

Ecological Impacts of Cumulative Anthropogenic Threats on Coastal Apex Predators

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Abstract: The cumulative effects of human activities—such as fishing, shipping, and pollutant discharge—can have profound impacts on coastal marine ecosystems. Apex predators can serve as reliable indicators of ecosystem health due to their vulnerability to disturbances. This paper takes the endangered Southern Resident Killer Whales (SRKW) along the northeastern Pacific coast of North America as a case study to analyze how the accumulation of human activities poses threats to the ecology of apex predators. The results indicate that food scarcity, vessel disturbance, and pollutant accumulation are the primary factors affecting the SRKW population; moreover, the cumulative nature of these stressors further exacerbates the burden on the ecosystem. By regulating fishing practices, reducing vessel noise, and controlling pollutant emissions, the adverse effects of human activities can be mitigated. This paper is expected to provide valuable insights for informing conservation strategies and guiding future development along more ecologically friendly trajectories for coastal ecosystems.

Keywords: Anthropogenic pressures, Coastal ecosystems, Apex predators, Southern Resident Killer Whales (*Orcinus orca*), Endangered species.

1. Introduction

As the region closest to land, coastal waters are subject to the most pronounced impacts of human activities. A variety of anthropogenic stressors—including fisheries, maritime traffic, pollution discharge, and coastal development—are directly and indirectly altering coastal marine ecosystems. For instance, unsustainable fishing practices may lead to trophic collapse and ecosystem failure; excessive vessel traffic can disrupt the behavioral activities of marine organisms, with collisions causing direct mortality; and land-based sewage discharges increase contaminant levels in both the water column and marine organisms, threatening their health and survival. Moreover, beyond the effects of individual activities, the spatial and temporal overlap of multiple stressors can produce broader and more synergistic ecological consequences. This means that even when the impact of a single activity appears limited, the accumulation of multiple disturbances may result in significant ecological harm. Therefore, incorporating cumulative effects into the integrated assessment of anthropogenic pressures is essential for evaluating ecological risk.

Apex predators can serve as indicator species for assessing the robustness of an ecosystem. On the one hand, because they occupy the highest trophic levels and rely on a fully functioning food web, any disturbance at lower trophic levels—such as changes in energy storage or the bioaccumulation of toxic substances—can propagate upward and affect them directly. On the other hand, through top-

down control, they regulate the abundance of species at lower trophic levels, and such cascading effects can influence the entire food web, thereby helping to maintain ecological balance. Therefore, the conservation of apex predators is critical for sustaining the structure and function of marine ecosystems.

The killer whale (*Orcinus orca*), a toothed cetacean, represents the largest species within the oceanic dolphin family, with an average body length exceeding 6 meters. These animals have a high degree of sociality and engage in complex vocal communication within groups. *Orcinus orca* is a top predator in the marine ecosystem along the northeast Pacific coast of North America, with a long lifespan and low reproductive rate. Individual populations typically specialize in studying specific types of prey, a phenomenon known as ecological specialization or ecology [1]. These biological and behavioral characteristics make them particularly sensitive to environmental changes. On the coastlines of British Columbia and Washington state, there are two similar but different populations, both belonging to an ecological type that feeds entirely on fish. Based on geographical distribution, these two communities are referred to as the Northern and Southern Residents. Despite their similar diets, they have exhibited markedly different population trends since the cessation of the live-capture trade—which drastically reduced killer whale numbers—in the mid-1960s. While the Northern Resident Killer Whale (NRKW) population has shown steady growth, the Southern Residents have experienced a continued decline. Studies suggest that this divergence may be attributed to differences in the degree of anthropogenic pressures affecting the two populations [2]. In response to these concerns, the Southern Resident population has been recognized as endangered by both Canada and the United States, with protection granted under Canada's Species at Risk Act since 2001 and under the U.S. Endangered Species Act since 2005. To date, many research institutions and environmental organizations, including the U.S. National Oceanic and Atmospheric Administration and Fisheries and Oceans Canada, have been involved in the long-term monitoring and study of both populations. These efforts have also included cross-border collaboration and have resulted in a robust foundation for scientific understanding.

