kochnev and Zdor 2016), suggested an average annual harvest of approximately 32 bears/year (range 18 – 52 bears/year). For analyses we represented the average annual harvest in Chukotka for the period 2008 – 2015 as a uniform distribution $\mathrm{Unif}(18{,}52)$. The mean of this distribution was 35 bears/year, which is approximately 9% higher than the suggested point estimate of 32 bears/year. We considered this reasonable because harvest levels in Kochnev and Zdor (2016) were presented as minimum estimates. We specified the sex composition of independent bears harvested in Chukotka as 43% female and 57% male (A. Kochnev, Russian Academy of Sciences, *personal communication*), and we assumed that age and reproductive status were similar to the Alaskan harvest. Although data were not available to evaluate this assumption, it was broadly consistent with qualitative harvest information in Kochnev and Zdor (2016), for example that harvest of adult females with dependent young (i.e., cubs-of-the-year [C0] or yearlings [C1]) is currently uncommon in Chukotka, which also is the case in Alaska (Schliebe et al. 2016).

The resulting composition of the harvest, for the purpose of calculating unharvested survival and creating harvest vulnerability vectors for use in the matrix projection model (see section "Harvest and simulated subpopulation assessments" in Methods), was approximately 0.12 subadult female (life-cycle stages 1 and 2; Fig. 1), 0.19 adult female without dependent young (stages 3 and 4), 0.05 adult females with dependent young (stages 5 and 6), 0.33 subadult male (stages 7-9), and 0.31 adult male (stage 10).

Scenarios of the vital rates

We performed the harvest risk assessment using two sets (i.e., scenarios) of the vital rates that corresponded to different representations of the demographic status of the CS subpopulation. This was necessary because Regehr et al. (in review) indicated that estimates of survival for independent bears from the CS-IPM may have included negative bias due to un-modeled heterogeneity in recapture probabilities and movement probabilities (Fletcher et al. 2012, Peñaloza et al. 2014). This type of bias is a known problem for capture-recapture studies of mobile species when the sampling area is smaller than the subpopulation range (e.g., Scientific Working Group to the Canada-Greenland Joint Commission on Polar Bear), and can lead to biased inference if not accounted for during demographic analyses that rely on estimated vital rates (Regehr et al. 2009).

For both scenarios, prior to analyses we removed samples of the vital rates corresponding to biologically implausible conditions. This was necessary primarily because of large sampling uncertainty (see section "Demographic parameters" in Results). Samples of the vital rates were considered implausible if they corresponded to an asymptotic maximum intrinsic growth rate (r_{max}) less than 0 or greater than 0.10. The lower constraint was imposed because it is highly unlikely that conditions experienced by the CS subpopulation during the period 2008 – 2016 resulted in zero potential for positive growth, which would mean that the subpopulation is guaranteed to go extinct even if environmental conditions remain stable (see section "Scenario 2 of the vital rates" in Methods). The upper constraint was justified because r_{max} = 0.10 is at the upper limit of estimated growth rates for polar bears (Regehr et al. 2017b), and near the theoretical upper limit based on species life history.

Scenario 1 of the vital rates

Scenario 1 consisted of estimates of abundance and vital rates directly from the CS-IPM, without adjustments stemming from concerns about negative bias in survival. To use the vital rates in the harvest risk assessment, it was necessary to specify the subpopulation size (N) relative to environmental carrying capacity (K) to which the vital rates were referenced (i.e., relative density [N/K]). In practice it is difficult estimate relative density because K is usually not known (Gerrodette and Demaster 1990). However, it may be possible to infer relative density based on knowledge of N, the rate of human-caused removals, and species-specific population dynamics. For example, harvest strategies designed to achieve maximum sustainable yield are likely to result in relative densities corresponding to a subpopulation size near maximum net productivity level (*MNPL*), defined as the subpopulation size that results in the greatest net annual increment in numbers resulting from reproduction minus losses due to natural mortality. (In this report, *MNPL* refers to the preceding biological definition and does not have a regulatory basis.) For most polar bear subpopulations a total harvest rate (i.e., percentage of the total population removed each year) of 4.5% or higher, at a 2:1 male-to-female sex ratio, is required to achieve maximum sustainable yield (Taylor et al. 1987, Regehr et al. 2017b). The median total harvest rate for the CS subpopulation during the period 2008 – 2016 was approximately 2.0% (see section "Demographic parameters" in Results). The fact that 2.0% is lower than 4.5% suggests that relative density of the CS subpopulation may currently be above *MNPL*, although this cannot be confirmed due to uncertainty in demographic parameters and harvest levels, and an incomplete understanding of density-dependent regulation for polar bears (Derocher and Taylor 1994). To accommodate this uncertainty, for each sample of the vital rates in Scenario 1 we randomly selected a reference density from a uniform distribution $\mathrm{Unif}(0.50{,}0.94)$. The upper limit of 0.94 was established based on exploratory projections using a simple population model with a theta-logistic equation for density dependence, which USFWS (2016) presents as a close approximation of the more complex density-dependent functions in Regehr et al. (2017b). Specifically, using this model, 0.94 is the equilibrium density for a hypothetical population with r_{max} = 0.10 (the plausible upper limit used in this report) and a total harvest rate of 2.0%.

Scenario 2 of the vital rates

Scenario 2 consisted of vital rates from the CS-IPM, similar to Scenario 1, but with survival of independent bears adjusted to result in a median asymptotic growth rate referenced to a relative density corresponding to *MNPL* (r_{MNPL}) of 0.05, based on the case studies for polar bears reviewed in Regehr et al. (2017b). We derived the survival rates for Scenario 2 by making an additive adjustment to survival on the logit scale, followed by back-transformation to the probability scale, thus constraining the adjusted estimates to the interval [0,1]. A normal random deviate was included to avoid variance shrinkage. The vital rates for Scenario 2 were referenced to a relative density corresponding to *MNPL*, to ensure that the capacity for subpopulation growth under this scenario was similar to empirical estimates for other subpopulations (Regehr et al. 2017b).

Scenario 2 represents the hypothesis that the CS subpopulation was capable of typical growth rates for polar bears during the period 2008 – 2016. We considered this to be reasonable based on multiple lines of evidence for productivity of the CS subpopulation, including estimates of reproductive parameters from the CS-IPM that are average-to-high for the species (Regehr et al. in review), indices of recruitment for the CS subpopulation during the period 2008 – 2016 that were similar to values from the 1980s and 1990s (Rode et al. 2014, Regehr et al. in review), indices of positive body condition (Rode et al. 2014) and low springtime fasting rates (Rode et al. 2017), observations of healthy polar bears in western Alaska from TEK

(Braund et al. 2018), and the positive status of ice-dependent seals in the region (Crawford et al. 2015).

3. Matrix projection model

During the harvest risk assessment, a matrix projection model (Regehr et al. 2017b) was parameterized with vital rates from the CS-IPM, and then used to project simulated polar bear subpopulations forward in time, subject to different harvest strategies. Advantages of this modeling approach, compared to previous methods to evaluate harvest for polar bears (e.g., Taylor et al. 2006), include a detailed model of density dependence, the ability to evaluate practical aspects of harvest management (e.g., the number of years elapsed between new population studies), and the ability to consider demographic effects of sea-ice loss due to climate change (Regehr et al. 2015, 2017b). The matrix projection model is based on the polar bear life cycle (Fig. 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 spring of year *t* to the spring of year *t* + 1. Analyses were referenced to independent bears because C0s and C1s were not included as individuals in the life cycle, but rather were used to define the reproductive status of their mother (adult females with C0, stage 5; adult females with C1, stage 6). Density effects for the CS subpopulation were represented by constructing density-dependent curves of the vital rates using the methods and shape parameters described in Appendix S2 of Regehr et al. (2017b). All projections were referenced to the CS subpopulation only and did not consider immigration, emigration, or metapopulation dynamics.

The projection model incorporated a mechanistic submodel for Allee effects in the mating system, to account for potential declines in reproduction at low densities or skewed sex ratios. Molnár et al. (2008, 2014) proposed that, under some conditions, reproductive rates for polar bears may decline due to limitations in the ability to find mates. 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. 2008), or if polar bear densities are low during the breeding season. Because Allee effects in the CS subpopulation have not been studied, the

Allee submodel was based on equation 3 in Molnár et al. (2014) with input parameters for a "generic population". Using an area of 815,000 km^2 (excluding land) within the CS subpopulation boundary (Regehr et al. in review), we calibrated the Allee submodel by calculating the degree of mating season aggregation that would result in a probability of fertilization equal to, or greater than, the estimated value of the most important breeding parameter (β_4; Fig. 1) from the CS-IPM. In subsequent years of projections (t = 2, 3, … T), the estimated probability of fertilization from the Allee submodel was standardized by dividing by its value at t = 1. The resulting dimensionless parameter was constrained to the interval [0,1] and multiplied by the value of β_4 obtained from the density-dependent curves of the vital rates. Under this approach, the value of β_4 at t = 1 was unmodified (i.e., there were no Allee effects under initial conditions). Similarly, simulated subpopulations that did not experience depletion of adult male bears or large reductions in density, did not experience reproductive declines due to Allee effects. It was important to consider Allee effects because, if they were not included, harvest strategies with high harvest rates and selection for male bears could result in subpopulations with unrealistically high growth rates, because most adults would be female and breeding probabilities would remain high even in the near-absence of mature males.

4. Environmental carrying capacity

The matrix projection model included density-dependent curves describing how each vital rate in the polar bear life cycle graph (Fig. 1) changes as a function of relative density (Regehr et al. 2017b). For use in population projections, we derived a proxy metric to represent potential changes in K using satellite data for sea-ice extent. Specifically, we used the number of "ice-covered days" within the CS subpopulation boundary, calculated using the methods of Stern and Laidre (2016). In brief, each year the sea-ice area reaches a maximum in March and a minimum in September. A threshold was defined halfway between the mean March sea-ice area and the mean September sea-ice area for the period 1979 – 2016. Then, the number of ice-covered days was calculated as the total number of days between when the sea-ice area drops below the threshold in spring, and rises above the threshold in fall. To represent future trends and variability in K, we fit linear models to the observed time series of ice-covered days, and then projected the metric forward in time using the methods of Gelman and Hill (2007) to simulate uncertainty in the slope and residual standard errors. Finally, we standardized the metric by dividing the projected values of ice-covered days at year t = 2, 3, … T by the fitted value at year t = 1. This resulted in a dimensionless parameter (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 the vital rates through the density-dependent curves. This modeling approach reflected the assumption that polar bear vital rates are affected by habitat change exclusively through density-dependent mechanisms.

We used three approaches to project the proxy for K forward in time (Fig. 2), reflecting alternative hypotheses for how and when environmental carrying capacity might decline due to sea-ice loss, as described below.

- K_{trend}(1): Linear projection based on the slope of the decline in ice-covered days from satellite observations, 1979 – 2016. This projection method, which has been used in other harvest risk assessments and conservation assessments for polar bears (Regehr et al. 2016, Regehr et al. 2017a), resulted in a relatively gradual decline in K (slope = -1.04 ice-covered days per year, standard error of the slope = 0.20, P for null hypothesis of no trend < 0.001, root mean squared error = 13.5).
- K_{trend}(2): Linear projection based on the slope of the decline in ice-covered days for the period 2000 – 2016. This projection method represented the hypothesis that future sea-ice declines will occur at the faster rate observed in recent decades. We selected 2000 as the starting year based on evidence that sea-ice dynamics in the CS region exhibited a regime shift in 2000 (Frey et al. 2015). Compared to K_{trend}(1), this method resulted in a more rapid decline in K, with higher interannual variation (slope = -1.57 ice-covered days per year, standard error of the slope = 0.70, P for null hypothesis of no trend = 0.04, root mean squared error = 14.0)
- K_{trend}(3): Linear projection for years t = 1 to 17 using the estimated variance from projection method K_{trend}(2), but with slope set to 0, followed by a linear projection for the years t = 18 to 36 using both the estimated variance and slope from K_{trend}(2). This represents the hypothesis that K will remain stable until 2036 (i.e., t = 18). This

transition year was informed by forecasted sea-ice conditions in the CS region using the methods, general circulation models (GCMs, n = 6), and representative concentration pathways (RCPs, n = 2) described in Douglas and Atwood (2017). Specifically, by the year 2036, for both RCP = 4.5 and 8.5, at least one GCM indicated that sea ice would be farther than 200 km away from the coastlines of Wrangel Island and Chukotka, the most important summering area for CS polar bears (Rode et al. 2015), for more than four months per year, in at least six of the 10 years during the period 2036 – 2045. Four months represents a period of food deprivation that other subpopulations of polar bears have demonstrated resilience to, whereas longer periods without sea ice may result in declining nutritional condition and vital rates (Molnár et al. 2010, Robbins et al. 2012).

5. State-dependent management framework

During population projections, simulated polar bear subpopulations were subject to different harvest strategies. For a given harvest strategy, the harvest level at each annual time step was calculated as a function of N and the intrinsic growth rate r (which depends on the vital rates) using a state-dependent management harvest approach (Regehr et al. 2017b), as follows:

$$H^{female}(t) = F_O \times \tilde{r}_{MNPL}(t) \times 0.5 \times \widetilde{N}(t) \qquad \text{[eqn 2]}$$

and

$$H^{male}(t) = H^{female}(t) \times SR \qquad \text{[eqn 3]}$$

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 (see section “6. Management objectives and risk tolerance” in Methods);

$\tilde{r}_{MNPL}$ is an estimate of the intrinsic population growth rate from subpopulation studies, referenced to a relative density corresponding to *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;

$\widetilde{N}$ is an estimate of N from subpopulation studies, selected from its sampling distribution to reflect risk tolerance and protect against overharvest when uncertainty is large (in this report, we follow the convention of selecting $\widetilde{N}$ as the 15th percentile of the sampling distribution for N);

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 define a harvest strategy, managers 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 increase the risk of negative subpopulation outcomes (e.g., extirpation). The parameter *SR* determines the sex ratio of the harvest. For example, *SR* = 2.0 corresponds to a 2:1 male-to-female sex ratio in the harvest, a common management objective for polar bears (Taylor et al. 2008). The values of $\tilde{r}_{MNPL}$ and $\widetilde{N}$ in equation (2) are estimated from subpopulation studies.

To implement harvest within a state-dependent framework, it is also necessary to specify how often periodic updates to the harvest level will occur. The management interval (*mgmt.interval*) is defined as the number of years between successive subpopulation studies and changes to the calculated harvest level based on updated estimates of abundance and vital rates. For example, under *mgmt.interval* = 10 years, a harvest level would be calculated in year *t* = 1 and then applied each year *t* = 1, 2, ... 10. During the later years of this period, a subpopulation study would be completed to provide updated estimates of abundance and the vital rates. Based on these estimates, a new harvest level would be calculated using equations 2 and 3, and applied to the subpopulation in each year *t* = 11, 12, … 20. Longer management intervals are generally associated with higher risk because there are fewer opportunities to identify and correct for overharvest that can occur due to biased estimates of demographic parameters, changing environmental conditions, or other factors. In addition to the management interval, evaluating the long-term effects of a harvest strategy requires specification of the precision of demographic parameters that will be estimated from future subpopulation studies. Higher precision is generally associated with lower risk, because there is less chance that sampling uncertainty will result in overestimates of demographic parameters that lead to inadvertent overharvest. During population projections, the relative standard deviation of future parameter estimates was calculated as the product of a user-specified modifier (*rsd.mod*) and the relative standard deviation of estimates of r_{MNPL} and N from the CS-IPM. For example, at the end of each management interval for population projections with *rsd.mod* = 0.5, the harvest level was recalculated using values of $\tilde{r}_{MNPL}$ and $\tilde{N}$ that were selected from sampling distributions for which the relative standard deviation was 50% lower than from the CS-IPM. Considering different values of *rsd.mod* allowed us to investigate how the precision of future subpopulation studies can affect sustainable harvest. This information can be useful for cost-benefit analyses (e.g., when evaluating the practical benefits of allocating additional research funding to increase precision in future estimates of N).

In this report, the values of F_O and *SR* for a given harvest strategy remained fixed for the duration of population projections, so that each harvest strategy had a consistent definition. In practice, these parameters could be adjusted in response to changing conditions. Unlike the management inputs, biological parameters in equations 2 and 3 (i.e., the true values of r_{MNPL} and N, as well as their estimated values $\tilde{r}_{MNPL}$ and $\tilde{N}$) could change over time. For example, in some projections N declined due to declining K, which would result in lower estimates of N used to calculate future harvest levels. The notation for time (*t*) in equations 2 and 3 indicates that the estimated parameters $\tilde{r}_{MNPL}$ and $\tilde{N}$ are updated periodically, as determined by the management interval. Equations 2 and 3 are written in terms of harvest level for convenience; the harvest rate (here, referenced to the number of independent bears in the subpopulation) for females is the right side of equation 2 before multiplying by $\tilde{N}$. We included an additional management rule requiring that the calculated harvest rate after the first management interval, expressed as the proportion of independent bears removed each year, cannot exceed 0.10. This is a common-sense method to protect against overharvest when sampling uncertainty is large (Regehr et al. 2017b).

6. Management objectives and risk tolerance

In the Agreement, SHL is defined as "a harvest level which does not exceed net annual recruitment to the population and maintains the population at or near its current level, taking into account all forms of removal, and considers the status and trend of the population". We evaluated harvest relative to two management objectives, which represented alternative interpretations of the biological definition of SHL.

- Management Objective 1: Maintain a harvested subpopulation at an equilibrium size greater than *MNPL*. To evaluate Management Objective 1, we used a single value of *MNPL* corresponding to a relative density N/K = 0.70, which is similar to the mean estimate of relative density at *MNPL* across a wide range of vital rates (Regehr et al. 2017b). This provided a consistent point of reference for management decisions across different harvest strategies and environmental conditions. In stochastic population projections, the probability of meeting Management Objective 1 at the final time step was denoted P_{MO1}.
- Management Objective 2: Maintain a harvested subpopulation at an equilibrium size greater than 90% of starting subpopulation size (i.e., subpopulation size at year t = 1). The probability of meeting Management Objective 2 at the final time step was denoted P_{MO2}.

Implications of the two interpretations of SHL are addressed at the end of this report (see section "Management objectives" in Discussion). Although results are presented for both objectives, we focused on Management Objective 1 as the more useful tool for investigating SHL.

