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CUMULATIVE EFFECTS ASSESSMENT FOR WEST COAST TRANSIENT (BIGG'S) KILLER WHALE POPULATION IN THE NORTHEAST PACIFIC

Bigg's killer whale T109B3 hunting Dall's porpoises. Photo: © Jared Towers

Figure 1. Map of encounters with West Coast population of Bigg's Killer Whale; all 1970-2022 encounters (white); 2005-2022 encounters within the Canadian portion of the Salish Sea (orange).

CONTEXT

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the West Coast Transient (WCT) population of Bigg's Killer Whales (BKW) (also known as Transient Killer Whales) as Threatened in 2001, due to their small population size, low reproductive rates, and elevated concentrations of toxic persistent and bioaccumulative chemical contaminants. This designation became law when the population was listed under Schedule 1 of the Canadian Species at Risk Act (SARA) in 2003.

Fisheries and Oceans Canada (DFO) Species at Risk Program requested that DFO Science Branch provide an assessment of the cumulative effects of current and potential anthropogenic impacts on Bigg's killer whales in Canadian Pacific waters. The science advice resulting from this assessment can be used to support the efforts towards survival and recovery of WCT specifically by helping to adaptively inform and/or implement recovery measures.

This Science Advisory Report is from the June 18-20, 2024 regional peer review on the Cumulative Effects Assessment for the West Coast Transient Killer Whale Population. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.

SUMMARY

- The West Coast Transient (WCT) population of the Bigg's Killer Whale (BKW) ecotype was listed as Threatened under the *Species at Risk Act* (SARA) in 2001. The SARA Recovery Strategy was completed in 2007 (DFO 2007) and is currently being amended.
- The SARA Recovery Strategy outlined the most pressing anthropogenic threats to WCT as chemical contaminants, and physical and acoustic disturbance (DFO 2007); and also described other threats: biological pollutants, trace metals, toxic spills, collision with vessels, and decline in prey availability or quality. Based on the Recovery Strategy, the current study focused on four identified threats: disturbance (acoustic); disturbance (physical); reduced prey availability; and contaminants.
- The current analysis uses an established cumulative effects framework that combines a Pathways of Effects (PoE) conceptual model with a Population Viability Analysis (PVA) to assess the cumulative effects of the four identified threats on killer whale vital rates.
- The study area focused on the Canadian portion of the Salish Sea (CSS) and the subset of WCT observed there during the years 2005 to 2022, to provide optimal overlap between knowledge of threats and population observations.
- Current knowledge of how threats affect mortality and fecundity rates of WCT in the CSS were synthesised into the overall PoE model consisting of 16 evidence-based linkages from identified threats to effects, eight from single threats and eight mediated through threat interactions. Future changes in anthropogenic activities and their potential threats, including those linked to climate change, were not included.
- The PoE linkages with sufficient knowledge to be quantified were retained to form a PVA-specific PoE model consisting of six evidence-based linkages, four from single threats, and two from threat interactions, these quantifiable threats informed the inputs and structure of the PVA model.
- The PVA model explored the sensitivity and relative importance of quantifiable threats (vessel strikes, PCBs, vessel noise, reduced prey availability), threat interactions (between PCBs and prey, and vessel noise and prey), and cumulative effects on the population trajectories of the WCT in the CSS.
- In the PVA, each quantifiable threat and interaction was modelled individually and also together in a cumulative effects scenario. The cumulative effects model included impacts of prey availability on the population carrying capacity, masking of prey sounds by vessel noise, vessel strike mortality, and PCB contamination on calf mortality.
- The cumulative model, including all four threats, replicates the observed population trend closely with the CSS population size contained within the 90% distribution of the model estimates indicating good model fit. Reduced prey availability had the most influence on abundance trends for WCT in the CSS.
- The cumulative effects PVA model can be used to explore the impacts of different mitigation and management options for individual threats on the population trajectory, noting that it is sensitive to the value for carrying capacity (i.e., the maximum CSS abundance that the environment can sustain as a result of prey availability).
- Future projections showed a steady increase in the CSS population over the initial ten to twenty years and then stable population size through the rest of the simulation. The carrying

capacity had the biggest effect on the simulated population trends, while the modeled prey trends had relatively small effects.

- The cumulative effects assessment framework used here, which combines a PoE with a PVA model, is an established approach that explicitly identifies and quantifies threat linkage pathways and associated uncertainties, with the potential for use in other populations and species.