This paper focuses on the endangered Southern Resident Killer Whales (SRKW) and aims to investigate the role of anthropogenic factors underlying the population's ongoing recovery challenges. Drawing on current research, it analyzes the individual and cumulative effects of multiple environmental stressors that pose threats to the population. In response to these pressures, the paper proposes a set of practical recommendations for conservation. By using SRKWs as a representative case, this study also seeks to enhance our understanding of the cumulative impacts of human activities on coastal marine ecosystems and to underscore the importance of their conservation.

2. Factors threatening endangered southern resident killer whales

2.1. Case description

The Southern Resident Killer Whale population, listed as endangered, primarily inhabits the outer coastal and inland waters of Washington State and British Columbia. According to the most recent census conducted in July 2024, the population currently consists of only 73 individuals. Based on current research, the key threats to the recovery of SRKWs include the decline in prey resources, disturbance from vessels, and exposure to toxic contaminants. Limited access to prey makes it difficult for individuals to meet their metabolic needs, leading to reproductive failure and ultimately constraining population growth [3]. Vessel noise and echo sounders interfere with the acoustic signals SRKWs rely on for communication and foraging, thereby disrupting their behavior and reducing prey capture efficiency [4]. The bioaccumulation of toxic pollutants further impairs their physical health and reproductive capacity, contributing to the slow pace of population recovery [5]. In addition to these primary threats, several less conspicuous but still significant factors must not be overlooked.

Due to the population's genetic isolation, ongoing population decline is likely to reduce genetic diversity, weakening their resilience to environmental stressors. Coastal development may also restrict their movement and access to key foraging areas, further exacerbating the difficulty of obtaining sufficient food. These factors, along with their potential interactions, collectively affect the persistence and rebound potential of the SRKW population.

2.2. Analysis of the anthropogenic threats

2.2.1. Insufficient prey

The diet of SRKWs consists exclusively of fish, with Chinook salmon (*Oncorhynchus tshawytscha*) serving as their primary prey year-round, while other salmonid species and non-salmonid fishes also contribute significantly to their overall diet composition [6]. Recent evidence suggests that a insufficient prey resources represent a significant threat to the viability of SRKW population, particularly concerning the abundance and accessibility of their primary prey, Chinook salmon.

Specifically, the abundance of Chinook salmon has been linked to the fecundity and survival of SRKWs, both of which are considered major factors limiting the population's recovery. According to theoretical estimates derived from demographic models, and under the assumption of a stable age structure and consistent survivorship, the estimated fecundity rate for SRKWs is 0.21s—markedly lower than the 0.26 observed in the recovering Northern Resident population. In reality, the reproductive performance of SRKWs may be even more compromised. Based on a median peak fecundity of 0.21, the 31 reproductive-age females within the population would be expected to produce approximately 48 calves between 2008 and 2015; however, only 28 births were documented during this timeframe, substantially below the expected number. This discrepancy indicates the presence of environmental constraints limiting reproductive success in real-world conditions. A time-series study analyzing the hormonal composition of SRKW fecal samples supports the role of nutritional stress in pregnancy failure [7]. Progesterone and testosterone levels were utilized as reliable hormonal markers to assess pregnancy status, timing, and overall maternal health, while using fecal glucocorticoid and thyroid hormone metabolites, as well as their ratios, to evaluate nutritional and disturbance-related stress. Among these, the temporal pattern of fecal glucocorticoids was particularly informative for distinguishing nutritional stress from vessel-related disturbance. Results indicated that unreliable prey availability during gestation contributed to a 69% reproductive failure rate during the observation period, more than half of which were classified as late spontaneous abortions associated with significant energy loss and physiological risk to the mother. These findings emphasize that sufficient Chinook salmon abundance is fundamental to the growth and sustainability of the SRKW population.