Assessing whether a given harvest strategy meets a management objective requires a statement of risk tolerance, which specifies the required probability of meeting the objective. In 2016, the Commission endorsed a recommendation from the Scientific Working Group (SWG) established under the Agreement to perform a quantitative harvest risk assessment that will "result in a range of sustainable harvest options and associated risk levels, which the Commission can use to determine an appropriate balance between protecting the [Alaska-Chukotka] population and meeting subsistence needs in a manner that is consistent with the terms of the Agreement" (SWG 2016). Because the Commission did not provide guidance on acceptable amounts of risk, we present most findings in this report at three placeholder degrees of risk tolerance (*risk.tol*), described below. We refer to these as low, medium, and high risk tolerances, noting that these descriptors are defined relative to each other and do not necessarily represent reference points for determining SHL.

- *risk.tol* = 0.10: Low risk tolerance. Allowing no more than a 10% chance of failing to meet a management objective (similarly, requiring a 90% probability of successfully meeting the objective).
- *risk.tol* = 0.30: Medium risk tolerance. Allowing no more than a 30% chance of failing to meet a management objective (similarly, requiring a 70% probability of successfully meeting the objective).
- *risk.tol* = 0.50: High risk tolerance. Allowing no more than a 50% chance of failing to meet a management objective (similarly, requiring a 50% probability of successfully meeting the objective).

We used *risk.tol* = 0.10 and 0.30 because these values were subjectively reasonable, and because they have been used to represent "low" and "medium" risk tolerances in other harvest assessments (Regehr et al. 2017a). We included *risk.tol* = 0.50 to provide a wider range of summarized results for the Commission to consider. Although it would be possible to report results at higher levels of risk tolerance, this would be of limited value because under some conditions negative subpopulation outcomes (e.g., extirpation) became increasingly likely above *risk.tol* = 0.50 for Management Objective 1 (see section "Simulations" in Results).

7. Population projections

Simulated polar bear subpopulations were projected 35 years into the future (i.e., from *t* = 1, 2, … 36), which is equivalent to approximately three polar bear generations (Regehr et al. 2016). This timeframe reduced the impact of transient dynamics at the start of projections, and allowed assessment of the long-term effects of harvest. At each time step the following operations were performed.

1. Simulated subpopulations were projected forward one year using the stage-structured matrix model: $\boldsymbol{n}(t+1) = \boldsymbol{A}(t) \times \boldsymbol{n}(t)$, where $\boldsymbol{n}(t)$ is a stage distribution vector representing the number of animals in each life-cycle stage at time step t, and $\boldsymbol{A}(t)$ is a 10×10 projection matrix (Caswell 2001). Entries in $\boldsymbol{A}(t)$ were defined in terms of vital rates in the life cycle graph (Fig. 1).
2. The calculated level of harvest was allocated among life cycle stages using a multinomial distribution with the probability for each stage calculated as the product of its proportional stage distribution and harvest vulnerability vector (see section "Harvest and simulated subpopulation assessments" in Methods).
3. Relative density of the simulated subpopulation was determined as the sum of metabolic energetic equivalent (*mee*) values in the subpopulation, divided by K expressed as energetic equivalents, using the methods of Regehr et al. (2017b). This approach of calculating relative density based on energetic requirements, rather than simple numbers of bears, allowed animals of different sizes, and thus different nutritional requirements, to have a different contribution to density effects.
4. Vital rates corresponding to the current relative density were determined from the density-dependent curves, with modifications applied to the parameter β_4 based on the Allee submodel. These vital rates were used to construct a projection matrix for the next time step $\boldsymbol{A}(t+1)$.

<u>Harvest and simulated subpopulation assessments</u>

For a given population projection, the harvest strategy was defined by specifying values for the management parameters F_O, *SR*, *mgmt.interval*, and *rsd.mod* (see section "5. State-dependent management framework" in Methods). The annual harvest level during the first management interval (i.e., years *t* = 2,3,…, *mgmt.interval* + 1) was calculated using equations 2 and 3 using biological parameters (i.e., values of $\tilde{r}_{MNPL}$ and $\widetilde{N}$) estimated from the CS-IPM for the period 2008 – 2016, as represented by either Scenario 1 or Scenario 2 of the vital rates. This ensured that harvest levels during the first management interval were calculated based on current information for the demographic status of the CS subpopulation (Regehr et al. in review) and were consistent across projections with the same harvest strategy.

At the beginning of subsequent management intervals, the harvest level was calculated with the same values of the management parameters, but using values of $\tilde{r}_{MNPL}$ and $\widetilde{N}$ derived from simulated subpopulation assessments. Conceptually, the simulated subpopulation assessments represent new studies, performed in the future, to obtain updated estimates of abundance and the vital rates. The simulated subpopulation assessments selected values of $\tilde{r}_{MNPL}$ and $\widetilde{N}$ from a multivariate normal distribution with a covariance structure calculated from the CS-IPM. This reflected the assumption that the design and precision of future subpopulation studies will be similar to capture-recapture research performed 2008 – 2016 (Regehr et al. in review). As noted previously, this assumption was relaxed for harvest strategies that specified *rsd.mod* < 1, which allowed us to examine the ramifications of future subpopulation studies that provide more precise estimates of N and the vital rates.

Throughout our analyses, harvest level refers to the number of independent bears removed from the CS subpopulation by humans each year (i.e., the combination of subsistence harvest, removals of problem bears, defense kills, etc.). This established consistency with the language "taking into account all forms of removal" in the definition of SHL in the Agreement. 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 stage structure of the observed harvest in Alaska and Chukotka (see section "Harvest mortality" in Methods) to the mean stage structure of the subpopulation as estimated from the CS-IPM. The resulting harvest vulnerability vectors for females (stages 1–6) and males (stages 7–10) were [0.72, 0.72, 1.0, 1.0, 0.14, 0.14] and [2.17, 2.17, 2.17, 1.0], respectively.

During 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, excess harvest was applied to adult bears of the same sex (i.e., stages 4 or 10). If the harvest exceeded the total number of males or females, excess harvest was applied to adults of the other sex. The harvest vulnerability vectors remained constant across projections and time steps. During population projections, harvest was applied deterministically such that the exact harvest level rounded to the nearest bear, as calculated from equations 2 and 3, was removed from the subpopulation each year. This specification was relaxed for some projections in which harvest was applied stochastically and distributed across years using a multiyear quota system (see section "Supplemental simulations" in Methods).

8. Simulations

We define a "simulation" as multiple population projections that have a fixed harvest strategy (i.e., all projections use the same management parameters), a fixed method to project K, and fixed posterior distributions of the vital rates corresponding to Scenario 1 or Scenario 2. Within a simulation, sampling variation was incorporated by performing projections for multiple samples of the vital rates, selected randomly and without replacement from the posterior distributions from the CS-IPM. Environmental variation was incorporated by performing five stochastic projections of K, using a fixed value of K_{trend}, for each sample of the vital rates. After excluding samples of the vital rates that were biologically implausible (see section "Demographic parameters" in Results) there were 10,620 projections per simulation for Scenario 1, and 10,850 projections per simulation for Scenario 2. These numbers of replicates were deemed sufficient to give reproducible results at the level of precision we report.

<u>Subpopulation outcomes</u>

For each simulation, we recorded the probabilities of meeting the two management objectives (see section "6. Management objectives" in Methods), as well as the subpopulation outcomes described below.

- $H_{mgmt.interval\ 1}$: Annual harvest level (bears/year) during the first management interval. Conceptually, $H_{mgmt.interval\ 1}$ represents the present-day harvest level associated with a given management strategy, as calculated from currently available demographic parameters.
- $H_{mgmt.interval\ 2}$: Median annual harvest level (bears/year) during the second management interval. The metric $H_{mgmt.interval\ 2}$, and the subpopulation outcomes $H_{t=18}$ and $H_{t=36}$ described in the next bullet, are reported because harvest levels can change over time for a given harvest strategy with fixed management parameters. For example, H will decline if N declines due to habitat loss or overharvest.
- $H_{t=18}$ and $H_{t=36}$: Median annual harvest level (bears/year) at time steps t = 18 and 36, respectively.
- $H_{yield.index}$: Median annual harvest, averaged over all time steps from t = 2 to 36. This is an index of cumulative yield over the 35-year duration of projections.
- $P_{extirpation}$: Probability of extirpation, defined as N falling below a quasi-extinction threshold of 100 independent bears, which is similar to values that have been used for brown bears (Wielgus 2002). We note that Regehr et al. (2017b) used higher quasi-extinction thresholds, calculated as 15% of starting N. We did not follow that approach because our analyses incorporated an Allee submodel that 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.
- $P_{male.dep}$: Probability of male depletion, defined as less than 50 adult males in life-cycle stage 10 (Fig. 1). This subpopulation outcome was reported to identify harvest strategies that led to severe depletion of adult males, which is possible when harvest rates are high and harvest is selective for male bears (Taylor et al. 2008).

Simulations for Scenario 1 of the vital rates

To limit computation time we did not perform a simulation for every possible combination of management parameters, methods to project K, and scenarios of the vital rates. Rather, for each scenario of the vital rates we performed three sets of simulations, each of which explored a different aspect of harvest management. The three sets of simulations followed a similar structure for Scenario 1 and Scenario 2.

Scenario 1 corresponded to the estimated vital rates from the CS-IPM (Regehr et al. in review) without adjustment for potential negative bias in survival. The first set of simulations was designed to evaluate sustainable harvest under different methods to project K. These simulations used fixed values of *mgmt.interval* = 10 years, *SR* = 2, and *rsd.mod* = 1, which we considered to be reasonable middle-of-the-road conditions for future harvest management. Simulations were performed over 35 years for all combinations of the following inputs:

1. Twelve values of the management factor F_O = [0.0, 0.2, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 1.7, 1.9, 2.2, 2.5], which corresponded to harvest strategies with a range of present-day harvest levels ($H_{mgmt.interval\ 1}$) from 0 to 108 bears/year. Our goal was to evaluate a range of harvest strategies that would likely encompass the present-day level of subsistence need in Alaska and Chukotka, recognizing that quantitative estimates of subsistence need were not available. We did not consider values of F_O greater than 2.5 to limit the number of harvest strategies that were clearly unsustainable (e.g., that resulted in $P_{extirpation}$ > 0.05).
2. Three methods to project K corresponding to $K_{trend}(1)$, $K_{trend}(2)$, and $K_{trend}(3)$.

The second set of simulations evaluated the effects of changes to the management interval and precision of demographic parameters. These simulations used fixed values of $K_{trend}(1)$ and *SR* = 2.0. Simulations were performed over 35 years for all combinations of the following inputs:

1. Five values of the management factor F_O = [0.7, 1.0, 1.2, 1.4, 1.7], which corresponded to a range of starting harvest levels ($H_{mgmt.interval\ 1}$) from 30 to 73 bears/year. This narrower range of values for F_O was informed by results from the first set of simulations.
2. Three values of the management interval corresponding to *mgmt.interval* = 5, 10, and 15 years.

3. Three levels of precision in estimates of abundance and vital rates from future subpopulation studies corresponding to *rsd.mod* = 0.25, 0.5, and 1.0. The value *rsd.mod* = 1.0 reflects the possibility that the precision of future demographic parameters will be similar to estimates from the CS-IPM (Regehr et al. in review). Although the lowest value of *rsd.mod* = 0.25 represented a large reduction in variance, it resulted in levels of precision that are plausible for polar bear studies (Regehr et al. 2017b).

The third set of simulations evaluated the effects of changing the harvest sex ratio. These simulations used fixed values of $K_{trend}(1)$, *mgmt.interval* = 10 years, and *rsd.mod* = 1. Simulations were performed over 35 years for all combinations of the following inputs:

1. Seven values of the management factor F_O = [0.5, 1, 1.2, 1.6, 1.8, 2, 2.5], which corresponded to a range of starting harvest levels ($H_{mgmt.interval\ 1}$) from 14 to 108 bears/year, depending on the harvest sex ratio.
2. Three values of harvest sex ratio corresponding to *SR* = 1.0, 1.5, and 2.0.

In total, we performed 102 simulations for Scenario 1 of the vital rates. In some instances, we evaluated harvest strategies that were incrementally higher and lower than the specific strategy that would meet a management objective at one of the three reported placeholder degrees of risk tolerance. When this occurred, we used linear interpolation to determine the specific harvest strategy that would meet the management objective. As a hypothetical example, if simulation A had $H_{mgmt.interval\ 1}$ = 50 bears/year and resulted in P_{MO1} = 0.72, and simulation B had $H_{mgmt.interval\ 1}$ = 60 bears/year and resulted in P_{MO1} = 0.68, we used linear interpolation to determine that a harvest strategy with $H_{mgmt.interval\ 1}$ = 55 bears/year would result in P_{MO1} = 0.70 and thus meet Management Objective 1 at *risk.tol* = 0.30.

Simulations for Scenario 2 of the vital rates

Scenario 2 assumed that vital rates from the CS-IPM (Regehr et al. in review) were negatively biased, and therefore adjusted estimates of survival to achieve a typical intrinsic growth rate for polar bears. For Scenario 2, we performed three sets of simulations with the same structure and specifications as Scenario 1, except that values of F_O differed because the two scenarios had different capacities to support harvest. In brief, for Scenario 2 the first set of simulations (to evaluate the effects of K_{trend}) used 13 values of the management factor F_O = [0.0, 0.3, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 2.0], which corresponded to $H_{mgmt.interval\ 1}$ from 0 to 149 bears/year. The second set of simulations (to evaluate the effects of *mgmt.interval* and *rsd.mod*) used five values of the management factor F_O = [0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.5], which corresponded to $H_{mgmt.interval\ 1}$ from 69 to 149 bears/year. The third set of simulations (to evaluate the effects of *SR*) used seven values of the management factor F_O = [0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.5, 1.7, 1.9, 2.1, 2.3], which corresponded to $H_{mgmt.interval\ 1}$ from 46 to 228 bears/year, depending on the harvest sex ratio. All other specifications were the same as for Scenario 1. In total, we performed 135 simulations for Scenario 2.

<u>Supplemental simulations</u>

We performed supplemental simulations to explore other conditions of interest. Supplemental simulations were performed for Scenario 1 of the vital rates only, with fixed values of K_{trend}(1), *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1. The supplemental simulations provided example results and were not intended as comprehensive investigations.

Multiyear quota system

The first supplemental simulations (SS1) evaluated the concurrent effects of (i) stochastic variation in annual harvest levels, which can arise from variation in the availability of bears to hunters (e.g., due to variation in sea-ice conditions) or other factors (Schliebe et al. 2016); and (ii) implementing harvest using a multiyear quota system (MQS) to accommodate stochasticity while ensuring that sustainable harvest levels are followed over multiyear periods. We modeled a MQS, with a 5-year period, as follows:

- A_{MQS}: Total number of harvest credits over a 5-year period, which was equal to 5 times the harvest level calculated using equations 2 and 3 in the first year of the MQS period (e.g., if SHL was 50 bears/year, A_{MQS} = 5 × 50 = 250 bears). The term "harvest credit" refers to the removal of one polar bear in accordance with the MQS.

- *y*: Number of years remaining in a 5-year period, at the beginning of year *z* of the 5-year period (where *z* = 1, 2, … 5).
- B_z: Number of harvest credits remaining in a 5-year period at the beginning of year *z*, where B_z = A_{MQS} − number of bears harvested in the 5-year period prior to the beginning of year *z*.
- C_z: Average number of harvest credits remaining per year within a 5-year period, at the beginning of year *z*, where C_z = B_z / *y*. Conceptually, C_z is the number of bears that could be removed in year *z* without reducing the average number of harvest credits per year for subsequent years within the 5-year period.
- D_z: Maximum harvest level for year *z*, where D_z = C_z for years *z* = 1 and 5, and D_z = C_z × 1.25 for years *z* = 2, 3, and 4 (i.e., the 1.25 multiplier is not used in the first and last years of a 5-year period).

During population projections for SS1, at each time step a stochastic harvest level was generated as a normal random variable with mean C_z and standard deviation 0.5C_z, where 0.5 is an index of interannual variation in the harvest, calculated as the mean relative standard error from a linear regression of U.S. harvest vs. year, 1988 – 2015 (data from Table 2 in Schliebe et al. 2016). Negative values of C_z were set to 0, and values of C_z > D_z were set to D_z. The MQS was implemented separately for females and males, and credits were not carried over from one 5-year period to the next. This description of the MQS differs slightly from the version adopted by the Commission in 2012 (U.S.-Russia Polar Bear Commission 2012), which included the 1.25 multiplier in all years of the 5-year period.

Consequences of ineffective harvest management

The second supplemental simulations (SS2) evaluated the potential consequences of ineffective harvest management, represented as: (i) harvest levels that were 25% higher than reported, and (ii) harvest levels that were not updated periodically using a state-dependent harvest management approach. During the first management interval, harvest strategies in SS2 had the same apparent harvest level as the first set of simulations for Scenario 1 of the vital rates. Conceptually, SS2 represents a situation in which a present-day sustainable harvest strategy is established under the false assumptions of accurate harvest reporting and state-dependent harvest management.

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). Matrix projection models were constructed and evaluated using the packages 'popbio' (Stubben et al. 2007) and 'popdemo' (Stott et al. 2012).

Results

Demographic parameters

The mode of the multiyear average estimate of total abundance (i.e., including C0s and C1s) for the CS subpopulation during the period 2008 – 2016 was 2,937 bears (95% CRI = 1,552 – 5,944; Regehr et al. in review). The median proportion of independent bears (i.e., age ≥ 2 years) in the subpopulation was 0.66 (95% CRI = 0.60 – 0.73) based on asymptotic stable stage distributions. The resulting multiyear average estimate of abundance, referenced to independent bears only, had a mode of 1,942 and a median of 2,114 (95% CRI = 1,023 – 3,962). The median asymptotic observed growth rate, based on vital rates from the CS-IPM that may have included negative bias, was -0.008 (95% CRI = -0.043 – 0.025). Approximately 67% of the sampling distribution for this observed growth rate was below 0.

The median harvest morality rate for the CS subpopulation, referenced to independent bears only, was 0.030 (95% CRI = 0.015 – 0.066). This credible interval reflects statistical uncertainty in estimates of abundance throughout the CS subpopulation range, and uncertainty in annual harvest levels in Chukotka. The median total harvest mortality rate, referenced to all bears in the CS subpopulation, was 0.020 (95% CRI = 0.010 – 0.044). To parameterize the matrix projection model, unharvested survival rates for independent bears were estimated from stage-specific harvest mortality rates and estimates of total survival from the CS-IPM (Table 2).

Scenario 1 of the vital rates

Approximately 24% of vital rate samples were excluded from analyses because they corresponded to r_{max} ≤ 0, and approximately 5% of samples were excluded because they corresponded to r_{max} > 0.10. The median asymptotic growth rate for Scenario 1 referenced to a relative density at *MNPL* was r_{MNPL} = 0.020 (95% CRI = 0.002 – 0.059). Behaviors of the density-dependent functions were consistent with Regehr et al. (2017b), including that *MNPL* occurred at 0.73 (95% CRI = 0.69 – 0.74) of K, and the ratio of subpopulation growth rate at *MNPL* to the maximum intrinsic growth rate (r_{MNPL} / r_{max}) was 0.84 (95% CRI = 0.82 – 0.84).

