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Remotely Sensed Metrics for Evaluating Wild Killer Whale Health

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Remotely Sensed Metrics for Evaluating Wild Killer Whale Health

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Contents

Figures

Tables

Plain Language Summary

Background

In order to create strategies that improve the future outlook for endangered species, such as Southern Resident killer whales, we study both population and individual health. However, wildlife health is not commonly defined in a measurable way. Instead, "health" is still a relatively arbitrary construct, making it difficult to monitor and understand both for individual animals and for populations of wild animals. This becomes critically important for small, endangered populations, where management actions to ensure the health and resiliency of individual animals can help the population survive. In small, highly endangered populations where animals are known individually, we can identify animals of concern, determine the cause of decline, and apply targeted and effective interventions. This requires a range of reliable tools for evaluating multiple aspects of health—tools that don't interfere with the animals any more than necessary. These tools can be deployed in the field, providing data we can interpret and, when indicated, act on.

We hosted a workshop with subject-matter experts to provide feedback on the practicality and potential of a suite of tools for remotely collecting health metrics for wild killer whales. Data and observations collected during field trials over the prior three years served as the foundation for evaluating these tools.

Key Takeaways

- Some of the remotely sensed health metrics have been trialed and are ready for routinely assessing aspects of the health of Southern Resident killer whales. Other health metrics are ready to evaluate the health of whales of concern. The rest need more research, more data, or further development to be considered useful.
- If we develop a conceptual model for Southern Resident killer whale health, we will better understand the relationships between external and internal stressors and the population's ability to function, satisfy daily needs, and adapt to a changing environment.
- Ideally, this should be a "determinants of health" model that encompasses many factors that influence an individual's well-being, excluding infections, diseases, and contaminants. These factors encompass both individual characteristics, biological processes, social relationships, environmental conditions, and human expectations.
- The healthy, sympatric population of Bigg's killer whales is an ideal reference population for better understanding health in Southern Resident killer whales. These mammal-eating killer whales are not endangered, and their growing population presents an ideal opportunity for developing, evaluating, and refining health metrics.

- An effective, routine, year-round health assessment initiative to monitor Southern Resident killer whale health will give us the comprehensive overview we need to evaluate changes in individual and population health to support conservation efforts. This requires multi-institutional collaboration and coordination. We highly recommend a centralized electronic medical records system for collating these independently collected health data as medical record entries. Such a system, readily accessible by managers, easy for scientists to upload data, and secure—so that scientists can provide data with set expectations and reassurances regarding data sharing—will be most effective for sharing up-to-date health data. Such an initiative will require a similar commitment of effort and resources as those available for managing North Atlantic right whale health.

Links used in this section:

- Southern Resident killer whales: https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/southern-resident-killer-whale-orcinus-orca
- Management actions: https://www.fisheries.noaa.gov/topic/marine-mammal-protection/conservation-and-management
- Health and resiliency: https://www.fisheries.noaa.gov/national/marine-life-distress/marine-mammal-health-and-stranding-response-program
- Sympatric population: https://en.wikipedia.org/wiki/Sympatry
- Bigg's killer whales: https://www.fisheries.noaa.gov/feature-story/new-research-reveals-full-diversity-killer-whales-two-species-come-view-pacific-coast
- Managing North Atlantic right whale health: https://www.fisheries.noaa.gov/species/north-atlantic-right-whale/conservation-management

Executive Summary

To improve understanding of the health of Southern Resident killer whales (SRKWs; *Orcinus orca*) and contribute information to support recovery of this endangered population, a workshop was convened to discuss development of innovative methods for remotely assessing the health status of, and for remotely diagnosing and treating, individual animals. In addition to being able to promote recovery by improving health outcomes for individual animals, the collection of diverse data on the health of SRKWs may allow for improved detection of how interactive stressors are affecting population recovery. Detailed health data may also have the potential to help understand how subtle population changes, or lack thereof, have been affected by novel management practices. At a workshop, subject experts collectively identified 20 tools that are ready to deploy for routinely assessing SRKW health, much like the tools a physician might use to evaluate a person's health at their annual physical. Of these, eight were behavioral, five were associated with body condition, four required breath samples, and three used fecal samples. They also identified 40 existing tools as ready to be deployed to better understand the health status of a Southern Resident killer whale of concern. These are more like diagnostic tools that would be employed by a physician to determine the underlying cause of disease in a sick person. Although not ready for field use, multiple tools were identified as having promise but needing further research and development. Additionally, there was consensus that development of a conceptual model for SRKW determinants of health could inform management decisions, including options ranging from fishery management measures to veterinary intervention on ailing animals. The top need identified for advancing understanding of SRKW health was electronic health records. While this is not a tool for evaluating health or diagnosing disease, such a record system would provide a critical platform for integrating and interpreting health data collected from both animals of concern and the population as a whole. While there was no in-depth discussion on the level of funding that might be needed to complete research and development of nascent health metrics and to operate a year-round health assessment team, there was acknowledgement that insufficient funding was a current hindrance.