However, many Chinook salmon populations within the SRKW's range are themselves severely impacted by human activities and are listed as threatened or endangered. This represents a classic case of anthropogenic stress propagating through ecological cascades within the food web, ultimately becoming magnified in apex predators like the Southern Resident Killer Whales. Current research indicates that, beyond natural predation, the primary drivers of Chinook salmon declines include climate change and fisheries harvest [8]. Large-scale climate variability exerts indirect but significant effects on Chinook salmon across multiple stages of their life history. For example, reductions in freshwater runoff can shrink available habitat and decrease juvenile survival rates during the freshwater phase. In the marine environment, climate indices such as the North Pacific Gyre Oscillation and the Pacific Decadal Oscillation have been linked to population productivity, marine survival, and returning spawner abundance. Fisheries, on the other hand, have exerted a direct impact on Chinook salmon population size. Prior to the implementation of stricter harvest regulations in the mid-1990s, overfishing was a major driver of Pacific salmon population declines. Even before

European contact, salmon harvesting played a central role in the subsistence and culture of coastal communities, and the expansion of fishing practices with industrialization has caused lasting impacts on many Chinook populations. In addition, pathogen transmission from aquaculture operations and migration barriers caused by dam construction also pose significant threats to their survival. Although population declines have since been stabilized to some extent, the overall abundance of Chinook salmon remains at low levels, continuing to constrain the recovery potential of SRKWs.

2.2.2. Impacts and sound from vessels

Since the ability of killer whales to hunt is largely dependent on their sophisticated use of echolocation to identify and pursue prey, sound is crucial for their survival. This dependence is even more pronounced in killer whales, who also rely on complex acoustic signals for social communication and cooperative behavior. Today, human activities, particularly vessel traffic, are introducing increasing levels of anthropogenic noise into the marine environment. This noise pollution is expanding rapidly and has become a significant and persistent threat to coastal killer whale populations. The habitat of SRKWs lies in close proximity to heavily developed human areas, encompassing three international ports and a high density of both recreational and commercial vessels. As a result, vessel noise is widespread and continuous and has become a critical factor affecting the whales' ability to forage and meet their energetic demands.

Theoretical calculations suggest that a typical modern vessel passing through the SRKW habitat can increase broadband ambient noise levels by 12 to 17 dB. This noise falls within the 20-70 kHz frequency range, which overlaps with the primary acoustic bandwidth used by SRKWs for social communication and echolocation. A study utilizing animal-borne biologging tags, which recorded both acoustic and movement data, quantitatively assessed the impacts of vessel presence and associated noise [5]. The findings showed that noise levels negatively affected multiple foraging stages of SRKWs, in patterns consistent with the predicted outcomes of auditory masking. As vessel speed and number increased, the success rate of prey capture significantly declined, and sex-specific differences were observed in the whales' behavioral responses to noise exposure.

Killer whales are obligate breath holders, and diving to forage incurs considerable metabolic costs. An analysis of deep-diving foraging success in SRKWs found that, under increasing noise levels, females tend to abandon prey pursuits, while males spend more time attempting to forage [9]. Since anthropogenic noise increases search time and reduces foraging efficiency, sustained search efforts under noisy conditions are considered a high-risk energetic strategy, suggesting that the energetic demand of foraging exceeds the high metabolic cost. Male killer whales, being larger in body size and possessing greater diving capacity, also have higher energy requirements. In contrast, females may be constrained by the need to care for vulnerable calves, limiting their ability to engage in prolonged or energetically costly dives. Furthermore, noise indirectly affects prey quality, as larger and more energy-rich Chinook salmon tend to inhabit deeper waters, making them harder to access in disturbed acoustic conditions. These combined effects interact in multiple ways to exacerbate the overall difficulty SRKWs face in acquiring sufficient energy for survival.

2.2.3. High levels of contaminants in water

Anthropogenic activities have resulted in the extensive introduction of persistent organic pollutants (POPs) into marine ecosystems, particularly in urban coastal regions with intensive industrial development. These pollutants are highly stable and resistant to degradation, allowing them to persist in seawater and sediments over long periods. As they move up the food web through biomagnification, they pose chronic health risks to top predators, including killer whales. Based on contaminant levels

measured in tissue samples, SRKWs are among the most POP-contaminated marine mammals in the world.