Scenario 2 of the vital rates

Approximately 3% of vital rate samples were excluded from analyses because they corresponded to r_{max} ≤ 0, and approximately 25% of samples were excluded because they corresponded to r_{max} > 0.10. This pattern of exclusion was different than Scenario 1 because survival rates were higher for Scenario 2, and thus more samples exceeded the upper limit on r_{max}. The median asymptotic growth rate for Scenario 2 referenced to a relative density at *MNPL* was r_{MNPL} = 0.044 (95% CRI = 0.001 – 0.065). Behaviors of the density-dependent functions were consistent with Regehr et al. (2017b), including that *MNPL* occurred at 0.70 (95% CRI = 0.68 – 0.74) of K, and r_{MNPL} / r_{max} was 0.83 (95% CRI = 0.82 – 0.84).

Simulations

Scenario 1 of the vital rates

The first set of simulations evaluated sustainable harvest under different assumptions about future carrying capacity. Harvest strategies that met Management Objective 1 ranged from present-day harvest levels of 33 bears/year at low risk tolerance (*risk.tol* = 0.10), to 85 bears/year at high risk tolerance (*risk.tol* = 0.50), depending on the projected trend in K (Table 3; additional results in Supplemental Table S1). For example, to meet Management Objective 1 at medium risk tolerance (*risk.tol* = 0.30) under K_{trend}(1), the highest allowable harvest occurred with a management factor F_O = 1.27. The corresponding harvest level during the first management interval ($H_{mgmt.interval\ 1}$) was 55 bears/year. To help visualize how the simulated subpopulations progressed over time, sample replicates for a similar harvest strategy are shown in Figure 3. Harvest strategies that met management objectives at the placeholder degrees of risk tolerance were generally associated with low probabilities of extirpation ($P_{extirpation}$) and male depletion ($P_{male.dep}$), with the highest values (i.e., $P_{extirpation}$ ≈ 1% and $P_{male.dep}$ ≈ 7%) corresponding to the harvest strategy that met Management Objective 1 at high risk tolerance when K was declining rapidly.

The probability of failing to meet Management Objective 1 (i.e., 1 - P_{MO1}) increased as a function of $H_{mgmt.interval\ 1}$ (Fig. 4). Across the three methods to project K, harvest strategies with similar values of $H_{mgmt.interval\ 1}$ also had similar probabilities of meeting Management Objective 1. Simulations with K_{trend}(2) had the highest value of $H_{mgmt.interval\ 1}$ at higher risk tolerances, because it was possible to implement a more aggressive harvest that removed animals rapidly, while still maintaining subpopulation size above *MNPL*, due to the fact that K (and thus *MNPL*) declined rapidly compared to K_{trend}(1) and K_{trend}(3). A related outcome was that the median harvest level at the end of projections ($H_{t=36}$) was the lowest for K_{trend}(2).

Sustainable harvest strategies relative to Management Objective 2 were more sensitive to the trend in K, and it was not possible to meet this objective at low risk tolerance for simulations with K_{trend}(1) and K_{trend}(2) (Table 3). This is because the more rapid declines in K led to higher probabilities that subpopulation size at *t* = 36 would be less than 90% of starting subpopulation size, even in the absence of harvest (see section "Scenario 2 of the vital rates" in Results, for additional findings relative to Management Objective 2).

The second set of simulations evaluated the interactive effects of the management interval (*mgmt.interval*) and the precision of demographic parameters from future population studies (*rsd.mod*). Shorter management intervals and higher levels of precision generally led to reduced risk and higher sustainable harvest (Fig. 5). The curves in Figure 5 converge on the right side of panels a) and b) due to overharvest. Specifically, when harvest rates were sufficiently high, subpopulation size was depleted and long-term yield declined regardless of the length of the management interval or precision of demographic parameters.

To facilitate interpretation, we summarized results from the second set of simulations as the proportional change in subpopulation outcomes resulting from different combinations of *mgmt.interval* and *rsd.mod*, referenced to a baseline simulation with *mgmt.interval* = 10 years and *rsd.mod* = 1.0 (Table 4). For example, harvest levels during the second management interval ($H_{mgmt.interval\ 2}$) were 28% higher for simulations with *mgmt.interval* = 10 years and *rsd.mod* = 0.50, compared to the baseline simulation. Values of $H_{mgmt.interval\ 2}$ increased with lower values of *rsd.mod* because of the effects of increased precision in the demographic parameters used to calculate the harvest level in equations 2 and 3. Specifically, the parameter $\widetilde{N}$, representing the 15th percentile of the sampling distribution of N, increased (i.e., approached the true value of N) as sampling uncertainty went down. Due to these increases in $H_{mgmt.interval\ 2}$, the sustainable harvest level in the first management interval ($H_{mgmt.interval\ 1}$) was negatively correlated with *rsd.mod*. This is a consequence of using a fixed value of F_O for each harvest strategy. Specifically, slightly lower values of F_O, which resulted in lower harvest during the first management interval, were required to offset the large increases in harvest level starting at the second management interval. As demonstrated by the proportional changes in the median annual harvest averaged over all time steps ($H_{yield.index}$), the overall effect of shortening the management interval or increasing the precision of demographic parameters, was to increase long-term sustainable yield without increasing risk.

The third set of simulations evaluated the effects of changing the harvest sex ratio. Sustainable harvest levels were moderately higher for harvest strategies that selected for male bears (Table 5, Fig. 6). For example, $H_{mgmt.interval\ 1}$ was approximately 12% higher and the median harvest at the end of projections ($H_{t=36}$) was approximately 37% higher for *SR* = 2.0 compared to *SR* = 1.0, for harvest strategies that met Management Objective 1 at the medium risk tolerance (Table 5). In our projections the benefits of focusing harvest on males, which have lower reproductive value than females (Hunter et al. 2007), were partially offset by reduced breeding probability (β_4) when male densities were low resulting from Allee effects in the mating system (Fig. 6).

Scenario 2 of the vital rates

The vital rates of Scenario 2 were adjusted to account for potential negative bias in estimates of survival from the CS-IPM, resulting in higher values of r_{max} and thus higher sustainable harvest levels compared to Scenario 1. For the first set of simulations, which evaluated the effects of different assumptions about future K, harvest strategies that met Management Objective 1 ranged from present-day harvest levels of 74 bears/year at low risk tolerance, to 174 bears/year at high risk tolerance, depending on the projected trend in K (Table 6; additional results in Supplemental Table S2). For example, a harvest strategy with F_O = 1.24, $H_{mgmt.interval\ 1}$ = 123 bear/year, *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1.0 met Management Objective 1 at medium risk tolerance under K_{trend}(1). The probability of failing to meet Management Objective 1 (i.e., 1 - P_{MO1}) increased as a function of $H_{mgmt.interval\ 1}$ (Fig. 7).

Patterns in the results for Scenario 2 were generally similar to Scenario 1, with several exceptions. For Scenario 2, harvest strategies that met Management Objective 1 at medium and high risk tolerances were sometimes associated with non-negligible values of $P_{extirpation}$, $P_{male.dep}$, or both (Table 6). For example, under K_{trend}(1) a harvest strategy with $H_{mgmt.interval\ 1}$ = 169 bears/year was associated with $P_{extirpation} \approx 7\%$ and $P_{male.dep} \approx 7\%$. This occurred because of the combined effects of high harvest rates and large sampling uncertainty. Specifically, under Scenario 2 the growth rate r_{MNPL} = 0.044 had a coefficient of variation of approximately 37% (see section "Demographic parameters" in Results). This led to the potential for overharvest due to sampling uncertainty which, in some instances, was sufficiently severe to cause rapid declines in N within a single management interval. Regehr et al. (2017b) also found that lower degrees of risk tolerance relative to Management Objective 1 were necessary to limit the risk of extirpation for subpopulations with high intrinsic growth rates.

It may seem counterintuitive that it was possible to meet Management Objective 2, which required subpopulation size at the end of projections ($N_{t=36}$) to be greater than 90% of subpopulation size at the start of projections ($N_{t=1}$), under some relatively high harvest strategies (Table 6). This outcome was partially due to the choice of relative density (i.e., N/K)

to which the vital rates for Scenario 2 were referenced. Specifically, for Scenario 2 projections started at a subpopulation size corresponding to *MNPL*, which occurs at approximately N/K = 0.70. Harvest levels that were below maximum sustainable yield allowed subpopulation size to increase at the beginning of projections, as N approached K, after which subpopulation size declined over the long term due to projected declines in K. For the projection methods $K_{trend}(1)$ and $K_{trend}(3)$, declines in K were sufficiently gradual that it was possible to meet Management Objective 2 as long as harvest levels were low enough to maintain a high relative density. For example, a harvest strategy with F_O = 1.14 and $H_{mgmt.interval\ 1}$ = 113 bears/year would meet Management Objective 2 at the high risk tolerance under $K_{trend}(1)$ (Table 6). For this harvest strategy, $N_{t=36}/N_{t=1}$ was approximately 0.90, as would be expected based on the definition of Management Objective 2. Results relative to Management Objective 2 should be interpreted with caution because they were sensitive to starting subpopulation density, which could not be estimated for the CS subpopulation.

The second set of simulations demonstrated that shorter management intervals, and higher levels of precision in estimated demographic parameters, can increase long-term sustainable yield (Table 7), with general patterns similar to Scenario 1.

The third set of simulations demonstrated that male-selective harvest can reduce harvest risk (Table 8), with general patterns similar to Scenario 1.

Multiyear quota system

In the first supplemental simulations (SS1), stochastic harvest and use of a MQS did not change the harvest strategies that met management objectives, or have other negative impacts, relative to comparable simulations with deterministic harvest. For example, the probability of failing to meet Management Objective 1, as a function of $H_{yield.index}$, was the same for SS1 as for the first set of simulations for Scenario 1 of the vital rates (Fig. 8).

Within each 5-year period of the MQS harvest levels exhibited a consistent pattern. Over all simulations in SS1, the median harvest level for year *z* of the 5-year period (where *z* = 1, 2, … 5), standardized by dividing by the harvest level in year *z* = 1, was [1.00, 1.15, 1.18, 1.21, 1.15]. This means, for example, that harvest in year *z* = 2 of each 5-year period was approximately 15% higher than harvest in year *z* = 1. This happened because the formula for the MQS did not include a 1.25 multiplier in years *z* = 1 and 5, and because stochastic harvest was constrained to not exceed the upper limits calculated under the MQS (i.e., we assumed that the MQS was followed exactly; see section "Supplemental simulations" in Methods).

Consequences of ineffective harvest management

In the second supplemental simulations (SS2), ineffective harvest management was associated with moderately higher risks of not meeting Management Objective 1, and substantially higher risks of extirpation, compared to state-dependent harvest management (Fig. 9). For example, for Scenario 1 a state-dependent harvest strategy with $H_{mgmt.interval\ 1}$ = 54 bear/year met Management Objective 1 at medium risk tolerance, and was associated with $P_{extirpation}$ < 0.1% (Table 3). In contrast, under ineffective management, a harvest strategy with the same apparent (but not actual) present-day harvest level had a higher probability of failing to meet Management Objective 1 (i.e., 1 - P_{MO1} ≈ 0.50) and was associated with $P_{extirpation}$ ≈ 15% (Fig. 9). This demonstrates the potential risks of incomplete harvest reporting and failure to follow a state-dependent harvest management approach, especially when K is declining and the available estimates of abundance and the vital rates have high uncertainty.

Discussion

In this report we summarize the results of a harvest risk assessment using modern methods together with the first quantitative estimates of abundance and vital rates for the CS polar bear subpopulation. The final results are a series of potential harvest strategies. It is intended that these results, along with other sources of information and considerations such as the level of subsistence need, will help inform the determination of SHL by the Commission.

Determination of sustainable harvest level

We evaluated the biological effects of a wide range of harvest strategies for the purpose of sensitivity analysis. Not all of the strategies represented viable management options. For example, for Scenario 2 of the vital rates, present-day harvest levels above approximately 170 bears/year would likely result in substantial overharvest, resulting in less than a 50% probability of meeting Management Objective 1, reduced harvest levels in future years due to subpopulation depletion, and high risks of extirpation and male depletion (e.g., $P_{extirpation}$ ≈ 7% and $P_{male.dep}$ ≈ 7% for a harvest strategy with the management factor F_O = 1.70; Table 6). Similarly, some of the lower harvest strategies might not be desirable despite being associated with low risks of negative subpopulation outcomes. For example, for Scenario 1 of the vital rates, starting harvest levels below 30 bears/year would have greater than a 90% probability of meeting Management Objective 1 and negligible risks of extirpation or male depletion, but would likely represent a substantial loss of opportunities for sustainable use (Table 3).

The two scenarios of the vital rates used in the harvest assessment, which correspond to a lower and higher demographic status, can be considered together to help narrow the range of potential sustainable harvest strategies. For Scenario 2, the harvest strategy that met Management Objective 1 at low risk tolerance corresponded to a present-day harvest level of 86 bears/year at a 2:1 male-to-female harvest sex ratio (Table 6, sub-table a). If Scenario 2 is an accurate representation of the demographic status of the CS subpopulation, this harvest strategy would be conservative in the sense of having a high probability of meeting objectives, incurring very low risks of negative subpopulation outcomes, and leading to future harvest levels that decline only gradually over time due to projected declines in carrying capacity. What would be the effects on the subpopulation, if this harvest strategy were implemented but Scenario 1 of the vital rates is more accurate? Under Scenario 1, a harvest strategy with a present-day harvest level of 86 bears/year would result in a probability of approximately 0.60 of failing to meet Management Objective 1 (Table 3, sub-table a). Other subpopulation outcomes for this harvest strategy would include $P_{extirpation}$ ≈ 1%, $P_{male.dep}$ ≈ 5%, and a subpopulation size after 35 years that was approximately 70% of starting subpopulation size. These population projections are shown in Figure 10 to help visualize the outcomes. Although a harvest level of 86 bears/year might exceed risk tolerances, if in fact Scenario 1 is an accurate representation of the demographic status of the CS subpopulation, this harvest strategy would be unlikely to cause severe negative effects over the next 35 years. Furthermore, under a state-dependent management approach there will be opportunities to reassess demographic status and, if necessary, adjust the harvest strategy to ensure sustainability.

The results in this report are part of the overall suite of information that the Commission may consider when exercising its responsibility to determine SHL. Our modeling results indicate that plausible lower and upper bounds on SHL might be identified by examining harvest strategies that met Management Objective 1 at medium risk tolerance for the two scenarios of the vital rates. This would result in a range of present-day harvest levels between approximately 50 and 120 bears/year (Tables 3 and 6). Within this range, the risk of negative subpopulation outcomes due to harvest increases with higher harvest levels, and the risk of unnecessarily limiting subsistence opportunities increases with lower harvest levels. Considering results from the two scenarios together, our findings suggest that a harvest strategy with a present-day harvest level in the vicinity of 80 – 90 bears/year, at a 2:1 male-to-female sex ratio, appears likely to meet the definition of SHL in the Agreement at a moderate degree of risk tolerance, assuming that a functional management system is implemented and harvest levels will be updated every 10 years (or more frequently) based on new subpopulation data. For example, a SHL of up to 87 bears/year at a 2:1 male-to-female harvest sex ratio would correspond to a sustainable harvest of up to 29 females and 58 males per year. These findings are conditional on following a state-dependent harvest management approach, with the management and biological conditions identified above, and on defining harvest relative to the CS subpopulation boundary. Harvest levels could be adjusted to accommodate different management or biological conditions (e.g., if the management interval is 15 years rather than 10 years, harvest could be reduced using information in Tables 4 and 7), different risk tolerances, or other factors that might be considered by the Commission but were beyond the scope of our analyses.

It can be useful to evaluate the harvest strategies discussed above in relation to other methods to evaluate take levels, and practical experience with harvest of polar bears. The Potential Biological Removal (PBR) method has been used in the U.S. to identify lethal take limits for marine mammal stocks (Wade 1998). Using the estimate of CS subpopulation size and associated uncertainty from the CS-IPM (Regehr et al. in review), a value of the PBR recovery factor F_r = 0.50 as recommended for threatened stocks or stocks with unknown status (Wade and Angliss 1997), a value of maximum intrinsic growth rate of 6% (e.g., USFWS 2010), and allowing for a 2:1 male-to-female sex ratio in the harvest, produces a calculated PBR level of 54 bears/year. The PBR method was developed in relation to incidental mortality (e.g., due to fisheries by-catch) and does not seek to balance protection of the subpopulation with a desire to provide opportunities for subsistence use. Thus, similarity between the calculated PBR level and a SHL of 50 bears/year (the lower bound discussed above) suggests that this harvest level would be conservative relative to the amount of human-caused mortality that polar bear stocks can support.

We can also evaluate the harvest strategies discussed here in relation to a total harvest rate of 4.5%, at a 2:1 male-to-female harvest sex ratio, which has been used for polar bears under favorable environmental conditions (Taylor et al. 1987) and generally has not been associated with negative subpopulation outcomes (Aars et al. 2006, Obbard et al. 2010, Durner et al. 2018). In this context, 4.5% represents the percentage of total subpopulation size (i.e., including dependent young) removed by humans each year. Although Taylor et al. (1987) suggested that a 4.5% harvest rate corresponds to maximum sustainable yield for polar bears, Regehr et al. (2017b) found that a 4.5% harvest rate was generally reasonable for average subpopulations and that higher rates could be supported under some conditions. Based on the sampling distribution of estimated abundance for the CS subpopulation from the CS-IPM (Regehr et al. in review), harvest strategies with present-day harvest levels of 50, 85, and 120 bears/year would correspond to median total harvest rates of approximately 1.6% (95% CRI = 0.8% – 3.2%), 2.7% (95% CRI = 1.4% – 5.5%), and 3.8% (95% CRI = 2.2% – 7.8%), respectively. The fact that the highest harvest level of 120 bears/year likely corresponds to a total harvest rate below 4.5% suggests that this range of strategies is consistent with harvest practices for other polar bear subpopulations in recent decades. The analytical reasons why this range corresponds to harvest rates below 4.5%, despite signs of productivity for the CS subpopulation, include the low precision of currently available demographic parameters compared to other subpopulations (Regehr et al. 2017b); relatively low survival rates for independent bears that may reflect negative bias or high relative density, the details of which are unknown; and use of a modeling approach that takes into account sea-ice loss due to climate change.