BACKGROUND

Coastal waters of the Northeastern Pacific are home to three distinct ecotypes of killer whale: Bigg's (also referred to as transient), resident, and offshore. These ecotypes do not interbreed and have clear differences in morphology, social structure, diet, acoustic behaviour, and genetics (Deecke et al. 2005; Ford and Ellis 1999; Ford et al. 2013; Ford et al. 1998; Morin et al. 2024). There are several distinct populations of the marine mammal eating Bigg's killer whales in the Northeastern Pacific, largely separated geographically, including the West Coast Transients, AT1 Transients, and Gulf of Alaska Transients (Ford et al. 2013; Matkin et al. 2012; Parsons et al. 2013). The West Coast Transient (WCT) population is the only population of the Bigg's killer whale (BKW) ecotype to regularly occur in waters off the Pacific coast of Canada and have been photo-identified since the 1970s (Bigg 1982; Ford et al. 2013).

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the WCT population of BKW as Threatened in 2001, due to their small population size, low reproductive rates, and their high levels of toxic chemical contaminants. The population was listed under Schedule 1 of the Canadian Species at Risk Act (SARA) in 2003 and was reaffirmed by COSEWIC in 2008 and 2023. A Recovery Strategy for Bigg's Killer Whales was published in 2007, with a goal to "attain long-term viability of the West Coast transient killer whale population by providing the conditions necessary to preserve the population's reproductive potential, genetic variation, and cultural continuity". The WCT are also included in three multi-species Action Plans, "Multi-species Action Plan for Gulf Islands National Park Reserve of Canada" (2018), "Multi-species Action Plan for Pacific Rim National Park Reserve of Canada" (2017), and "Multi-species Action Plan for Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site" (2016). An amended Recovery Strategy for Bigg's Killer Whales is being developed to update background information and identify critical habitat, and an Action Plan, also under development, includes a high priority recovery measure (#7) to "Assess cumulative effects of potential anthropogenic impacts on Transient Killer Whales using an appropriate impact assessment framework for aquatic species".

Fisheries and Oceans Canada (DFO) Species at Risk Program requested that DFO Science Branch provide an assessment of the cumulative effects of current and potential anthropogenic impacts on Bigg's killer whales in Canadian Pacific waters.

Biology

The range of WCT killer whales extends along the Pacific coast of North America, from southern California to southeastern Alaska. Within this region, they are primarily found inshore of the continental shelf edge (Ford et al. 2013; Towers et al. 2019). WCT can be found throughout coastal waters of western Canada year-round and have been documented with increasing regularity in the Salish Sea from the 1970s to present (Baird and Dill 1995; Houghton et al. 2015).

The Bigg's ecotype of killer whales specialize in hunting marine mammals. The primary prey species of the WCT killer whale population is harbour seal (*Phoca vitulina*), followed by harbour porpoise (*Phocoena phocoena*), and Steller sea lion (*Eumetopias jubatus*) (Ford et al. 2013). They also hunt and consume Dall's porpoise (*Phocoenoides dalli*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), California sea lion (*Zalophus californianus*), Northern elephant seal (*Mirounga angustirostris*), common minke whale (*Balaenoptera acutorostrata*), and grey whale (*Eschrichtius robustus*) (Baird and Dill 1995; Ford and Ellis 1999; Ford et al. 2013; Ford et al. 1998).

Increasing population growth and abundance has resulted in higher density of WCT killer whales within their range. This is most apparent in their core habitat around Vancouver Island, specifically the Salish Sea. The frequency with which WCT have been documented in this region has increased significantly over time from only a few encounters documented each year through the 1970s and 1980s (Bigg 1982; Ford and Ellis 1999) to hundreds of encounters each year throughout the 2010s and 2020s (Ford et al. 2013; Houghton et al. 2015; Shields et al. 2018; DFO-Cetacean Research Program and Bay Cetology unpublished data).

ASSESSMENT

The cumulative effects assessment consisted of two phases. First, an overall Pathways of Effects (PoE) conceptual model used current knowledge to identify the different ways threats and threat interactions can impact vital rates, visualised using evidence-based linkages. Then to inform the population model, a PVA-specific PoE model was created by removing those linkages that could not be quantified. Phase two, the Population Viability Analysis (PVA) model, first required the parameterisation of the effects of quantifiable threats and threat interactions to killer whale vital rates based on current knowledge (Table 1). These were then used in the PVA to assess individual and cumulative effects of the quantifiable threats on killer whale population persistence through time. The PVA model was built upon and adapted from an existing model developed for resident killer whales (DFO 2007; Lacy et al. 2017; Murray et al. 2019).

Data and Methods

The Canadian portion of the Salish Sea was chosen as the study area because it had the best coverage of available knowledge on threats combined with relatively consistent killer whale survey effort. In order to construct and test the quantitative PVA model for WCTs, recent, specific data about the population was required, including: annual fecundity, mortality, and immigration rates, as well as annual population size.