According to the dietary habits of SRKWs, the primary source of POPs in their tissues is the bioaccumulation of contaminants in their main prey—Chinook salmon. Analyses of tissue composition in Pacific salmon have shown that Chinook salmon generally contain higher concentrations of POPs compared to other salmonid species. Notably, Chinook salmon sampled from southern regions—primarily consumed by SRKWs—exhibit the highest POP concentrations and the lowest lipid content within the population [10]. This elevated contaminant load reflects not only the historically high levels of POP input in adjacent urban-industrial regions but also relates to the higher fat content of Chinook salmon relative to other salmonids, due to the lipophilic nature of POPs. However, despite both SRKWs and NRKWs relying heavily on Chinook salmon, SRKW tissues contain several times higher POP concentrations than those of Northern Residents. This disparity is largely due to the lower lipid content in southern Chinook salmon, which likely compels SRKWs to consume a greater quantity of prey to meet their energy demands—thereby increasing their cumulative exposure to POPs.

Based on a systematic assessment of three of the most prevalent and elevated POPs detected in SRKW tissues: polychlorinated biphenyls, polybrominated diphenyl ethers, and dichlorodiphenyltrichloroethane and its metabolites, these contaminants pose serious physiological threats to SRKWs, including hormonal disruption, neurotoxicity, and immunosuppression [10]. These risks are particularly pronounced in calves, which are more vulnerable during early developmental stages. Due to the lipophilic nature of POPs, contaminants can be transferred from mothers to offspring via gestation and lactation. During pregnancy, high levels of maternal POPs exposure have been significantly associated with an increased likelihood of fetal death, as well as mortality during the perinatal and neonatal stages, thereby reducing population-level reproductive success. During lactation, rapid lipid transfer enables the conveyance of large quantities of contaminants to calves in a short time, posing a critical threat during a period when they are physiologically most vulnerable. POPs interfere with the endocrine system, leading to fluctuations in hormone levels that affect growth, development, and sexual maturation. Their neurotoxic effects may impair memory and learning capacity, potentially compromising foraging efficiency and social behaviors. Additionally, immune system suppression reduces disease resistance, increasing susceptibility to infection and mortality. These effects are often long-term and irreversible, significantly undermining the viability and resilience of the SRKW population.

2.2.4. Cumulative effects of multiple stressors

Beyond the impact of individual stressors, the interactive and combined impacts of various human-induced stressors on Southern Resident Killer Whales should not be overlooked. For instance, insufficient prey availability leads to increased lipid metabolism in SRKWs, which in turn releases greater amounts of lipophilic compounds, including persistent organic pollutants, thereby intensifying contaminant exposure risks [7]. In addition, vessel noise increases the difficulty of foraging, compounding the energetic stress already imposed by reduced prey accessibility [9]. The accumulation of these stressors amplifies the overall physiological and behavioral burden on SRKWs, highlighting the need for comprehensive and integrative conservation strategies that address multiple threats simultaneously.

3. Suggestions

To mitigate the threat of prey limitation, the foremost priority is to enhance monitoring of climate-induced terrestrial weather changes, oceanographic processes, and their associated ecological effects, and to develop science-based fisheries management policies that promote the recovery of Chinook

salmon populations. Additionally, attention must also be given to pathogen transmission from aquaculture and the barriers to salmon migration posed by river infrastructure. According to a series of bilateral workshops jointly convened by the U.S. National Marine Fisheries Service and Fisheries and Oceans Canada, the effects of Chinook salmon fisheries on SRKWs were evaluated, providing expert scientific support for binational cooperation in fisheries management and species conservation [11]. During the freshwater phase of Chinook salmon's life cycle, when they are most affected by human-altered habitats, river engineering structures play a critical role in shaping population recovery. While dams can help regulate seasonal runoff and in part buffer the effects of terrestrial climate variation on habitat conditions, they also pose significant challenges to salmon migration and spawning. Therefore, adaptive management and ecological retrofitting of these hydrological infrastructures can help mitigate the adverse impacts of climate change on salmon habitats, restore migratory pathways, and ultimately support the recovery of Chinook salmon populations as a crucial prey resource for SRKWs.