Determination of SHL is a decision for the Commission based on risk tolerances relative to meeting biological management objectives, providing opportunities for subsistence use, and other considerations. Our analyses sought to accurately represent the status of the CS subpopulation and associated uncertainties based on the available information, and did not make purposefully conservative assumptions. First, we used vital rates that were estimated from the Bayesian CS-IPM with informative priors reflecting the assumption that survival of CS bears during the period 2008 – 2016 should be similar to point estimates from other case studies (Regehr et al. in review). This was consistent with other lines of evidence for productivity of the CS subpopulation obtained from scientific studies (e.g., Rode et al. 2014) and TEK (e.g., Braund et al. 2018). Second, we excluded samples of the vital rates that were considered biologically implausible due to large sampling uncertainty. Third, we developed a more optimistic Scenario 2 of the vital rates, also reflecting evidence for subpopulation productivity (see above) as well as potential negative bias in estimates of survival for independent bears from the CS-IPM (Regehr et al. in review). Finally, we represented the future effects of sea-ice loss through density-dependent reductions in carrying capacity only, and did not consider potential density-independent reductions in intrinsic growth rate. Violation of one or more of these assumptions could result in risks of negative subpopulation outcomes that are higher than presented in this report. Methods to mitigate such risks include selecting a harvest strategy corresponding to a low risk tolerance, following a state-dependent approach under which harvest management is directly linked to continued subpopulation monitoring and research, and ensuring accurate reporting of all human-caused removals.

<u>Extension of findings to the Alaska-Chukotka population</u>

Currently available estimates of abundance and vital rates from the CS-IPM (Regehr et al. in review) are spatially referenced to the area within the CS subpopulation boundary as recognized by the PBSG. Analyses in this report, which used data from Regehr et al. (in review), also are referenced to the CS subpopulation and cannot be applied directly to the Alaska-

Chukotka polar bear population as recognized under the Agreement, for several reasons. First, the area to which the Agreement applies is larger than the CS subpopulation area, and likely includes more bears. Second, the Alaska-Chukotka population may have different vital rates, given that information is lacking on the status of the Kara Sea subpopulation to the west (Durner et al. 2018), and the Southern Beaufort Sea subpopulation to the east appears to be experiencing negative effects of sea-ice loss (Regehr et al. 2010, Rode et al. 2014, Bromaghin et al. 2015). Third, anthropogenic factors, including human-caused removal levels, are different for the area to which the Agreement applies, and contemporary data are not available to determine how harvest around the community of Utqiaġvik, Alaska is partitioned between the CS and Southern Beaufort Sea subpopulations.

To determine SHL for the Alaska-Chukotka population as recognized under the Agreement, we suggest first identifying a sustainable harvest strategy for the CS subpopulation based on the findings in this report, then applying the indicated harvest rate to an estimate of abundance for the Alaska-Chukotka population. Estimates of abundance for the Alaska-Chukotka population are difficult to derive, and will likely have larger uncertainty than estimates in Regehr et al. (in review), because some parts of the area to which the Agreement applies, especially regions west of Wrangel Island, were infrequently used by polar bears marked during capture-recapture research in American territory (Wilson et al. 2014, 2016), and concurrent large-scale capture-recapture research was not conducted in Russian territory. Thus, determination of SHL for the Alaska-Chukotka population may warrant a lower degree of risk tolerance to reflect additional uncertainty in the ecological and demographic status of polar bears within the area to which the Agreement applies.

Effects of biological and management conditions on sustainable harvest

Harvest strategies were defined in terms of the key elements that can be identified and adaptively managed, including the harvest rate and harvest level, the sex and age composition of the harvest, the management interval, and the precision of demographic parameter estimates used to inform management. As expected, harvest levels that met management objectives were higher when using vital rates corresponding to a more resilient subpopulation

(Scenario 2) than when using estimated vital rates that likely included negative bias (Scenario 1).

Harvest strategies that met Management Objective 1 had similar present-day harvest levels for the different assumptions for future trends in carrying capacity (K), although harvest levels declined more rapidly over time for the more rapid declines in K (Tables 3 and 6). This suggests that a primary consequence of declining carrying capacity is to reduce future harvest levels, whereas near-term harvest may be less affected if a state-dependent harvest management approach is followed. Our supplemental simulations demonstrated clearly that, if a state-dependent approach is not followed, near-term harvest levels must be reduced substantially to mitigate the risks associated with future declines in K (Fig. 9).

Our simulations illustrated that shorter management intervals, and more precise estimates of subpopulation size and vital rates, can substantially reduce the risk of negative subpopulation outcomes associated with a given harvest strategy. These findings can help managers balance trade-offs between research frequency and intensity (and therefore cost), the sustainable harvest rate, and harvest risks. For example, for Scenario 2, reducing the relative standard deviation in future estimates of demographic parameters by 50%, compared to sampling uncertainty from the CS-IPM (Regehr et al. in review), would lead to a 9% increase in cumulative harvest over the next 35 years without increasing risk (Table 7). However, further reducing sampling uncertainty to 25% of the amount from the CS-IPM would only provide an incremental benefit of a 1% increase in cumulative harvest. Alternatively, keeping sampling uncertainty constant and reducing the management interval from 15 to 10 years would increase cumulative harvest by 7%, and further reducing the management interval to 5 years would provide an additional 8% increase in cumulative harvest. This information can be used in cost-benefit analyses performed as part of research and monitoring planning.

We defined the management interval as the exact number of years between changes to the harvest level. For example, during population projections a 10-year management interval meant that new simulated subpopulation assessments were completed, and changes to the harvest level implemented, every 10 years. In practice, time lags in the coupled research-management system will likely result in departures from this simplified representation. For example, even if changes to SHL are implemented every 10 years, each change might be based on data from subpopulation studies 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 simplified definition used here.

Male-biased harvest is a common wildlife management and conservation tool (Mysterud 2011). For polar bears, seeking to harvest at a 2:1 male-to-female ratio is intended to protect adult females (Taylor et al. 2008), which have the highest reproductive value (Hunter et al. 2007). We found that sustainable harvest levels were moderately higher for harvest strategies that selected for male bears (Tables 5 and 8). In our simulations, however, the benefits of focusing harvest on males were partially offset by Allee effects in the mating system (Molnár et al. 2014). Specifically, when harvest rates were sufficiently high, sex-selective harvest resulted in fewer adult males being available to fertilize females, which caused reductions in breeding probability. These findings do not provide evidence against the conservation value of sex-selective harvest, and should be interpreted with caution given that the matrix projection model included an Allee submodel that was based on generalized mechanisms (Molnár et al. 2014) that have not been investigated for the CS subpopulation.

Similar to some other subpopulations (e.g., Derocher et al. 1997), estimated harvest vulnerability vectors for the CS subpopulation suggested that subadult males are more likely to be harvested than would be expected based on their representation in the subpopulation, and that adult females with dependent young are less likely to be harvested. Accurate information on the sex and age of harvested bears is important for management because of individual differences in reproductive value (e.g., removal of subadult males will generally have less effect on subpopulation growth compared to removal of adult females).

Polar bear harvest levels vary from year to year as a function of environmental conditions, population dynamics (e.g., cohort size, given that younger bears are generally more susceptible to harvest), and other factors (Schliebe et al. 2016). In 2012, the Commission endorsed a multiyear quota system (MQS) as a method to accommodate interannual variation in the availability of polar bears to hunters while ensuring that sustainable harvest levels were followed over a multiyear period (U.S.-Russia Polar Bear Commission 2012). In addition to serving as a conservation tool, the polar bear MQS is appealing to some stakeholders because of its similarity to the block quota system used for bowhead whales (*Balaena mysticetus*) in the U.S. (Suydam et al. 2010). Our findings support that the polar bear MQS can help to accommodate stochasticity in harvest without increasing risk.

Our simulations demonstrated the potentially severe negative consequences of ineffective harvest management. Incomplete harvest reporting and failure to follow a state-dependent harvest management approach, especially when demographic parameters are uncertain and environmental conditions are changing, can substantially increase the risk of negative subpopulation outcomes, including extirpation. We recommend that future analyses explore the broader effects of incomplete harvest reporting, which include loss of biological data from harvest samples and potential mischaracterization of demographic status of the subpopulation (e.g., bias in estimates of unharvested survival, a critical input to the harvest risk assessment, could result from biased estimates of harvest mortality caused by incomplete reporting).

Management objectives

Management Objective 1 sought to keep the subpopulation size greater than maximum net productivity level (*MNPL*). This objective was included in the U.S. Polar Bear Conservation Management Plan (USFWS 2016) as MMPA Demographic Criterion 2. It is designed to maintain subpopulations on the right side of the harvest "yield curve" (Appendix C in USFWS 2016), which protects against overharvest while allowing the possibility for harvest levels to approach maximum sustainable yield. Because *MNPL* is defined relative to carrying capacity, which may change over time, this objective accommodates potential changes in environmental conditions.

Harvest strategies that meet Management Objective 1 will satisfy the requirement of not exceeding "net annual recruitment to the population", per the definition of SHL in the Agreement, when subpopulation size is near *MNPL*. The definition of SHL also includes the objective of maintaining abundance "at or near its current level" while considering the "status and trend of the population". We interpreted this language as defining SHL relative to a biologically-meaningful abundance level (i.e., *MNPL*), and not a static abundance level (at an unspecified point in time) that does not take into account relative density or other aspects of subpopulation status. Harvest strategies that meet Management Objective 1 represent a sound method to ensure that harvest does not have an additive negative impact on subpopulations when abundance is changing for reasons other than harvest (e.g., habitat loss), which we interpreted as consistent with the requirement to consider the “trend of the population”. Furthermore, Management Objective 1 was developed to be consistent with the intention that the definition of SHL in the Agreement (Article-by-Article Analysis; United States T. Doc. 107-10) should be compatible with Article II of the *1973 Agreement on the Conservation of Polar Bears*, which stipulates that countries “shall manage polar bear populations in accordance with sound conservation practices based on the best available scientific data”.

Management Objective 2 sought to keep the subpopulation size greater than 90% of its starting value, which in our analyses was the multiyear average estimate of abundance for the period 2008 – 2016 (Regehr et al. in review). Management Objective 2 is a narrower interpretation of SHL that is referenced to a static abundance level. Consequently, harvest strategies that meet this objective could result in undesirable outcomes under some conditions. For example, Management Objective 2 could allow high-risk harvest strategies that maintain a subpopulation on the left side of the yield curve, if relative density was low at the time that management started (e.g., due to overharvest at an earlier point in time). Similarly, this objective could require very restrictive harvest strategies that maintain subpopulation size on the far right side of the yield curve (i.e., near carrying capacity), if relative density was high at the time that management started (e.g., due to conservative harvest practices prior to obtaining reliable biological information). Furthermore, Management Objective 2 does not allow for changing environmental conditions. If subpopulation size were to decline for reasons other than harvest (e.g., due to habitat loss), this objective could effectively permit zero harvest once abundance dropped below 90% of its starting value. Our simulations demonstrated that evaluating sustainable harvest relative to Management Objective 2 is sensitive to subpopulation density at the start of projections, which presents challenges because relative density is difficult to estimate. In combination, we suggest these considerations limit the usefulness of Management Objective 2. We therefore focused on Management Objective 1 when evaluating the sustainability of different harvest strategies.

In the future, harvest risk assessments for CS polar bears could consider additional management objectives, including those based on conservation or management criteria other than the definition of SHL. Specifically, the Agreement seeks to provide Alaskan and Chukotkan Native people with the opportunity to harvest polar bears for subsistence purposes in a sustainable manner. Meeting nutritional and cultural needs through harvest is also a Fundamental Goal in the U.S. Polar Bear Conservation Management Plan (USFWS 2016), and responsible subsistence harvest is recognized as an important part of conservation for polar bears and other marine mammals (Laidre et al. 2015). In this report, levels of subsistence need were not directly incorporated into analyses. We suggest this as an area for future work. For example, it may be possible for responsible organizations to estimate subsistence need based on input from communities and hunters in Alaska and Chukotka, examination of past harvest levels, or other methods. If the level of subsistence need is quantified, the probability that harvest strategies will meet needs could be included as a quantitative output from a harvest risk assessment (e.g., IWC 2018). Furthermore, understanding trends in subsistence need could help inform whether the ability to meet needs might change over time, for example in relation to habitat change. This information could help the Commission identify appropriate harvest strategies while avoiding unnecessarily high values of SHL that may be biologically feasible but exceed the capacity for subsistence use.

Demographic status of the Chukchi Sea subpopulation

The observed growth rate of -0.008, estimated directly from the vital rates from the CS-IPM (Regehr et al. in review), suggests that the CS subpopulation was stable or slightly declining during the period 2008 – 2016. However, if estimates of survival for independent bears were negatively biased (see section “2. Demographic parameters” in Methods), this and other estimates of growth rate would be negatively biased as well. To accommodate suspected bias, we evaluated harvest under two scenarios of the vital rates, which also used different approaches to specify relative density. For Scenario 1, the corresponding growth rate referenced to a relative density at *MNPL* (r_{MNPL}) was 0.020, suggesting a relatively limited capacity for growth in the absence of harvest compared to other subpopulations (Regehr et al. 2017b). In addition to potential bias in estimates of survival, interpretation of this growth rate is complicated by lack of direct information on the relative density of the CS subpopulation. For example, if relative density is currently high (i.e., N >> *MNPL*), subpopulation growth in the absence of harvest would naturally be low because of crowding and competition. Although the SWG recently considered it likely that the CS subpopulation size is above *MNPL* (SWG 2018) due to the combination of low apparent harvest rates and the effects of habitat loss, this has not been tested directly. Conceptually, we suggest that Scenario 1 likely represents a lower bound for the demographic status of the CS subpopulation during the period 2008 – 2016.

Scenario 2 of the vital rates resulted in r_{MNPL} = 0.044 after exclusion of implausible samples of the vital rates. The methods used to adjust survival rates for independent bears under Scenario 2 preserved the variance of the original parameter estimates from the CS-IPM. By design, this growth rate was similar to the average capacity for growth of other polar bear subpopulations (Regehr et al. 2017b). Scenario 2 reflects the possibility that low estimates of survival in Regehr et al. (in review) were the result of either negative bias or high relative density (i.e., $N/K \rightarrow 1$), in which case the subpopulation would be capable of typical growth if density was reduced. We suggest that Scenario 2 is a more plausible representation of the demographic status of the CS subpopulation from 2008 – 2016, on the basis of multiple lines of evidence. Specifically, reproductive parameters are average-to-high for the species (Regehr et al. in review), indices of recruitment for the CS subpopulation are similar to values from the 1980s and 1990s (Rode et al. 2014, Regehr et al. in review), body condition appears stable or improved in recent years (Rode et al. 2014), availability and access to prey have been maintained in the spring (Rode et al. 2017), observations from TEK indicate healthy bears in western Alaska (Braund et al. 2018), and the status of ice-dependent seals in the region appears positive (Crawford et al. 2015).

It is possible that the CS subpopulation was capable of stronger growth than indicated by Scenario 2 during the period 2008 – 2016, and that it will remain so for some years into the future. For example, an intrinsic growth rate of approximately 8% was estimated for the Baffin

Bay subpopulation (Regehr et al. 2017) which, similar to the CS subpopulation, inhabits a biologically productive region but also is showing ecological effects of sea-ice loss (Scientific Working Group to the Canada-Greenland Joint Commission on Polar Bear 2016). Lacking quantitative evidence for stronger-than-average growth for the CS subpopulation, however, we did not evaluate higher scenarios of the vital rates than Scenario 2. This decision was supported by the fact that the CS region is experiencing high rates of sea-ice loss due to climate change (Stern and Laidre 2016), which has been identified as the primary threat to polar bears (Atwood et al. 2016). During the period 1979 – 2014, the open-water period in the CS region increased by 80 days (Serreze et al. 2016), and declines in summer sea-ice extent are projected to continue (Douglas 2010). Ecological effects of habitat change on the CS subpopulation have been documented (Rode et al. 2015) and the future demographic effects of sea-ice loss are uncertain, but likely negative. Thus, even if Scenario 2 was a more accurate representation of the CS subpopulation during the period 2008 – 2016, it is possible that density-independent limitation resulting from climate change will reduce intrinsic growth rates in coming decades, resulting in conditions more similar to Scenario 1.

The Agreement stipulates that conservation and management of CS polar bears should be based on reliable biological information, including "scientific data and traditional knowledge of native people". Accordingly, Braund et al. (2018) completed a pilot TEK study based on interviews with experienced polar bear hunters in western Alaska. The content and structure of this study were established, in part, through correspondence with the SWG to identify the types of information that could be useful to parameter estimation and management models for polar bears. Although it was a pilot study and sample sizes were small, findings from Braund et al. (2018) were consistent with the choice of informative priors in the Bayesian CS-IPM used to estimate demographic parameters (Regehr et al. in review) and with previously documented TEK (Voorhees et al. 2014). To our knowledge, this is the first example of referencing TEK in a subpopulation assessment for polar bears using a Bayesian approach to parameter estimation. We suggest continued work on how TEK can be collected in a systematic and reproducible manner that facilitates its use in quantitative subpopulation studies and harvest risk assessments.

Environmental variation

Our projection methods for carrying capacity (K) were not based on an explicit model of polar bear nutrition or demography in relation to sea-ice change (e.g., Molnár et al. 2011). Nonetheless, we suggest that the three methods represent a useful range of assumptions for how and when climate change could affect the demography of CS bears, for the purpose of evaluating the interactive effects of habitat loss and harvest. The most pessimistic projection method, $K_{trend}(2)$, reflected continuation of the relatively rapid sea-ice loss observed since the year 2000 (Frey et al. 2015). This projection method corresponded to reductions in K of approximately 9% per decade. The most optimistic projection method, $K_{trend}(3)$, reflected a stable K until 2036, followed by declines. Near-term stability in K is plausible based on evidence from nutritional studies (Rode et al. 2014), demography (Regehr et al. in review), and TEK (Braund et al. 2018) that the CS subpopulation has, to date, remained productive despite sea-ice loss. Choice of 2036 as a transition point was informed by sea-ice forecasts from general circulation models (Douglas and Atwood 2017) to evaluate when the duration of the ice-free season may exceed thresholds likely to cause negative nutritional effects for polar bears (Robbins et al. 2012).