Annual vital rates and population size

Annual fecundity rates were defined as the number of births divided by the number of living reproductive females in each year in the Canadian Salish Sea (CSS) subset (DFO-CRP unpublished data). To estimate annual mortality rates and abundance, Cormack-Jolly-Seber (CJS) mark-recapture models were fitted to the annual capture histories of 415 unique individuals; representing whales who have been documented using the study area at any time between 2005 and 2022,and therefore have been exposed to the high intensity and diversity of threats in the Salish Sea. Abundance was calculated by dividing the number of observed individuals each year by the recapture probabilities (Lebreton et al. 1992). Immigration of WCT into the Salish Sea had been documented in the beginning of the time series (Houghton et al. 2015; Shields et al. 2018; DFO-CRP and Bay Cetology unpublished data), and was therefore included in the models.

Threat Quantification and PVA Modelling

Quantification of each of the four identified threats was based on current knowledge and data and these quantifiable threats form the inputs to the PVA model (Table 1). Population Viability Analysis (PVA) was used to simulate the effects of the threats on the target population and was implemented using Vortex, an open access software which allows for individual-based simulation of populations (Lacy and Pollak 2023). As the model simulates how threats affect population trends, the baseline population trend upon which threat scenarios are compared is a fundamental component. Given the focal population is already affected by threats, fecundity and mortality rates for the relatively un-impacted Southern Alaska Resident Killer Whale (SARKW) population (Matkin et al. 2014) were used as a baseline population trend, and quantifiable threats were modelled as modifiers of the SARKW baseline vital rates (Murray et al. 2019).

The model was used to simulate the effects of individual threats (noise, strikes, contaminants), interactions between threats (noise-prey; contaminants-prey), and a combined, cumulative effects model including all threats and interactions (Table 1). To start the simulation, the list of individuals present in the CSS subset in 2005 was used. Model simulations were run on each scenario 1,000 times and summary statistics were recorded for the population growth rate (r) and population size at each time step (N_t).

The overall PoE model (Figure 1A) contained sixteen evidence-based linkages (circled numbers) from identified threats to effects, representing current knowledge on the effects of threats on vital rates. The PVA-specific PoE model (Figure 1B) represents the six threat to effect linkage pathways that could be quantified with enough confidence for input into the PVA model (quantifiable threats). Ten linkages from the overall PoE model lacked sufficient evidence to be quantified.

Table 1. Description of the quantification of identified threats, and specific parameters used in the PVA model to simulate the effects of quantifiable threats to the Canadian Salish Sea (CSS) subset of the West Coast Transient killer whale population.

Quantifiable threat(s)	Parameters	Supporting data and implementation
Reduced Prey Availability	The influence of density dependence (via prey availability) on annual mortality was implemented with carrying capacity as a function of the prey index. Though exact prey preferences and degree of prey switching in WCT are uncertain, observed predation events indicate individuals of this population successfully target a variety of prey species.	Prey species population data used to create a combined prey index using harbour seal (DFO 2022); Steller sea lion (DFO 2021); and harbour porpoise (Matthew Hamer and Joseph Evenson, unpublished data, 2016). Prey proportions in index based on species in Salish Sea predation events from DFO-CRP and Bay Cetology, unpublished data.
Vessel Strikes	Vessel strikes increase adult mortality. They were modelled under two scenarios of annual probability of fatal vessel strike: 0.2 deaths within the population per year from the estimated number of strikes, and 0.73 as an extreme estimate.	Reports from whale necropsies with presumed cause of death due to vessel strikes (Lee et al. 2023; Raverty et al. 2020), noting that not all whale deaths are observed so this is likely an underestimate.

Quantifiable threat(s)	Parameters	Supporting data and implementation
Vessel Noise	The effect of acoustic disturbance was explored through two scenarios for the reduction in detection of harbour seals or harbour seal haulouts. Prey availability is expected to be reduced due to acoustic masking of prey sounds across haulouts.	Vessel noise model (Burnham et al. 2023). Harbour seal haulout location and abundance (DFO 2022).
PCB+ Contamination	An accumulation and depuration model was used to estimate PCB transfer from mother to calf and a consequent effect on calf mortality. A correction factor of 1.75x was applied to mean PCB concentration to capture the contribution and associated risk of other POPs, this corrected amount called PCB+. Calf survival was based on maternal PCB+ concentration in the model. Multiple scenarios for contaminant accumulation rate were tested (1, 2, and 6 mg kg^{-1} lw per year).	PCB accumulation and depuration model for mammals (Hall et al. 2018). Maternal PCB values measured in Bigg's killer whales (n=27; Guy 2018; Ross et al. 2013). PCB correction factor from Mos et al. (2010).
Prey–Noise	Noise disturbance is theorised to have a higher influence on prey availability under low prey conditions. This interaction was implemented using a threshold effect, applied only when the prey index fell below 1.0 (mean prey level).	Implementation of noise effect only occurs when prey index drops below threshold value (Murray et al. 2019).
Prey-PCB+	When prey availability is low, killer whales can metabolise blubber for energy. This interaction represents the possibility that PCBs stored in maternal blubber are metabolised under low prey conditions, triggering the calf mortality effect. This PCB+ threshold effect was applied when prey availability less than the mean index (1.0).	Implementation of PCB+ contamination effect occurs when prey index drops below threshold value (Murray et al. 2019).