Reducing the impact of vessel noise on Southern Resident Killer Whales largely depends on the strength of governmental policy development and enforcement. According to an acoustic trial aimed at reducing vessel noise, lowering vessel speed was found to significantly reduce acoustic disturbance and benefit SRKW foraging behavior [12]. In addition to implementing speed and noise restrictions within critical foraging habitats, the establishment of stricter whale-watching regulations can help alleviate environmental pressures from ecotourism and promote public awareness of cetacean conservation. Furthermore, the development and adoption of quieter propulsion technologies and vibration-dampening structures can reduce noise at its source. Public outreach and education play an essential role in raising societal awareness of acoustic habitat protection, facilitating the acceptance and execution of related policies. Moreover, advancing research on the impacts of acoustic disturbance on SRKWs will help refine management strategies and inform evidence-based policymaking.

The sources of POPs in the marine environment are diverse, and their impacts are long-lasting, making effective pollution control dependent on multi-level and multi-sectoral collaboration. For scientific research institutions, it is essential to strengthen monitoring and analytical efforts to clearly identify the sources of marine POPs and to track emerging contaminants. Research should also focus on evaluating the effects of different POPs on SRKWs, thereby providing scientific support for the formulation of evidence-based conservation policies. In addition, developing advanced technologies for the effective treatment and removal of existing contaminants is critical for long-term management. For government agencies, strict regulations are needed to limit emissions, phase out the production and use of substances with high environmental risks, and enhance oversight of pollutant sources. Furthermore, governments should actively promote international cooperation and inter-agency coordination to reduce the overall circulation of POPs in marine ecosystems. Ultimately, the success of POPs governance will largely depend on effective collaboration among scientific institutions, government authorities and the general public. Coordinated actions and mutual support among these stakeholders are essential to achieve meaningful progress in marine pollution control and the protection of SRKWs.

Ongoing research and scientific assessment of the SRKW population itself are also essential components of conservation efforts. Long-term monitoring of key indicators such as health status, reproductive success, mortality rates, and individual behavioral responses can help more accurately identify threat mechanisms and population vulnerabilities. With the availability of extensive research data and advanced modeling approaches, it is now possible to better evaluate the ecological needs of SRKWs and to assess the cumulative impacts of multiple anthropogenic stressors on the population [13]. Incorporating these findings into management decisions enables the development of more

targeted and effective conservation strategies, which can help mitigate the negative effects of human activities and improve the long-term survival prospects of the SRKW population.

4. Conclusion

The endangered SRKWs illustrate the profound ecological impacts of cumulative human activities on coastal apex predators. Prey limitation, vessel disturbance and pollutant accumulation are the three primary threats hindering the recovery of the SRKW population. Climate change, fisheries exploitation and infrastructure development have collectively disrupted Chinook salmon populations, the main prey of SRKWs. As nutritional needs go unmet, reproductive failure rates increase, recruitment is compromised, and starvation intensifies the release of lipophilic POPs from body fat reserves. Vessel noise masks SRKW hearing, interfering with their use of echolocation for foraging, which in turn exacerbates the energetic stress caused by prey scarcity. Pollutant discharge leads to high concentrations of POPs in both habitats and prey species, which are then biomagnified through the food web, impairing the physiological and reproductive health of SRKWs, especially the most vulnerable calves, and ultimately threatening the viability of the entire population. In response to these challenges, this paper has proposed targeted recommendations, including increased investment in scientific research and stronger policy support from governmental agencies. These measures aim to facilitate the restoration of Chinook salmon populations, reduce vessel-related disturbances, and mitigate the impacts of pollutants. The findings are expected to offer valuable insights for SRKW conservation, raise awareness of the ecological consequences of coastal human activities, and support the implementation of eco-friendly coastal strategies. Nevertheless, this paper has several limitations. Potential mismatches in the temporal and spatial scales of the studies cited, as well as methodological differences across research efforts, may introduce uncertainties. Future studies with more comprehensive and precise data are needed to further enhance our understanding of how cumulative anthropogenic threats affect the ecology of coastal apex predators.

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