Our model did not consider more rapid declines in K, density-independent declines in intrinsic growth rate, or catastrophic event (e.g., Derocher et al. 2013), although the framework could readily be extended to consider these and other factors. If the CS subpopulation experiences negative density-dependent effects that are larger or more abrupt than represented in our analyses, 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 in this report might cease to meet management objectives and might result in higher risks of negative subpopulation outcomes. A state-dependent management approach with accurate harvest reporting and a relatively short management interval (e.g., 10–15 years), potentially combined with an ongoing monitoring program that is capable of detecting large demographic shifts in near real time, can mitigate such risks. The tradeoff associated with such a robust approach is the requirement to devote greater resources to monitoring and large-scale subpopulation studies. Population dynamics and harvest strategies for declining populations are reviewed in detail in USFWS (2016).

Regehr et al. (2017b) subjectively partitioned total uncertainty in estimated demographic parameters as 75% sampling uncertainty and 25% process variation (Taylor et al. 2002), with the process variation implemented as density-independent stochastic variation in the vital rates. In this report, we considered all uncertainty in estimated demographic parameters, after exclusion of biologically implausible samples, to be sampling uncertainty. Process variation was included in population projections by simulating uncertainty in the slope and residual standard errors of the proxy for K. At each time step, process variation operated on the vital rates through the density-dependent functions. The amount of process variation differed across projection methods for K, and was highest for $K_{trend}(2)$, which was based on a linear model fitted to sea-ice data from 2000 – 2016 (Fig. 2). In future demographic analyses with larger sample sizes, it may be possible to delineate sampling and process variation within the parameter estimation framework.

Research and monitoring

The harvest strategies evaluated in this report require the existence of a coupled research-management system under which both the harvest rate and the harvest level are adjusted periodically, based on new information from subpopulation assessments, TEK, and other sources. Although we evaluated the effects of different management intervals and levels of precision in demographic parameters, we did not consider the practical aspects of research and monitoring. For example, if future budgetary or logistical constraints (e.g., stability of the sea-ice platform) do not permit studies of individually-marked animals similar to recent capture-recapture research in the U.S. (Regehr et al. in review), quantitative estimates of vital rates may not be available. Conversely, new research methods might lead to more accurate and efficient estimates of some demographic parameters, such as subpopulation abundance (e.g., Conn et al. 2016). Determination of SHL for the CS subpopulation should be based on a realistic assessment of future research and monitoring activities. Furthermore, we suggest that the SWG consider examining a suite of low-cost monitoring tools that could be used on an ongoing basis to identify changes in demographic status that might necessitate a change in the harvest strategy (e.g., a reduction in harvest level or a shortening of the management interval between large-scale subpopulation studies). Potential monitoring techniques include tracking trends in sea-ice habitat, obtaining indices of nutritional condition and reproductive rates from research and harvest data, community-based observations, and systematic and repeatable TEK studies. Given that polar bears are among the most-studied Arctic marine mammals (Laidre et al. 2015), it may be possible to estimate relationships between metrics that are relatively easy to obtain (e.g., reproductive indices) and less tractable demographic parameters (e.g., maximum intrinsic growth rate), based on a meta-analysis of existing case studies (Vongraven et al. 2012). This could help to identify values of intrinsic growth rate to use in harvest risk assessments when accurate estimates of vital rates are lacking.

Conclusions

- The Commission is responsible for determining SHL based on risk tolerances relative to meeting biological management objectives, meeting subsistence need, and other factors. It is intended that this report, along with other sources of information and considerations, help inform the Commission's determination of SHL.
- Several lines of evidence from scientific studies and TEK suggest that the CS polar bear subpopulation was productive during the period 2008 – 2016.
- The CS region has experienced rapid sea-ice loss that is projected to continue. Ecological effects of sea-ice loss on CS polar bears have been documented, and negative demographic effects are likely to occur in the future. However, the functional relationships between sea-ice dynamics and demographic status for polar bears are not completely understood.
- The first quantitative estimates of abundance and vital rates for the CS subpopulation were recently obtained from capture-recapture research conducted in American territory. Total abundance for the area within the CS subpopulation boundary, as recognized by the PBSG, was approximately 2,937 bears (95% CRI = 1,552 – 5,944). Because the newly available demographic parameters were referenced to the CS subpopulation, findings in this report

also are referenced to the CS subpopulation, and would require modification if applied to the Alaska-Chukotka polar bear population as recognized under the Agreement.

- We performed a harvest risk assessment for the CS subpopulation using modern methods that consider the effects of climate change. We evaluated a range of potential harvest strategies and presented results as the probability of meeting management objectives based on the definition of SHL in the Agreement, as well as the probabilities of achieving other subpopulation outcomes (e.g., extirpation).
- Our findings suggest plausible lower and upper bounds on present-day harvest levels of approximately 50 and 120 bears/year, respectively. Within this range, the risk of negative subpopulation outcomes due to harvest increases with higher harvest levels, and the risk of unnecessarily limiting subsistence opportunities increases with lower harvest levels. The entire range of 50 to 120 bears/year likely corresponds to a total harvest rate less than 4.5%, which has been commonly used for polar bear subpopulations under favorable environmental conditions. Considering the assumptions and results of the harvest risk assessment in aggregate, harvest strategies with a present-day harvest level in the vicinity of 80 to 90 bears/year, at a 2:1 male-to-female sex ratio, would likely meet the definition of SHL in the Agreement at a moderate degree of risk tolerance with respect to the biological effects of harvest. This assumes that a functional management system is implemented and that harvest levels will be updated every 10 years based on new subpopulation data. If ongoing sea-ice loss results in declining carrying capacity for polar bears, which is expected based on scientific studies, the sustainable harvest level would decline in coming decades.
- All harvest strategies in this report require a state-dependent approach under which the harvest rate and harvest level are updated periodically based on new subpopulation data, according to a predefined management interval (i.e., the number of years elapsed between reassessments of harvest). Shorter management intervals and more precise subpopulation data can reduce harvest risk. Determination of SHL should be based on a realistic assessment of future research, monitoring, and management conditions. Our analyses sought to accurately represent the status of the CS subpopulation and associated

uncertainties based on the available information, and did not make purposefully conservative assumptions.

- Incomplete harvest reporting and failure to follow a state-dependent harvest management approach can lead to a much higher risk of negative subpopulation outcomes, including extirpation. This is especially true when habitat is changing, and current subpopulation data have large uncertainty, which are both the case for the CS subpopulation.

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Tables and Figures

Table 1. Abbreviations, parameters, and indexing definitions used in the harvest risk assessment for the Chukchi Sea polar bear subpopulation.

Term	Definition
A_{MQS}	A parameter in the multiyear quota system. Total number of harvest credits over a 5-year period.
Agreement	A bilateral treaty between the U.S. and Russia entitled the *Agreement between the Government of the United States of America and the Government of the Russian Federation on the Conservation and Management of the Alaska-Chukotka Polar Bear Population*.
Alaska-Chukotka population	The Alaska-Chukotka population of polar bears, as recognized under the Agreement. The area of the Alaska-Chukotka population is larger than, and encompasses, the boundaries of the Chukchi Sea subpopulation as recognized by the Polar Bear Specialist Group.
β_i	Breeding probability, defined as the probability, conditional on survival, of an individual in life-cycle stage *i* breeding and producing a litter of cubs-of-the-year, with at least one member of the litter surviving until the next year (Figure 1).
B_z	A parameter in the multiyear quota system. Number of harvest credits remaining in a 5-year period at the beginning of year *z*.
C_z	A parameter in the multiyear quota system. Average number of harvest credits remaining per year within a 5-year period, at the beginning of year *z*.
C0	Cub-of-the-year, defined as a polar bear less than one year of age and dependent upon its mother for survival. In the polar bear life cycle it is assumed that C0 are born on 01 January of each year.
C1	Yearling, defined as a polar bear between 1 and 2 years of age, and dependent upon its mother for survival.
C2	Two-year-old, defined as a polar bear between 2 and 3 years of age. Polar bears are typically weaned during the spring of their second year.
Commission	Four-member Commission consisting of federal and Native representatives from the U.S. and Russia, as established under the Agreement.
CS-IPM	Integrated population model used to estimate abundance and vital rates for the Chukchi Sea polar bear subpopulation from capture-recapture, radiotelemetry, and count data collected during research studies, 2008 – 2016 (Regehr et al. In review).
CS	Chukchi Sea
CS subpopulation	The Chukchi Sea subpopulation of polar bears, as recognized by the Polar Bear Specialist Group (PSBG) of the International Union for the Conservation of Nature. In report we follow the example of the PBSG by referring to polar bear "subpopulations", except when using common terminology (e.g.,

	"population projections") or when referring to the "Alaska-Chukotka population" as recognized under the Agreement. The boundaries of the CS subpopulation are encompassed by the area of the Alaska-Chukotka population as recognized under the Agreement.
D_z	A parameter in the multiyear quota system. Maximum harvest level for year *z* of a 5-year period.
f	The average number of two-year-old polar bears in a litter of yearlings that survives (Figure 1).
F_O	A factor used to calculate harvest level under a state-dependent harvest management approach. Specified values of F_O directly adjust the harvest rate, reflecting management objectives and the risk tolerance of managers with respect to harvest.
H	Harvest level, measured in numbers of independent polar bears. Superscripts "female" and "male" are used to indicate sex-specific harvest levels.
$H_{mgmt.interval\ 1}$	Annual harvest level (bears/year) during the first management interval of a population projection. Conceptually, $H_{mgmt.interval\ 1}$ represents the present-day harvest level associated with a given management strategy.
$H_{mgmt.interval\ 2}$	Median annual harvest level (bears/year) during the second management interval of a population projection.
$H_{t=18}$	Median annual harvest level (bears/year) at time step t = 18 of a population projection.
$H_{t=36}$	Median annual harvest level (bears/year) at time step t = 36 of a population projection.
$H_{yield.index}$	Median annual harvest, averaged over all time steps from t = 2 to 36 of a population projection.
Independent bears	Polar bears age ≥ 2 years. Includes all polar bears in a subpopulation except for yearlings and cubs-of-the-year.
K	Carrying capacity, defined as the maximum number of individuals in a subpopulation that can be supported by the environment. In this report, K is measured in numbers of independent polar bears. Within the matrix projection model K is converted to metabolic energetic equivalents for the purpose of tracking subpopulation density relative to carrying capacity.
K_{trend}(1)	Method to project the proxy for carrying capacity (K) forward in time based on the entire available time series of ice-covered days from satellite observations, 1979 – 2016.
K_{trend}(2)	Method to project the proxy for carrying capacity (K) forward in time based on the time series of ice-covered days from satellite observations for the period 2000 – 2016.
K_{trend}(3)	Method to project the proxy for carrying capacity (K) forward for years t = 1 to 17 using the estimated variance from projection method K_{trend}(2), but with slope set to 0, followed by a linear projection for the years t = 18 to 36 using both the estimated variance and slope from K_{trend}(2)..

mee	Metabolic energetic equivalent value, defined as the energetic requirements of an individual bear, expressed relative to the energetic requirements of an average adult female, as presented in Regehr et al. (2017b). Larger bears (e.g., adult males) have higher *mee* values that smaller bears (e.g., subadult females), and therefore occupy more "energetic space" and make a greater individual contribution to density effects.
mgmt.interval	Management interval, defined as the number of years between successive subpopulation studies and changes to the calculated harvest level based on updated estimates of abundance and vital rates.
MQS	Multiyear quota system
N	Subpopulation size, measured in numbers of polar bears.
$\widetilde{N}$	An estimate of subpopulation size selected as the 15th percentile of its sampling distribution, used to calculate harvest level under a state-dependent harvest management approach.
$P_{extirpation}$	Probability of extirpation, defined as the subpopulation size falling below a quasi-extinction threshold of 100 independent bears.
$P_{male.dep}$	Probability of male depletion, defined as less than 50 adult males in life-cycle stage 10 (Figure 1).
P_{MO1}	Probability of meeting Management Objective 1, defined as maintaining a harvested subpopulation at an equilibrium size greater than maximum net productivity level.
P_{MO2}	Probability of meeting Management Objective 2, defined as maintaining a harvested subpopulation at an equilibrium size greater than 90% of starting subpopulation size.
PBSG	Polar Bear Specialist Group of the International Union for the Conservation of Nature
r	Population growth rate. The maximum intrinsic growth rate (r_{max}) occurs at a low density relative to carrying capacity. The growth rate at a density referenced to maximum net productivity level is denoted r_{MNPL}. Values of r refer to unharvested, potential growth rates that provide measures of the resilience of a subpopulation.
$\tilde{r}_{MNPL}$	An estimate of population growth rate referenced to a relative density corresponding to *MNPL* and selected as the 50th percentile of its sampling distribution, used to calculate harvest level under a state-dependent harvest management approach.
risk.tol	Placeholder degree of risk tolerance, which specifies the required probability of meeting a management objective. For example, a harvest strategy that met a management objective at *risk.tol* = 0.10, would have less than a 10% probability of failing to meet the management objective (in other words, more than a 90% probability of successfully meeting the objective).
σ_i	Annual probability of unharvested survival of an individual polar bear in life-cycle stage *i* (Figure 1).

σ_{L0}	Annual probability that at least one member of a litter of cubs-of-the-year survives, conditional on survival of the mother (Figure 1).
σ_{L1}	Annual probability that at least one member of a litter of yearlings survives, conditional on survival of the mother (Figure 1).
σ^{total}	Total survival, defined as the annual probability of remaining alive, considering all sources of mortality, and not permanently emigrating from the study area.
SHL	Sustainable harvest level. This is a biological term, defined in the Agreement as "a harvest level which does not exceed net annual recruitment to the population and maintains the population at or near its current level, taking into account all forms of removal, and considers the status and trend of the population".
SR	A factor that specifies the male-to-female ratio in removals (e.g., *SR* = 2.0 indicates a 2:1 male-to-female harvest ratio).
State-dependent harvest management	An approach to harvest management under which harvest depends on the current status (i.e., "state") of a subpopulation. Under state-dependent harvest management, harvest levels are updated periodically (e.g., every 10 years) based on new estimates of abundance and vital rates obtained from scientific studies.
TEK	Traditional ecological knowledge
USFWS	U.S. Fish and Wildlife Service
<u>Indexing notation</u>	
i	Life-cycle stage defining the sex, age, or reproductive status of an individual polar bears, i = 1, 2, …, 10 (Figure 1).
t	Year. When used to reference annual time steps during subpopulation projections, t = 1, 2, …, T.
y	Number of years remaining in a 5-year period of the multiyear quota system, y = 1,2 , …, 5.
z	Current year in a 5-year period of the multiyear quota system, z = 1, 2, …, 5.

Table 2. Estimates of unharvested survival for the Chukchi Sea polar bear subpopulation. Estimates were derived by adjusting estimates of total survival from Regehr et al. (In review) using estimates of harvest mortality rate (this report). Survival probability σ_i is the annual probability of survival of an individual in stage *i*, as defined in the life-cycle graph underlying the matrix projection model (Fig. 1). Values are reported as the mode and 95% credible intervals (CRI) for consistency with Regehr et al. (In review).

	Scenario 1				**Scenario 2**		
	mode	**CRI_{lower}**	**CRI_{upper}**		**mode**	**CRI_{lower}**	**CRI_{upper}**
σ_1	0.82	0.70	0.91		0.88	0.75	0.94
σ_2	0.82	0.70	0.91		0.88	0.75	0.94
σ_3	0.91	0.88	0.95		0.94	0.90	0.97
σ_4	0.91	0.88	0.95		0.94	0.90	0.97
σ_5	0.91	0.88	0.95		0.94	0.90	0.97
σ_6	0.91	0.88	0.95		0.94	0.90	0.97
σ_7	0.75	0.63	0.86		0.83	0.69	0.92
σ_8	0.75	0.63	0.86		0.83	0.69	0.92
σ_9	0.75	0.63	0.86		0.83	0.69	0.92
σ_{10}	0.91	0.85	0.96		0.94	0.88	0.98

Table 3. Subpopulation outcomes for harvest strategies that met management objectives at the placeholder degrees of risk tolerance, from the first set of simulations using Scenario 1 of the vital rates. Sub-tables a), b), and c) show results for the three methods used to project the proxy for carrying capacity $K_{trend}(1)$, $K_{trend}(2)$, and $K_{trend}(3)$, respectively. Values of the management factor (F_O) in the first row of each sub-table correspond to the harvest strategy that met Management Objective 1 or Management Objective 2, at the specified degree of risk tolerance (*risk.tol* = 0.10, 0.30, and 0.50). Values in subsequent rows are subpopulation outcomes for that management strategy, as defined in the main text and Table 1. The row with gray highlighting shows the harvest level (bears/year) during the first management interval ($H_{mgmt.interval\ 1}$), which would be the present-day harvest level for that strategy. The symbol "-" indicates that no positive harvest met the management objective at the specified degree of risk tolerance. All simulations used *SR* = 2.0, *mgmt.interval* = 10 years, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

a) $K_{trend}(1)$	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.83	1.27	1.68		-	0.73	1.10
$H_{mgmt.interval\ 1}$	36	55	72		-	31	48
$H_{mgmt.interval\ 2}$	32	47	59		-	28	42
$H_{t=18}$	32	47	59		-	28	42
$H_{t=36}$	28	37	39		-	24	34
$H_{yield.index}$	36	52	63		-	32	46
$P_{extirpation}$	0.000	0.001	0.003		-	0	0
$P_{male.dep}$	0.004	0.013	0.032		-	0.002	0.009

Table 3 continued

b) K_{trend}(2)	Management Objective 1				Management Objective 2		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.77	1.39	1.96		-	-	0.41
$H_{mgmt.interval\ 1}$	33	60	85		-	-	17
$H_{mgmt.interval\ 2}$	27	48	61		-	-	14
$H_{t=18}$	27	48	61		-	-	14
$H_{t=36}$	19	29	29		-	-	10
$H_{yield.index}$	31	52	64		-	-	16
$P_{extirpation}$	0.000	0.001	0.009		-	-	0
$P_{male.dep}$	0.014	0.034	0.067		-	-	0.004
c) K_{trend}(3)	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.76	1.24	1.69		0.29	0.95	1.28
$H_{mgmt.interval\ 1}$	33	53	73		12	41	55
$H_{mgmt.interval\ 2}$	30	47	58		10	38	48
$H_{t=18}$	30	47	58		10	38	48
$H_{t=36}$	27	39	42		9	33	40
$H_{yield.index}$	34	53	65		12	43	54
$P_{extirpation}$	0.000	0.001	0.002		0	0	0.001
$P_{male.dep}$	0.002	0.009	0.027		0	0.004	0.011