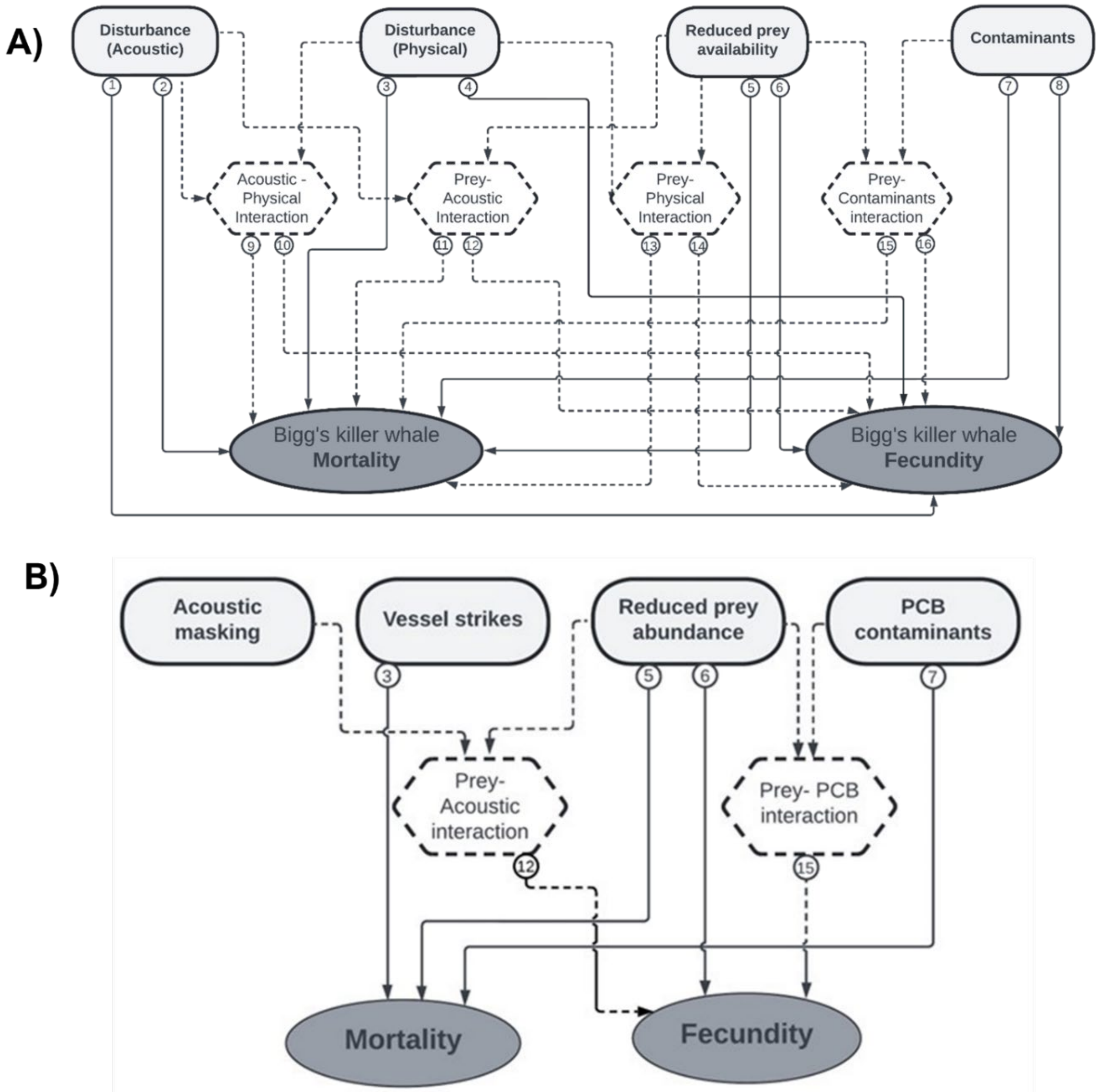

Figure 2. A) Overall Pathways of Effects (PoE) model for Bigg's Killer Whales showing the 16 threat to effect linkages supported by evidence, eight connecting directly to effects on population parameters (mortality and fecundity) and eight connecting through four threat interactions; B) Population Viability Analysis (PVA) specific PoE model illustrating the six quantifiable evidence-based linkages from threats to effects included in the PVA model.