Table 4. Proportional change in subpopulation outcomes as a function of the management interval and level of precision in demographic parameters from future subpopulation studies, from the second set of simulations using Scenario 1 of the vital rates. Proportional change is defined relative to a baseline harvest strategy with a management interval (*mgmt.interval*) of 10 years, and a level of precision similar to currently available parameter estimates from Regehr et al. (In review) as indicated by *rsd.mod* = 1.0. Subpopulation outcomes, which are defined in the main text, correspond to harvest strategies that would be considered sustainable if accepting a 30% chance of failing to meet Management Objective 1 (i.e., *risk.tol* = 0.30). Across simulations, harvest strategies differed in the specified values of the management factor F_O, *mgmt.interval*, and *rsd.mod*. All simulations used $K_{trend}(1)$ and *SR* = 2.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

$H_{mgmt.interval\ 1}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	-0.24	-0.27	-0.29
0.50	-0.16	-0.20	-0.24
1.00	0.11	0.00	-0.07
$H_{mgmt.interval\ 2}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.38	0.36	0.32
0.50	0.28	0.28	0.19
1.00	0.11	0.00	-0.11
$H_{t=18}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.43	0.36	0.32
0.50	0.32	0.28	0.19
1.00	0.06	0.00	-0.11

Table 4 continued

$H_{t=36}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.67	0.56	0.44
0.50	0.53	0.39	0.31
1.00	0.22	0.00	-0.08
$H_{yield.index}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.23	0.12	0.02
0.50	0.19	0.10	-0.02
1.00	0.12	0.00	-0.08

Table 5. The effects of harvest sex ratio on sustainable harvest levels, from the third set of simulations using Scenario 1 of the vital rates. Sub-tables a), b), and c) show results for a male-to-female ratio in human-caused removals corresponding to *SR* = 1.0, 1.5, and 2.0, respectively. Values of the management factor (F_O) in the first row of each sub-table correspond to the harvest strategy that met Management Objective 1 or Management Objective 2, at the specified degree of risk tolerance (*risk.tol* = 0.10, 0.30, and 0.50). Values in subsequent rows are subpopulation outcomes for that management strategy, as defined in the main text and Table 1. The row with gray highlighting shows the harvest level (bears/year) during the first management interval ($H_{mgmt.interval\ 1}$), which would be the present-day harvest level for that strategy. The symbol "-" indicates that no positive harvest met the management objective at the specified degree of risk tolerance. All simulations used *SR* = 2.0, *mgmt.interval* = 10 years, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

a) *SR* = 1.0	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	1.11	1.71	2.27		-	0.92	1.50
$H_{mgmt.interval\ 1}$	31	49	66		-	26	43
$H_{mgmt.interval\ 2}$	24	36	42		-	20	32
$H_{t=18}$	24	36	42		-	20	32
$H_{t=36}$	21	27	29		-	18	25
$H_{yield.index}$	29	43	51		-	24	38
$P_{extirpation}$	0.000	0.000	0.002		-	0	0
$P_{male.dep}$	0.000	0.001	0.004		-	0	0

Table 5 continued

b) *SR* = 1.5	Management Objective 1				Management Objective 2		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.96	1.46	1.95		-	0.79	1.30
$H_{mgmt.interval\ 1}$	35	52	70		-	28	46
$H_{mgmt.interval\ 2}$	29	42	52		-	24	37
$H_{t=18}$	29	42	52		-	24	37
$H_{t=36}$	24	33	37		-	19	31
$H_{yield.index}$	33	48	58		-	27	43
$P_{extirpation}$	0.000	0.000	0.002		-	0	0
$P_{male.dep}$	0.001	0.006	0.016		-	0.001	0.004
c) *SR* = 2.0	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.83	1.27	1.68		-	0.73	1.10
$H_{mgmt.interval\ 1}$	36	55	72		-	31	48
$H_{mgmt.interval\ 2}$	32	47	59		-	28	42
$H_{t=18}$	32	47	59		-	28	42
$H_{t=36}$	28	37	39		-	24	34
$H_{yield.index}$	36	52	63		-	32	46
$P_{extirpation}$	0.000	0.001	0.003		-	0	0
$P_{male.dep}$	0.004	0.013	0.032		-	0.002	0.009

Table 6. Subpopulation outcomes for harvest strategies that met management objectives at the placeholder degrees of risk tolerance, from the first set of simulations using Scenario 2 of the vital rates. Sub-tables a), b), and c) show results for the three methods used to project the proxy for carrying capacity $K_{trend}(1)$, $K_{trend}(2)$, and $K_{trend}(3)$, respectively. Values of the management factor (F_O) in the first row of each sub-table correspond to the harvest strategy that met Management Objective 1 or Management Objective 2, at the specified degree of risk tolerance (*risk.tol* = 0.10, 0.30, and 0.50). Values in subsequent rows are subpopulation outcomes for that management strategy, as defined in the main text and Table 1. The row with gray highlighting shows the harvest level (bears/year) during the first management interval ($H_{mgmt.interval\ 1}$), which would be the present-day harvest level for that strategy. The symbol "-" indicates that no positive harvest met the management objective at the specified degree of risk tolerance. All simulations used *SR* = 2.0, *mgmt.interval* = 10 years, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

a) $K_{trend}(1)$	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.87	1.24	1.70		0.50	0.86	1.14
$H_{mgmt.interval\ 1}$	86	123	169		50	86	113
$H_{mgmt.interval\ 2}$	79	96	91		44	78	94
$H_{t=18}$	79	96	91		44	78	94
$H_{t=36}$	70	85	78		39	70	83
$H_{yield.index}$	84	106	116		49	84	102
$P_{extirpation}$	0.001	0.012	0.070		0	0.001	0.008
$P_{male.dep}$	0.005	0.025	0.069		0.001	0.005	0.018

Table 6 continued

b) K_{trend}(2)	Management Objective 1				Management Objective 2		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.76	1.24	1.75		-	-	0.32
$H_{mgmt.interval\ 1}$	74	123	174		-	-	32
$H_{mgmt.interval\ 2}$	65	93	87		-	-	26
$H_{t=18}$	65	92	87		-	-	26
$H_{t=36}$	48	66	59		-	-	19
$H_{yield.index}$	68	100	111		-	-	29
$P_{extirpation}$	0.001	0.013	0.081		-	-	0
$P_{male.dep}$	0.014	0.050	0.098		-	-	0.002
c) K_{trend}(3)	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.87	1.25	1.74		0.68	1.05	1.42
$H_{mgmt.interval\ 1}$	86	124	172		67	104	141
$H_{mgmt.interval\ 2}$	81	98	90		64	92	100
$H_{t=18}$	81	98	90		64	92	100
$H_{t=36}$	76	92	83		61	87	93
$H_{yield.index}$	89	111	120		70	101	117
$P_{extirpation}$	0.001	0.013	0.078		0	0.003	0.027
$P_{male.dep}$	0.004	0.022	0.067		0.002	0.011	0.034

Table 7. Proportional change in subpopulation outcomes as a function of the management interval and level of precision in demographic parameters from future subpopulation studies, from the second set of simulations using Scenario 2 of the vital rates. Proportional change is defined relative to a baseline harvest strategy with a management interval (*mgmt.interval*) of 10 years, and a level of precision similar to currently available parameter estimates from Regehr et al. (In review) as indicated by *rsd.mod* = 1.0. Subpopulation outcomes, which are defined in the main text, correspond to harvest strategies that would be considered sustainable if accepting a 30% chance of failing to meet Management Objective 1 (i.e., *risk.tol* = 0.30). Across simulations, harvest strategies differed in the specified values of the management factor F_O, *mgmt.interval*, and *rsd.mod*. All simulations used $K_{trend}(1)$ and *SR* = 2.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

$H_{mgmt.interval\ 1}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	-0.24	-0.28	-0.33
0.50	-0.15	-0.21	-0.26
1.00	0.19	0.00	-0.12
$H_{mgmt.interval\ 2}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.35	0.33	0.22
0.50	0.29	0.26	0.17
1.00	0.06	0.00	-0.06
$H_{t=18}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.38	0.33	0.22
0.50	0.31	0.26	0.17
1.00	0.08	0.00	-0.06

Table 7 continued

$H_{t=36}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.38	0.32	0.20
0.50	0.33	0.26	0.13
1.00	0.15	0.00	-0.11
$H_{yield.index}$			
	mgmt.interval		
rsd.mod	**5 years**	**10 years**	**15 years**
0.25	0.20	0.10	-0.03
0.50	0.17	0.09	-0.02
1.00	0.08	0.00	-0.07

Table 8. The effects of harvest sex ratio on sustainable harvest levels, from the third set of simulations using Scenario 2 of the vital rates. Sub-tables a), b), and c) show results for a male-to-female ratio in human-caused removals corresponding to *SR* = 1.0, 1.5, and 2.0, respectively. Values of the management factor (F_O) in the first row of each sub-table correspond to the harvest strategy that met Management Objective 1 or Management Objective 2, at the specified degree of risk tolerance (*risk.tol* = 0.10, 0.30, and 0.50). Values in subsequent rows are subpopulation outcomes for that management strategy, as defined in the main text and Table 1. The row with gray highlighting shows the harvest level (bears/year) during the first management interval ($H_{mgmt.interval\ 1}$), which would be the present-day harvest level for that strategy. The symbol "-" indicates that no positive harvest met the management objective at the specified degree of risk tolerance. All simulations used *SR* = 2.0, *mgmt.interval* = 10 years, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

a) *SR* = 1.0	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	1.08	1.56	1.94		-	1.07	1.37
$H_{mgmt.interval\ 1}$	72	103	128		-	71	90
$H_{mgmt.interval\ 2}$	58	77	82		-	57	71
$H_{t=18}$	58	77	82		-	57	71
$H_{t=36}$	49	64	66		-	49	61
$H_{yield.index}$	65	86	98		-	64	78
$P_{extirpation}$	0.000	0.005	0.019		-	0	0.001
$P_{male.dep}$	0.001	0.002	0.006		-	0.001	0.002

Table 8 continued

b) *SR* = 1.5	Management Objective 1				Management Objective 2		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.99	1.38	1.86		-	0.96	1.24
$H_{mgmt.interval\ 1}$	82	113	154		-	80	103
$H_{mgmt.interval\ 2}$	73	91	91		-	71	85
$H_{t=18}$	73	91	91		-	71	85
$H_{t=36}$	64	79	81		-	63	76
$H_{yield.index}$	78	100	113		-	76	93
$P_{extirpation}$	0.001	0.008	0.043		-	0.001	0.004
$P_{male.dep}$	0.001	0.012	0.037		-	0.001	0.008
c) *SR* = 2.0	**Management Objective 1**				**Management Objective 2**		
	***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**		***risk.tol* = 0.10**	***risk.tol* = 0.30**	***risk.tol* = 0.50**
F_O	0.87	1.24	1.70		0.50	0.86	1.14
$H_{mgmt.interval\ 1}$	86	123	169		50	86	113
$H_{mgmt.interval\ 2}$	79	96	91		44	78	94
$H_{t=18}$	79	96	91		44	78	94
$H_{t=36}$	70	85	78		39	70	83
$H_{yield.index}$	84	106	116		49	84	102
$P_{extirpation}$	0.001	0.012	0.070		0	0.001	0.008
$P_{male.dep}$	0.005	0.025	0.069		0.001	0.005	0.018

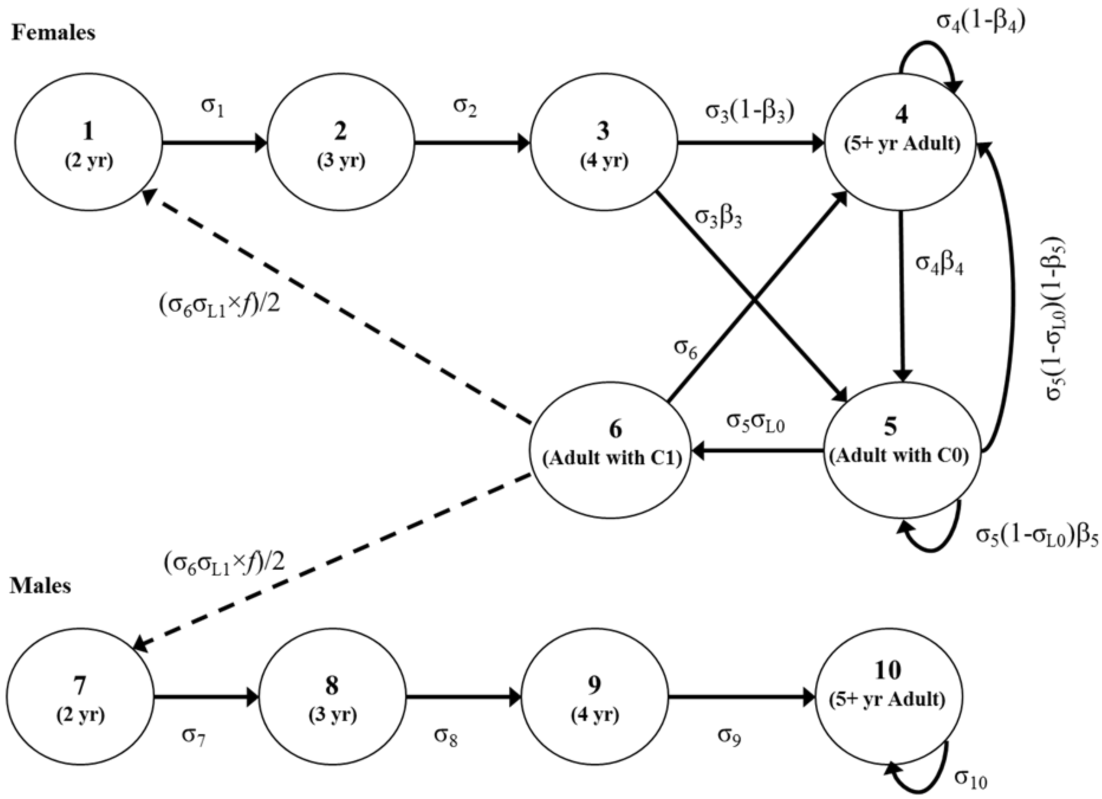

Figure 1. The polar bear life cycle graph underlying the matrix-based projection model, reproduced from Figure 1 in Regehr et al. (2017b). Stages 1–6 are females and stages 7–10 are males; σ_i is the annual probability of survival of an individual in stage *i*; σ_{L0} and σ_{L1} are the probabilities 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.

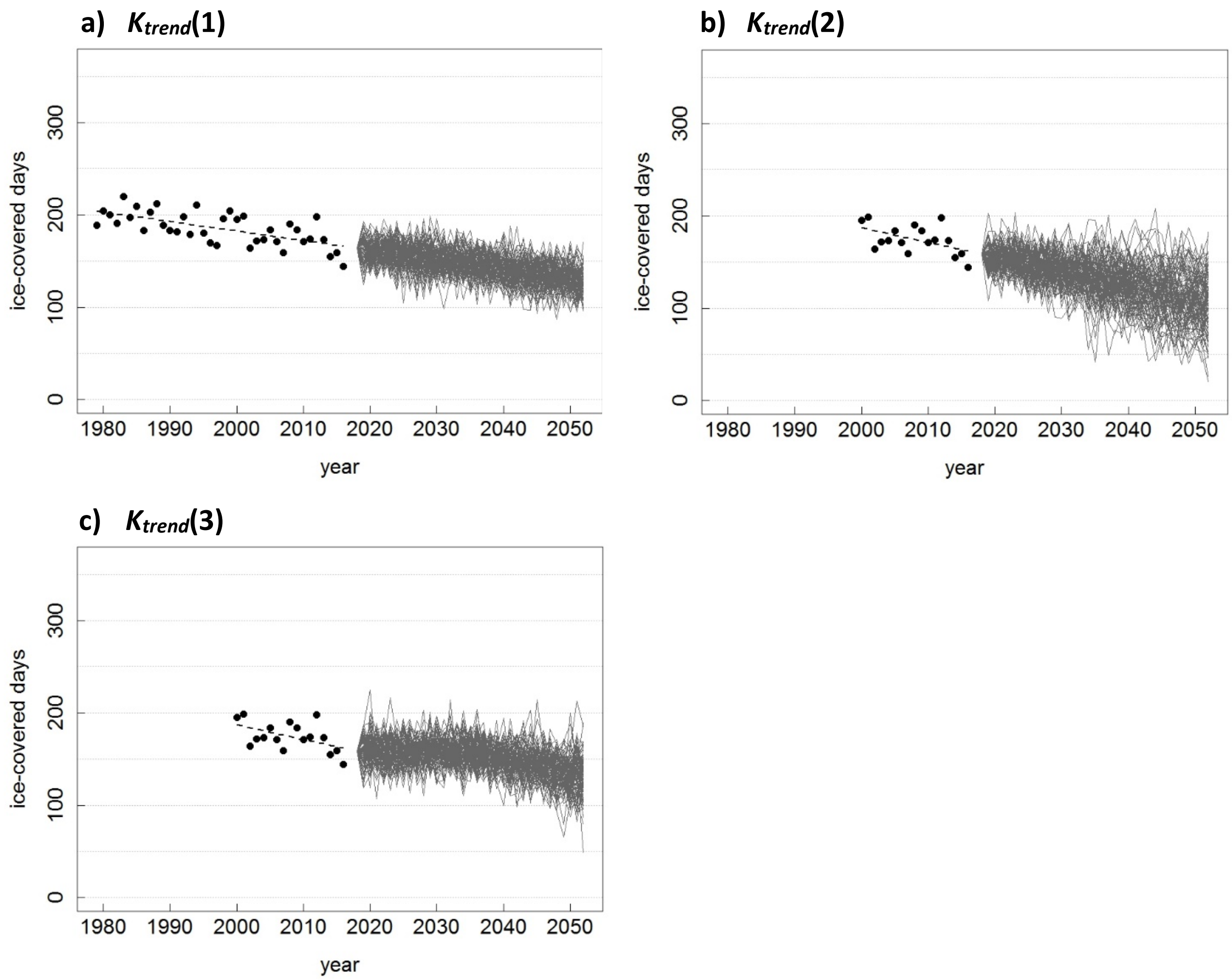

Figure 2. Sample projections of the number of ice-covered days in the Chukchi Sea, which were standardized to represent the proxy for environmental carrying capacity (K) used in population projections. Panels a), b), and c) show the three projection methods $K_{trend}(1)$, $K_{trend}(2)$, and $K_{trend}(3)$, respectively, which are described in the main text.