Results

Pathways of Effects (PoE) conceptual model

Current knowledge of how threats affect mortality and fecundity rates of WCT in the CSS were synthesized into the overall PoE model. The overall model consisted of 16 evidence-based linkages from identified threats to effects, eight from single threats and eight mediated through threat interactions (Figure 1A). The PoE linkages with sufficient knowledge to be quantified were retained to form a PVA-specific PoE model consisting of six evidence-based linkages, four from single threats, and two from threat interactions, these quantifiable threats informed the inputs and structure of the PVA model (Figure 1B).

PVA Modelling

The results of the scenario simulations (Figure 2) include the baseline (SARKW rates) and observed (CJS mark-capture-recapture model) trends in annual population size for comparison; the assumption is that appropriate models would replicate the observed population dynamics for the WCT CSS population.

The seal and haulout acoustic disturbance scenarios were similar to each other and overlapped with the observed population trend (Figure 2B). Vessel strike scenarios caused only a small depression in the population trend through time for both scenarios and overlapped with the baseline scenario trend (Figure 2C). In the prey availability scenarios, The influence of carrying capacity (K) on annual mortality was implemented with K as a function of the prey index (Figure 2D). The values that most closely aligned with the observed trend were 3.5% mortality at K, and K = 459 individuals. This threat had the largest effect on the simulated population, overlapping with the observed population trend (Figure 2D). The PCB+ contamination threat showed some evidence of population depression in the later years but mostly overlapped with the baseline scenario trend (Figure 2E). Multiple scenarios for PCB accumulation rate were tested (1, 2, and 6 mg kg^{-1} lw per year). The best match between simulated and sampled PCB concentrations was the scenario with 6 mg kg^{-1} lw per year accumulation rate.

The interaction effect of prey availability and PCB+ had little effect on the simulated population, overlapping with the baseline simulation (Figure 2F). The interaction of noise and prey had a substantial effect, overlapping the observed population size (Figure 2F). All of the individual and interaction scenarios showed positive population growth rates, ranging from the low 3.4% for prey effects on carrying capacity (Prey-K) to the highest, 6.82% for PCB+ 1mg.

The cumulative effects scenario included four threats with the most evidence-based parameters for each: Prey availability effect on mortality at K, acoustic disturbance effect on seal detection through prey availability, vessel strikes with 0.2 probability of a fatal strike within the population per year, and a threshold interaction between prey availability and PCB contaminants that results in calf mortality when above the threshold PCB concentration. The cumulative model replicated the observed population trend closely with the WCT population size fitting within the 90% distribution of the model estimates (Figure 3).

Future projections

The projection of the cumulative effects model 100 years into the future used two values for K, 330 and 459 individuals, each with probability of survival at K of 96.5%. The differing prey trends had only small effects in the scenarios. The higher carrying capacity scenarios showed a steady increase in the population over the first twenty years and then stable population size of approximately 400 individuals through the rest of the simulation (Figure 4). This means that for this subset of the WCT population in the Canadian Salish Sea (CSS subset), prey-mediated carrying capacity is the most important predictor of population size.

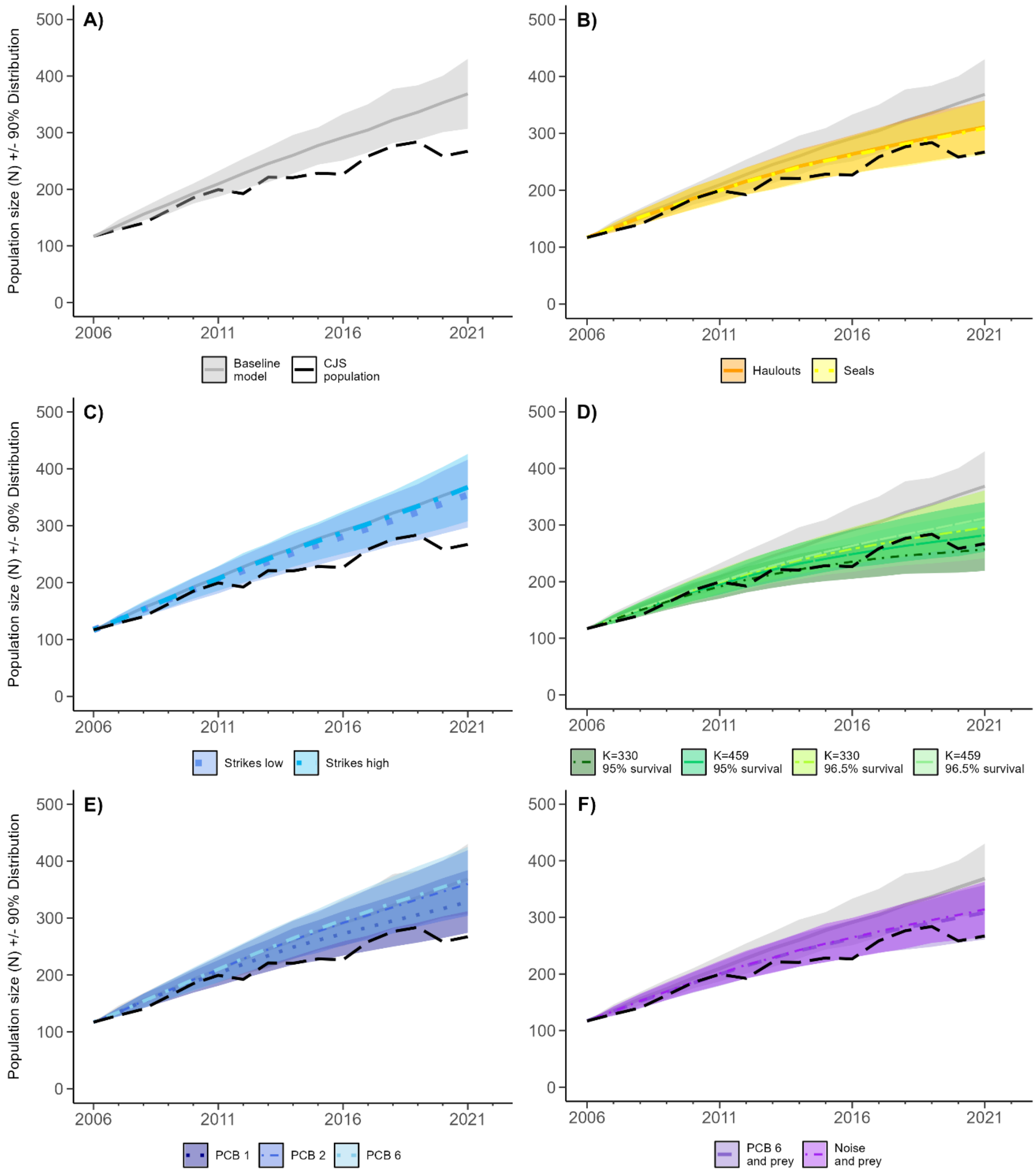

Figure 3. Results of the CSS subset PVA scenarios with the 90% distribution around the model mean. Panel A) baseline model (grey) and actual population trend from the CJS mark-capture-recapture modelling (black dashed), B) acoustic disturbance modelled on impact on masking on number of seals and on seal haulouts, C) physical disturbance with ship strike risk, both high and low, D) impact of prey on carrying capacity via mortality, E) contaminants at three levels of accumulation, and F) interactions between contaminants, noise and prey.

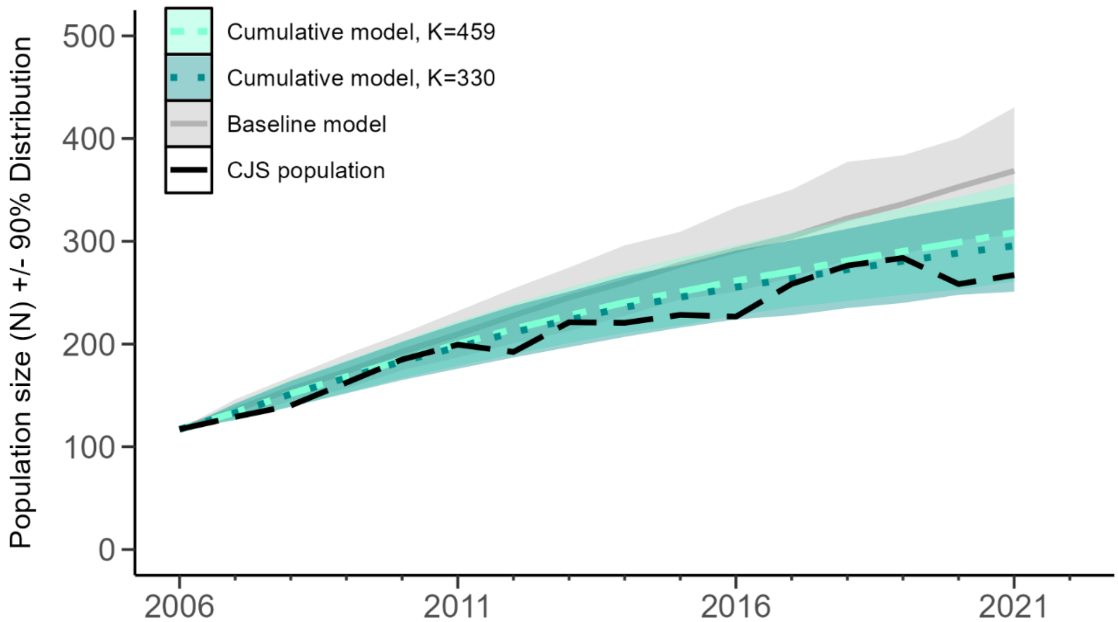

Figure 4. Cumulative effects scenario including all threats (Prey effect on carrying capacity via mortality, noise, strikes, and prey-PCB interaction, with probability of survival at carrying capacity of 96.5%), showing the model mean with the 90% distribution. Baseline model (grey) and CJS mark-capture-recapture model trend (black dashed line) included for comparison.