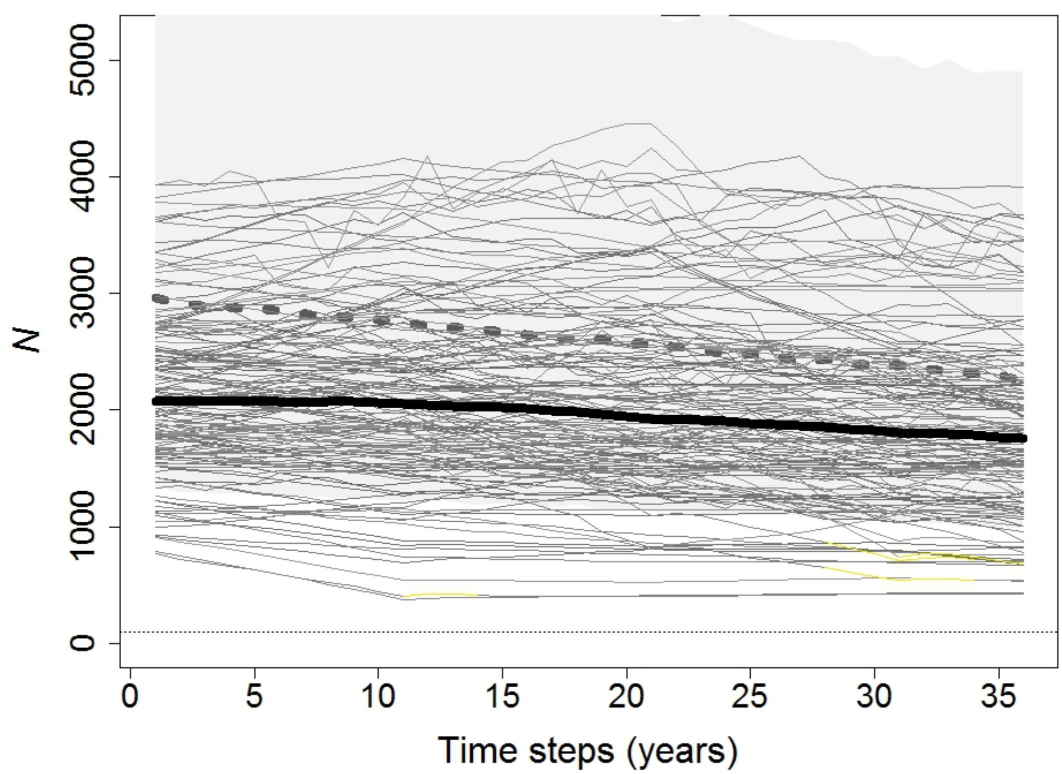

Figure 3. Sample replicates (black lines) from population projections for Chukchi Sea polar bears using Scenario 1 of the vital rates. The grey shaded area represents the upper 95% confidence interval for carrying capacity (K), expressed as numbers of bears, corresponding to the projection method K_{trend}(1). The y-axis is subpopulation size (N) referenced to independent bears, and the heavy black line is the median subpopulation size. Replicates are shaded yellow and red for time steps at which they experienced male depletion or extirpation, respectively. The dashed line near 0 on the y-axis is the quasi-extinction threshold. Projections are for a harvest strategy with F_O = 1.3, *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1.0. This harvest strategy equates to a starting harvest level of 56 bears/year (Table 3), which would be considered sustainable if managers were to accept a 30% chance of not meeting Management Objective 1 (i.e., *risk.tol* = 0.30). Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

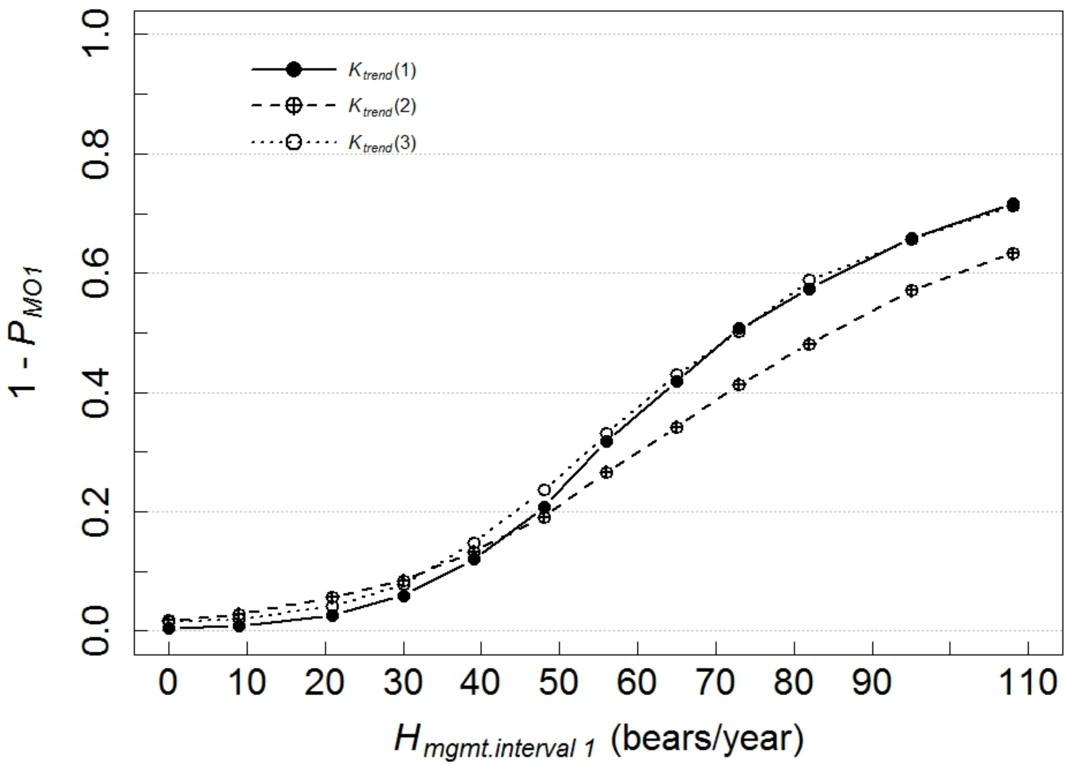

Figure 4. Probability of failing to meet Management Objective 1 (1 - P_{MO1}) as a function of the harvest level during the first management interval ($H_{mgmt.interval\ 1}$), for the first set of simulations using Scenario 1 of the vital rates. Lines correspond to the three methods to project the proxy for environmental carrying capacity (K) forward in time [Kt_{rend}(1), Kt_{rend}(2), Kt_{rend}(3)]. Each point represents one simulation. Across simulations, harvest strategies differed only in the specified value of the management factor F_O. All harvest strategies used *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

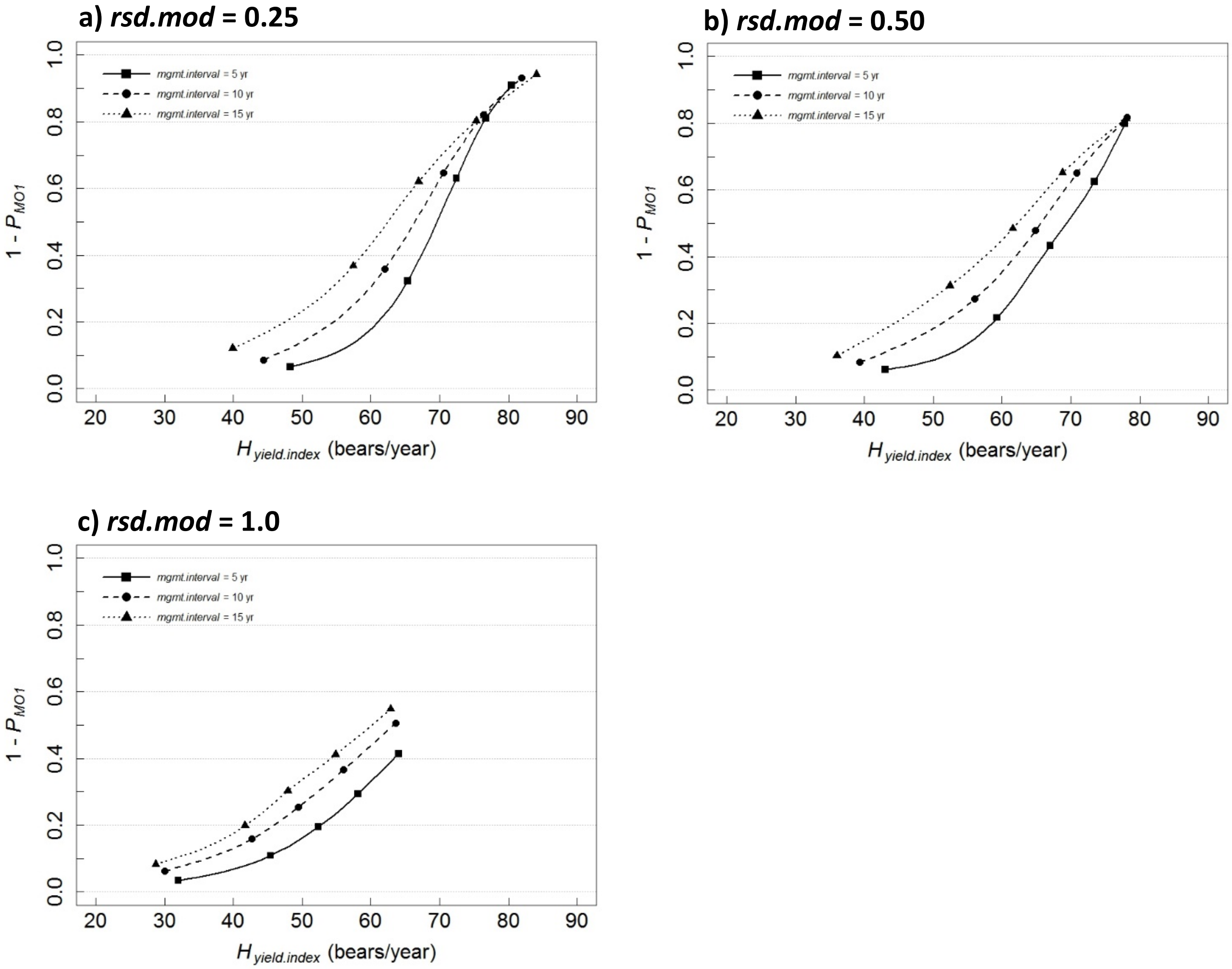

Figure 5. Probability of failing to meet Management Objective 1 (1 - P_{MO1}) as a function of an index of expected yield ($H_{yield.index}$), for the second set of simulations using Scenario 1 of the vital rates. Panels a), b), and c) correspond to the three levels of precision in demographic parameters from future subpopulation studies as specified by the management parameter *rsd.mod* = 0.25, 0.50, and 1.0, respectively. Lines correspond to different management intervals (*mgmt.interval* = 5, 10, 15 years). Each point represents results from one simulation. Across simulations, harvest strategies differed in the specified values of the management factor F_O, *mgmt.interval*, and *rsd.mod*. All simulations used the projection method K_{trend}(1) and *SR* = 2.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

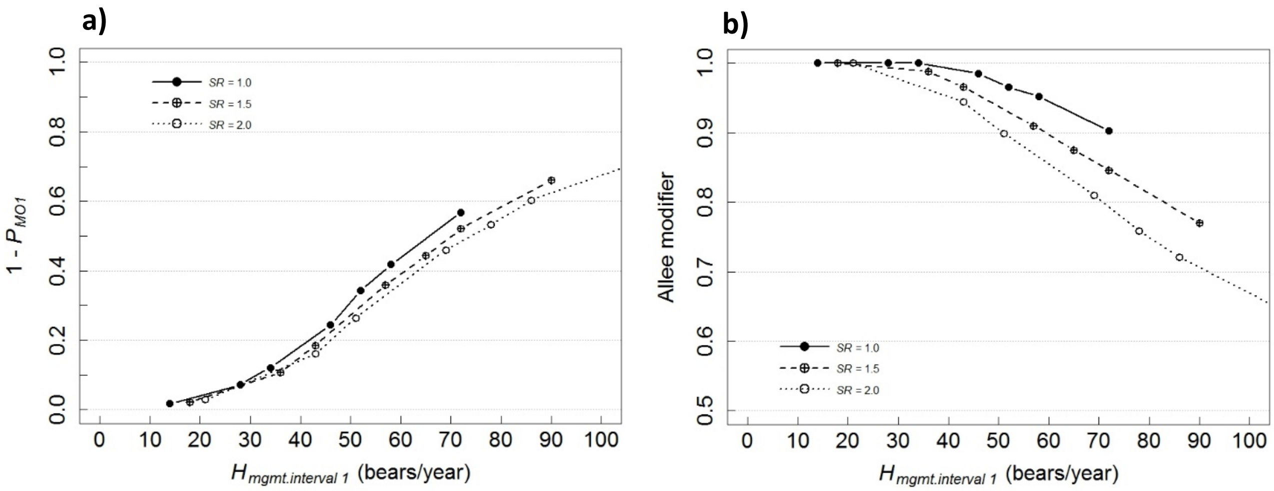

Figure 6. Effects of changing the harvest sex ratio, for the third set of simulations for Scenario 1 of the vital rates. Lines correspond to the male-to-female ratio in human-caused removals (*SR* = 1.0, 1.5, and 2.0). Panel a) shows the probability of failing to meet Management Objective 1 (1 - P_{MO1}) as a function of the harvest level during the first management interval ($H_{mgmt.interval\ 1}$). Panel b) shows the proportional reduction in breeding probability (β_4; Fig. 1) at the annual time step *t* = 36 (Allee modifier) as a function of $H_{mgmt.interval\ 1}$. Each point represents results from a single simulation. Across simulations, harvest strategies differed in the specified values of the management factor F_O and *SR*. All harvest strategies used *mgmt.interval* = 10 years, *rsd.mod* = 1, and K_{trend}(1). Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

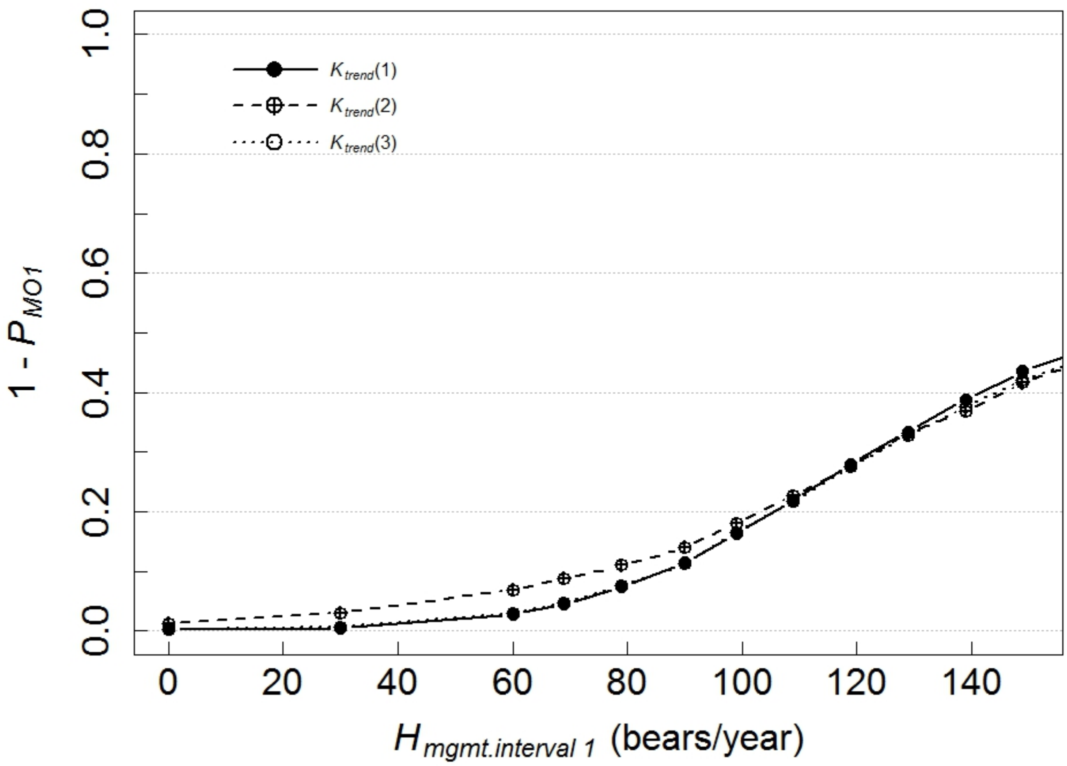

Figure 7. Probability of failing to meet Management Objective 1 (1 - P_{MO1}) as a function of the harvest level during the first management interval ($H_{mgmt.interval\ 1}$), for the first set of simulations using Scenario 2 of the vital rates. Lines correspond to the three methods to project the proxy for environmental carrying capacity (K) forward in time [*Kt*$_{rend}$(1), *Kt*$_{rend}$(2), *Kt*$_{rend}$(3)]. Each point represents one simulation. Across simulations, harvest strategies differed only in the specified value of the management factor F_O. All harvest strategies used *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

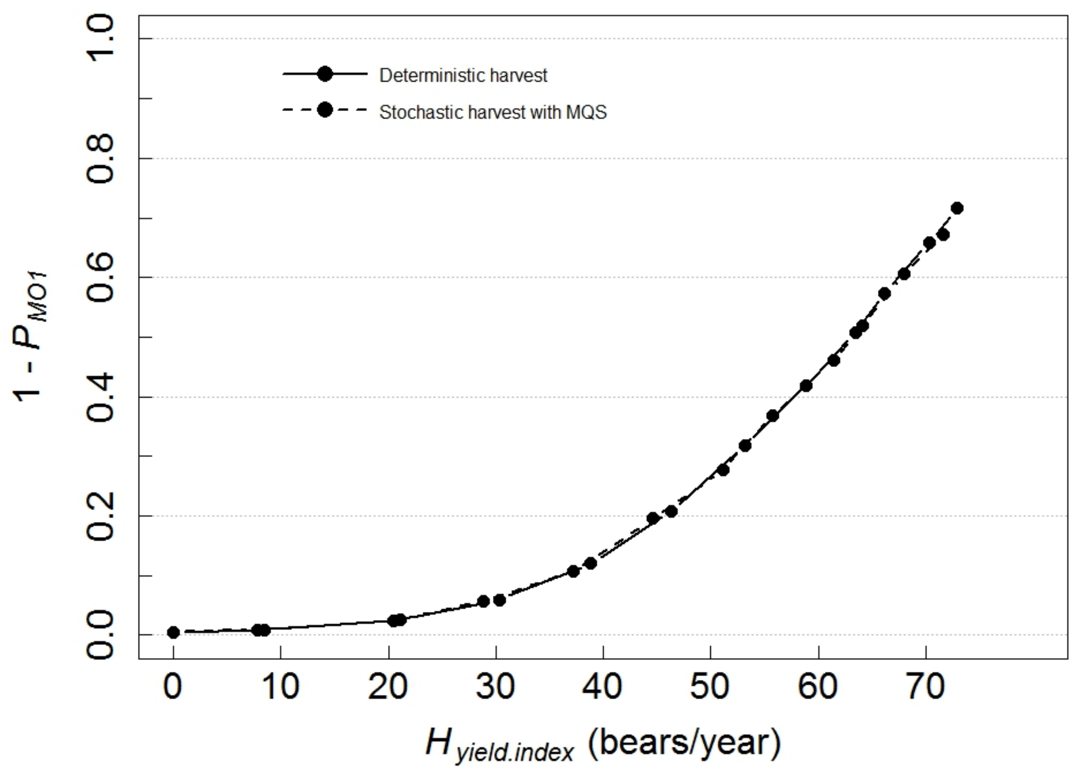

Figure 8. Probability of failing to meet Management Objective 1 (1 - P_{MO1}) as a function of an index of expected yield ($H_{yield.index}$), for the first set of simulations using Scenario 1 of the vital rates with deterministic harvest (solid line), and for the first supplemental simulations (dashed line) with stochastic harvest and a multiyear quota system (MQS). Each point represents one simulation. Across simulations, harvest strategies differed only in the specified value of the management factor F_O, and in whether harvest was deterministic or stochastic with a MQS. All harvest strategies used *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1.0. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