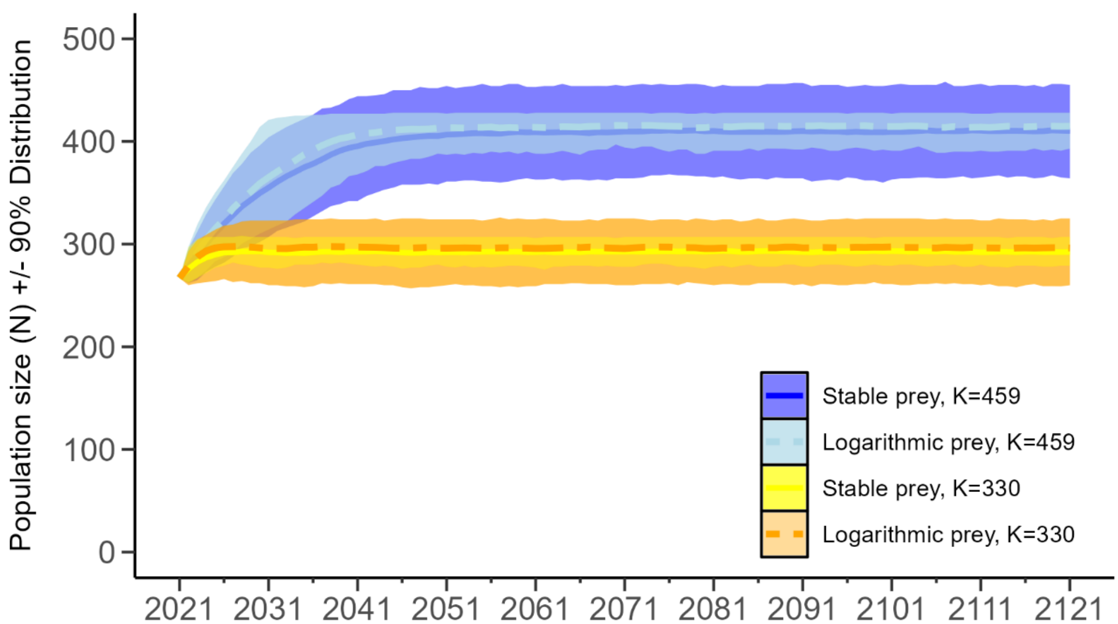

Figure 5. Future projections of WCT population size from 2021 through 2121 using two scenarios of prey index, stable prey levels or logarithmic increase, at two levels of carrying capacity. Projections used a probability of survival at carrying capacity of 96.5%.

Sources of Uncertainty

- The West Coast Transient (WCT) killer whale population lacks the level of data and literature available for the better-studied Southern and Northen Resident Killer Whale populations. It was necessary to carry out new analyses to characterise threats, as well as a new population analysis to estimate annual abundance trends and vital rates, given the last population assessment available was from 2007 (Ford et al. 2007).
- This analysis was restricted to the members of the WCT population that were observed in the Canadian Salish Sea (the CSS subset). Therefore, the modelling of abundance and vital rates is limited to this subset of the population and should not be considered a full WCT population assessment for Species at Risk purposes.
- Some parameters were taken from published work on other populations, for example, vital rates for the Southern Alaska Resident Killer Whale population were assumed to represent a relatively-unimpacted baseline on which to add threat impacts.
- There are data limitations and uncertainties for each of the identified threats to Bigg's Killer Whales (acoustic and physical disturbance, chemical contaminants, and reduced prey availability) and their impacts on mortality and fecundity rates. Threat modelling was dependent on data availability and as a consequence, included varying spatial and temporal scales. An iterative, adaptive approach should be taken to update the cumulative effects model as new data become available and as data and knowledge about other potential threats emerge.
- Given prey availability is a key component of the cumulative effects model for WCT, an accurate representation of this component is critical. Abundance time series data from three main WCT prey species were used to parameterise this threat: DFO stock assessment survey data was used for harbour seal and Steller sea lion, and harbour porpoise data came from a long-term survey in the US portion of the Salish Sea. There was no time series data available for the Dall's porpoise population.
- Demographic parameters (fecundity and mortality) and our understanding of WCT killer whale population dynamics include substantial uncertainty. Results of the assessment should therefore be interpreted with caution.
- The overall PoE identified that priority threats can affect vital rates in multiple ways, but only some of these effects could be quantified for input into the PVA model. Additional threats were identified in the SARA recovery document and the PoE, but were not quantifiable (e.g., biological pollutants, trace metals, toxic spills). This adds to the level of uncertainty in our conclusions and future projections because they could not be included in the PVA scenario modelling.
- The future projections of WCT's continued population growth to carrying capacity were based on the assumption that the current levels of threats remain the same, without mitigation actions, management measures, or changes in threat levels. The effects of climate change on the threats, vital rates, and other linked components of the ecosystem were not included and have the potential to significantly affect future projections.

CONCLUSIONS

This cumulative effects assessment advances the field by successfully adapting an established cumulative effects framework for resident killer whales to a different killer whale ecotype. It combines a Pathways of Effects (PoE) conceptual model with a Population Viability Analysis

(PVA) to assess the individual and cumulative effects of identified threats (physical and acoustic disturbance, PCB contaminants, and prey availability) on vital rates, and is a tool that can be used to evaluate how the threats may affect the future of the West Coast Transient population of Bigg's killer whales.

The overall PoE model was simple to adapt and provided a transparent and effective tool for scoping and structuring inputs to this assessment using evidence-based linkages to connect threats with effects on vital rates. This model highlighted the importance of considering threat interactions, as half of the evidence-based linkages were mediated through threat interactions. It also highlighted specific knowledge gaps, as ten linkages in the overall model were not able to be quantified. The PVA-specific PoE model, used to inform the subsequent PVA model for WCT in the CSS, consisted of six quantifiable evidence-based linkages, two threat interactions, with reduced prey availability being the most prominent threat.

Each of the identified threats and interactions were parameterised and modelled separately in the PVA, and together in the cumulative effects model. The cumulative effects model captured all identified threats and the observed population dynamics effectively. Projections of the model 100 years into the future suggest that under stable or increasing prey availability, the CSS subset of the WCT population should continue to increase (until reaching carrying capacity).

Prey availability had the greatest contribution to the cumulative effects model, with variations in the parameter causing the largest changes in sensitivity testing. For the increasing WCT population, carrying capacity may limit the continued growth of the population with the expectation that prey species are at high levels and also nearing, or at, carrying capacity. Projections of the outlook for the CSS subset of the WCT population are therefore highly dependent on prey availability and, as such, threats that affect prey populations are indirectly linked to the WCT population.

The future projections of WCT's continued population growth to carrying capacity may be affected by increases in threat levels, such as increased ship traffic, the introduction of mitigation measures such as ship speed reductions, and the effects of the changing climate on threats, prey populations, and ecosystem dynamics.

This is the first cumulative effects assessment for the WCT killer whale population, and is an effective tool for exploring the effects and relative importance of the quantifiable threats on population trajectories of the CSS subset of the WCT population. It is of particular value for managers, who can vary input parameters to explore the way different threat mitigation and management scenarios might theoretically impact the population trajectory, noting that it is very sensitive to the value included in the model for carrying capacity.

The cumulative model defined for the CSS subset of the WCT population included several advances in threat characterisation and population assessment that are a result of ongoing research, such as underwater acoustic monitoring, pinniped and cetacean surveys, and contaminant impacts. Model use and refinement in future versions can help to adaptively inform and/or implement WCT recovery measures identified in the Recovery Strategy for the Transient Killer Whale (*Orcinus orca*) in Canada (DFO 2021). The Bigg's Killer Whale cumulative effects assessment components (Pathways of Effects and Population Viability Analysis models) should be reviewed and updated as new data and knowledge become available.

Future directions

While the WCT killer whale population is a relatively well-known and frequently-observed population, there was comparably less data and literature than was available for Southern and Northen resident killer whales. Ongoing monitoring of the WCT population as well as their prey populations will help elucidate the ecosystem's carrying capacity and further refine future projections.

The analysis of population size conducted for the current work was not an assessment of population status. It also was not designed to identify which threats or combinations of threats are affecting Bigg's killer whales. Rather, we evaluated the potential response of the WCT killer whale population in the CSS to primary threats that were identified in the SARA listing, as well as the availability of prey in the region.

More generally, many uncertainties remain and efforts would be improved by increased research. In particular, the effects of acoustic disturbance and vessel presence on WCT are a significant knowledge gap. Emerging research will improve our understanding of these threats (e.g., DFO 2017, 2024; Tennessen et al. 2024) and allow future refinements of the cumulative effects model for WCT.

OTHER CONSIDERATIONS

Climate change impacts and future changes in the threats, their impact on Bigg's Killer Whale populations, prey populations, and the ecosystem were not included in the current assessment and should be considered in future modeling efforts, when possible.

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