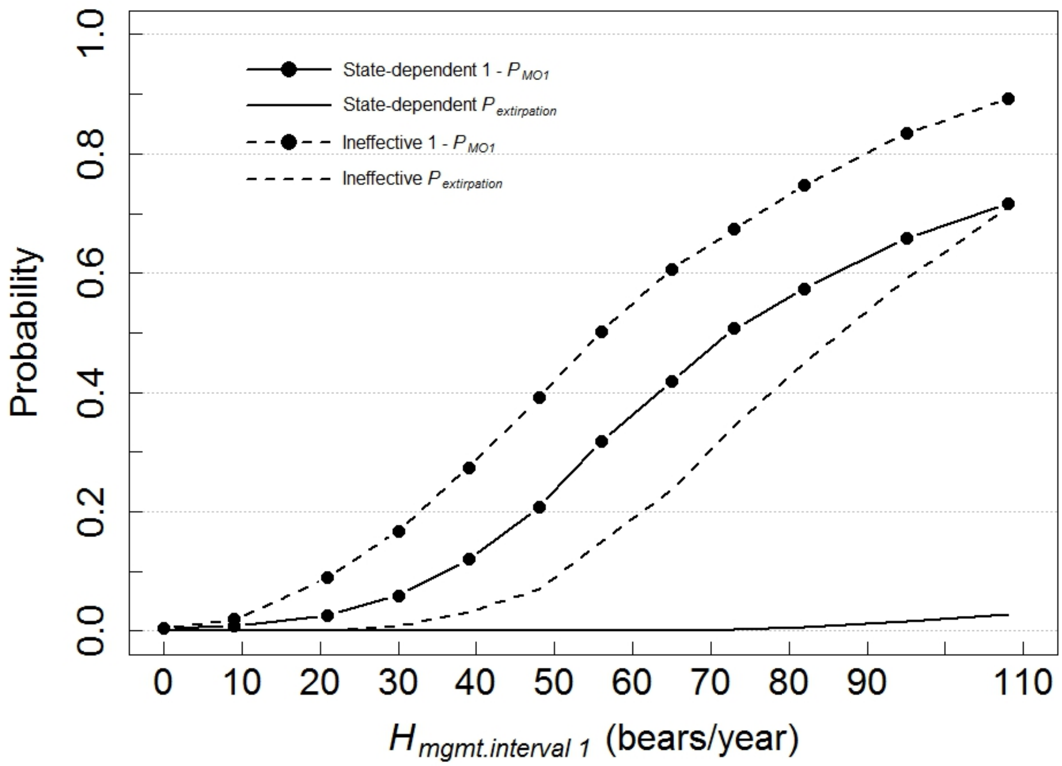

Figure 9. Probability of subpopulation outcomes as a function of the harvest level during the first management interval ($H_{mgmt.interval\ 1}$), for Scenario 1 of the vital rates with a state-dependent harvest management approach (solid lines), and for the second supplemental simulations (dashed lines) with ineffective harvest management, which included harvest levels that were 25% higher than reported and failure to adhere to a state-dependent approach. Subpopulation outcomes are the probability of failing to meet Management Objective 1 (1 - P_{MO1}) and the probability of extirpation ($P_{extirpation}$). Each point represents results from one simulation. Across simulations, harvest strategies differed only in the specified value of the management factor F_O, and in the type of harvest management. All simulations used K_{trend}(1), and simulations with a state-dependent harvest management approach used *mgmt.interval* = 10 years, *SR* = 2, and *rsd.mod* = 1. Biological and management inputs are defined in the main text.

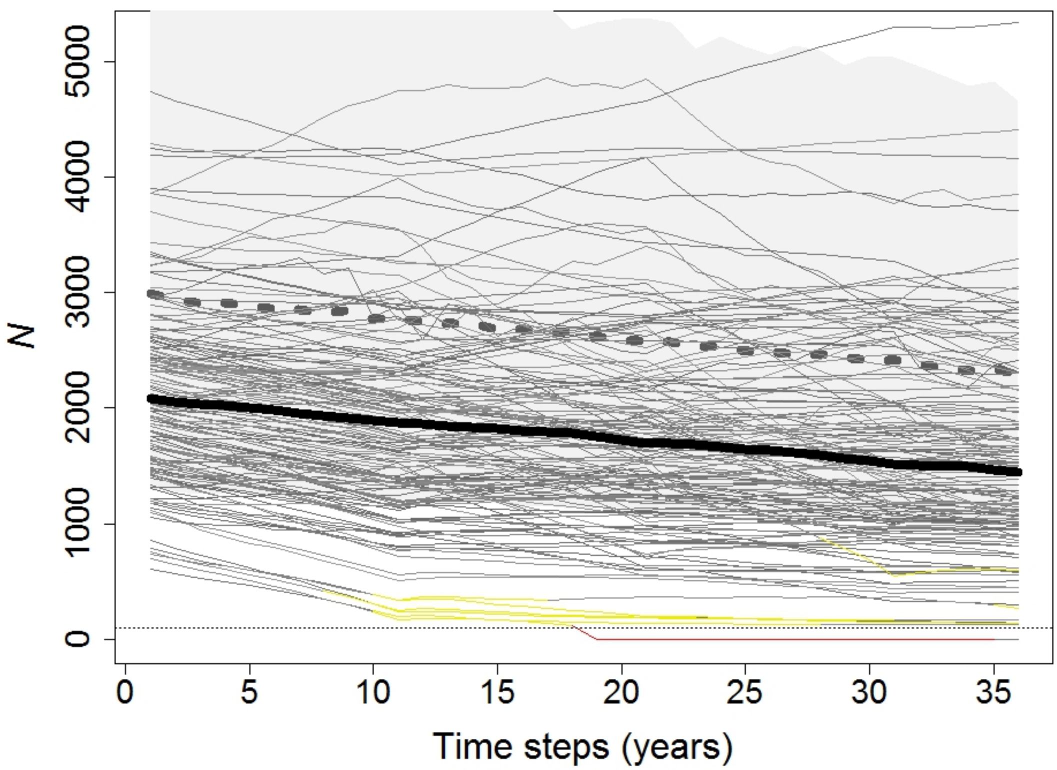

Figure 10. Sample replicates (black lines) from a simulation to evaluate the effects of applying a harvest strategy that would be low risk under Scenario 2 of the vital rates, to a subpopulation with vital rates from Scenario 1. The grey shaded area represents the upper 95% confidence interval for carrying capacity (K), expressed as numbers of bears, corresponding to the projection method K_{trend}(1). The y-axis is subpopulation size (N) referenced to independent bears, and the heavy black line is the median subpopulation size. Replicates are shaded yellow and red for time steps at which they experienced male depletion or extirpation, respectively. The dashed line near 0 on the y-axis is the quasi-extinction threshold. Projections are for a harvest strategy with F_O = 2.0, *mgmt.interval* = 10 years, *SR* = 2.0, and *rsd.mod* = 1.0. This harvest strategy corresponds to a present-day harvest level of 86 bears/year, and for Scenario 1 of the vital rates (shown here) results in approximately a 60% chance of failing to meet Management Objective 1. If a similar harvest strategy were applied to a subpopulation with Scenario 2 of the vital rates (not shown), it would result in a 10% chance of failing to meet

Management Objective 1. Biological and management inputs are defined in the main text. All simulations followed a state-dependent harvest management approach.

Supplemental Materials

Supplemental Table S1. Subpopulation outcomes at the final time step of population projections (*t* = 36) for harvest strategies evaluated during the first set of simulations using Scenario 1 of the vital rates. Sub-tables a), b), and c) show results for the three methods used to project the proxy for carrying capacity $K_{trend}(1)$, $K_{trend}(2)$, and $K_{trend}(3)$, respectively. Values of the management factor (F_O) serve to define each harvest strategy. Other management inputs were *SR* = 2.0, *mgmt.interval* = 10 years, and *rsd.mod* = 1.0. Values in subsequent rows are subpopulation outcomes for each management strategy, as defined in the main text and Table 1. The row with gray highlighting shows the harvest level (bears/year) during the first management interval ($H_{mgmt.interval\ 1}$), which would be the present-day harvest level for that strategy. Values of "Allee effect on β_4" correspond to the multiplier on adult female breeding probability resulting from Allee effects in the mating system. Other biological and management inputs are defined in the main text. Corresponding strategies that met management objectives at the placeholder degrees of risk tolerance are shown in Table 3. All simulations followed a state-dependent harvest management approach.

a) $K_{trend}(1)$												
F_O	0.00	0.20	0.50	0.70	0.90	1.10	1.30	1.50	1.70	1.90	2.20	2.50
$H_{mgmt.interval\ 1}$	0	9	21	30	39	48	56	65	73	82	95	108
$N_{t=36}$	2257	2214	2132	2053	1967	1862	1762	1655	1558	1463	1339	1231
$N_{t=36}/N_{t=1}$	1.09	1.07	1.03	0.99	0.95	0.90	0.85	0.80	0.75	0.71	0.65	0.59
$N_{t=36}/K_{t=36}$	0.99	0.97	0.93	0.90	0.86	0.82	0.77	0.73	0.68	0.64	0.59	0.54
$H_{t=36}$	0	6	16	23	30	34	37	40	39	38	36	31
$H_{yield.index}$	0	8	21	30	39	46	53	59	63	66	70	73
$1 - P_{MO1}$	0.00	0.01	0.03	0.06	0.12	0.21	0.32	0.42	0.51	0.57	0.66	0.72
$1 - P_{MO2}$	0.14	0.16	0.23	0.29	0.38	0.50	0.61	0.70	0.76	0.80	0.85	0.88
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.04	0.06	0.08

Allee effect on β_4	1.00	1.00	1.00	0.99	0.96	0.92	0.88	0.83	0.78	0.74	0.69	0.64
b) K_{trend}(2)												
F_O	0.00	0.20	0.50	0.70	0.90	1.10	1.30	1.50	1.70	1.90	2.20	2.50
$H_{mgmt.interval\ 1}$	0	9	21	30	39	48	56	65	73	82	95	108
$N_{t=36}$	1886	1847	1774	1715	1651	1583	1502	1426	1354	1274	1178	1073
$N_{t=36}/N_{t=1}$	0.91	0.89	0.86	0.83	0.80	0.76	0.73	0.69	0.65	0.62	0.57	0.52
$N_{t=36}/K_{t=36}$	1.00	0.99	0.95	0.92	0.89	0.85	0.81	0.76	0.72	0.68	0.63	0.57
$H_{t=36}$	0	4	12	17	22	27	29	30	30	30	27	24
$H_{yield.index}$	0	8	20	28	36	43	50	55	60	63	68	70
$1-P_{MO1}$	0.02	0.03	0.06	0.08	0.13	0.19	0.27	0.34	0.41	0.48	0.57	0.63
$1-P_{MO2}$	0.44	0.46	0.52	0.55	0.62	0.70	0.76	0.82	0.85	0.88	0.91	0.93
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
$P_{male.dep}$	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.04	0.05	0.06	0.08	0.10
Allee effect on β_4	1.00	1.00	0.97	0.93	0.90	0.86	0.82	0.77	0.73	0.69	0.63	0.60
c) K_{trend}(3)												
F_O	0.00	0.20	0.50	0.70	0.90	1.10	1.30	1.50	1.70	1.90	2.20	2.50
$H_{mgmt.interval\ 1}$	0	9	21	30	39	48	56	65	73	82	95	108
$N_{t=36}$	2414	2363	2271	2189	2075	1961	1856	1744	1644	1536	1390	1277
$N_{t=36}/N_{t=1}$	1.17	1.14	1.10	1.06	1.00	0.95	0.90	0.84	0.79	0.74	0.67	0.62
$N_{t=36}/K_{t=36}$	0.99	0.97	0.94	0.90	0.86	0.81	0.77	0.72	0.68	0.63	0.57	0.53
$H_{t=36}$	0	6	17	24	32	36	40	41	42	41	39	33
$H_{yield.index}$	0	9	22	31	41	49	55	60	65	69	72	75
$1-P_{MO1}$	0.02	0.02	0.04	0.08	0.15	0.24	0.33	0.43	0.50	0.59	0.66	0.71
$1-P_{MO2}$	0.07	0.09	0.13	0.18	0.27	0.39	0.51	0.61	0.68	0.74	0.80	0.83
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.04	0.05	0.07
Allee effect on β_4	1.00	1.00	1.00	1.00	0.98	0.95	0.90	0.85	0.81	0.76	0.70	0.66

Supplemental Table S2. Subpopulation outcomes at the final time step of population projections (*t* = 36) for harvest strategies evaluated during the first set of simulations using Scenario 2 of the vital rates. Sub-tables a), b), and c) show results for the three methods used to project the proxy for carrying capacity $K_{trend}(1)$, $K_{trend}(2)$, and $K_{trend}(3)$, respectively. Values of the management factor (F_O) serve to define each harvest strategy. Other management inputs were *SR* = 2.0, *mgmt.interval* = 10 years, and *rsd.mod* = 1.0. Values in subsequent rows are subpopulation outcomes for each management strategy, as defined in the main text and Table 1. The row with gray highlighting shows the harvest level (bears/year) during the first management interval ($H_{mgmt.interval\ 1}$), which would be the present-day harvest level for that strategy. Values of "Allee effect on β_4" correspond to the multiplier on adult female breeding probability resulting from Allee effects in the mating system. Other biological and management inputs are defined in the main text. Corresponding strategies that met management objectives at the placeholder degrees of risk tolerance are shown in Table 6. All simulations followed a state-dependent harvest management approach.

a) K_{trend}(1)													
F_O	0.00	0.30	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	2.00
$H_{mgmt.interval\ 1}$	0	30	60	69	79	90	99	109	119	129	139	149	198
$N_{t=36}$	2368	2287	2177	2136	2083	2037	1988	1933	1883	1841	1785	1745	1479
$N_{t=36}/N_{t=1}$	1.10	1.06	1.01	0.99	0.97	0.95	0.92	0.90	0.88	0.86	0.83	0.81	0.69
$N_{t=36}/K_{t=36}$	0.99	0.96	0.91	0.90	0.88	0.86	0.83	0.81	0.79	0.77	0.75	0.73	0.62
$H_{t=36}$	0	23	48	59	67	72	78	82	84	86	86	85	69
$H_{yield.index}$	0	29	60	69	79	87	94	100	105	109	112	115	119
$1-P_{MO1}$	0.00	0.00	0.03	0.04	0.07	0.11	0.16	0.22	0.28	0.33	0.39	0.44	0.60
$1-P_{MO2}$	0.01	0.04	0.13	0.18	0.25	0.33	0.41	0.47	0.54	0.59	0.63	0.65	0.76
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.13
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.04	0.05	0.10
Allee effect on β_4	1.00	1.00	0.95	0.92	0.89	0.86	0.82	0.79	0.77	0.74	0.71	0.69	0.65
b) K_{trend}(2)													

F_O	0.00	0.30	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	2.00
$H_{mgmt.interval\ 1}$	0	30	60	69	79	90	99	109	119	129	139	149	198
$N_{t=36}$	1950	1903	1797	1768	1710	1675	1634	1613	1561	1502	1472	1426	1179
$N_{t=36}/N_{t=1}$	0.91	0.89	0.84	0.82	0.80	0.78	0.76	0.75	0.73	0.70	0.68	0.66	0.55
$N_{t=36}/K_{t=36}$	0.99	0.96	0.91	0.90	0.88	0.86	0.84	0.82	0.79	0.77	0.75	0.73	0.60
$H_{t=36}$	0	18	39	45	51	56	60	64	66	67	67	66	52
$H_{yield.index}$	0	27	55	64	72	80	87	93	98	102	105	108	114
$1 - P_{MO1}$	0.01	0.03	0.07	0.09	0.11	0.14	0.18	0.23	0.28	0.33	0.37	0.42	0.58
$1 - P_{MO2}$	0.45	0.49	0.59	0.62	0.66	0.70	0.73	0.77	0.79	0.83	0.83	0.85	0.89
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.03	0.13
$P_{male.dep}$	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.06	0.06	0.07	0.12
Allee effect on β_4	1.00	0.96	0.88	0.85	0.82	0.78	0.75	0.72	0.69	0.66	0.64	0.61	0.57
c) *K*													
F_O	0.00	0.30	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	2.00
$H_{mgmt.interval\ 1}$	0	30	60	69	79	90	99	109	119	129	139	149	198
$N_{t=36}$	2536	2454	2333	2282	2242	2188	2133	2082	2023	1980	1928	1874	1569
$N_{t=36}/N_{t=1}$	1.18	1.14	1.08	1.06	1.04	1.02	0.99	0.97	0.94	0.92	0.90	0.87	0.73
$N_{t=36}/K_{t=36}$	1.00	0.97	0.92	0.90	0.88	0.86	0.84	0.82	0.80	0.78	0.76	0.74	0.62
$H_{t=36}$	0	24	54	63	72	78	85	90	92	93	93	94	72
$H_{yield.index}$	0	30	63	73	83	91	98	104	109	114	116	119	121
$1 - P_{MO1}$	0.00	0.01	0.03	0.05	0.08	0.11	0.17	0.22	0.28	0.33	0.38	0.42	0.59
$1 - P_{MO2}$	0.02	0.03	0.08	0.11	0.15	0.20	0.27	0.33	0.40	0.45	0.49	0.53	0.67
$P_{extirpation}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.03	0.13
$P_{male.dep}$	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.09
Allee effect on β_4	1.00	1.00	0.98	0.95	0.92	0.89	0.86	0.83	0.80	0.77	0.75	0.73	0.67