Acknowledgments

This workshop was funded by the Rose Foundation, SeaWorld Parks, the SeaDoc Society (a program of the Karen C. Drayer Wildlife Health Center at the University of California, Davis School of Veterinary Medicine), and the San Diego Zoo Wildlife Alliance. In-kind salary support, and in some cases travel, was provided by all the participants' institutions. We thank all workshop participants for their time and help reviewing health metrics, and Dr. D. P. Noren for reviewing this technical memorandum and providing comments that strengthened it.

Introduction

The Southern Resident killer whale (SRKW; *Orcinus orca*) population was listed as endangered in 2003 under the Canadian Species at Risk Act, and in 2005 under the U.S. Endangered Species Act (ESA). Despite recovery efforts on both sides of the border, the population remains small and vulnerable and has failed to maintain a positive population trajectory since listing (NMFS 2021). While prey availability, vessel disturbance, high levels of persistent organic pollutants, and small population size (inbreeding) are primary causes for decline, the lack of recovery since listing has led scientists and wildlife managers to become increasingly concerned about how these threats impact the health of individuals within the population, and the lack of tools available to assess the health of individual animals (NMFS 2021, Trego et al. 2025). A subject-matter expert panel found that poor body condition of individuals is associated with loss of fetuses, calves, adults, and the general population decline (Matkin et al. 2017). Only one in five dead whales are recovered for autopsies (Barbieri et al. 2013), and the mechanism and cause of death can only be determined for a portion of those recovered (Raverty et al. 2020). To date, quantitative assessment of body condition is the only objective measure of the health status of individual whales (Fearnbach et al. 2018). Despite the immense potential value of these data, health changes that result in weight loss detectable by photogrammetry can be more chronic than acute and, regardless of whether body condition changes are picked up early or late in the disease process, photogrammetry data do not provide information on the underlying cause(s) of the loss of body condition.

The SRKW population recovery plan includes recovering salmon, reducing vessel disturbance, and mitigating for persistent organic pollutants, and provides for the possibility of individual animal intervention, as has been attempted in the past (Gaydos et al. 2019) and could be done in the future (Williams et al. 2024a). Veterinary intervention (Deem et al. 2001) has been used to aid in recovery of free-ranging endangered species like Hawaiian monk seals (*Monachus schauinslandi*; Gobush et al. 2011) and the Florida manatee (*Trichechus manatus latirostris*; Adimey et al. 2016). Also, veterinary intervention was responsible for 50% of the population growth seen in endangered habituated mountain gorillas (*Gorilla beringei beringei*; Robbins et al. 2011). Recently, modeling has indicated that disease diagnostics and veterinary intervention may be necessary for recovering SRKWs (Williams et al. 2024a). Similar to how removing a snare from a breeding age female mountain gorilla facilitates her survival, continued reproduction, and contribution to the population's growth, a relatively simple veterinary response—such as remotely treating a female killer whale with an infected propeller wound with long-acting antibiotics—could allow her to survive and continue to contribute to SRKW population growth. In 2017, a population viability analysis suggested that a 2.3% growth in SRKW population could be achieved by reducing underwater noise by 50% and increasing salmon availability by 15% (Lacy et al. 2017). Kardos et al. (2023) suggested that genetic rescue would also benefit the SRKW population. More recently, a population viability analysis showed that for SRKWs to attain even a 1% population growth, efforts to reduce noise and contaminants and increase salmon should be combined with noninvasive health assessments, informed veterinary clinical intervention, and post-treatment monitoring to reduce mortality in high-value animals like reproductively active females (Williams et al. 2024a). Despite ongoing uncertainty concerning the number of preventable killer whale deaths, as well as the practical capacity for intervention to prevent them, this analysis indicates a potentially significant role for veterinary intervention in the management of this population. In recent priority action plans for Southern Resident killer whales (2021–25), developing tools to better measure the health of individual whales was recognized as a priority action (NMFS 2021) as well as in a subsequent health workshop (Trego et al. 2025).

Over the last several decades there have been copious advances in treating captive and live-stranded cetaceans (Nollens et al. 2017). Unfortunately, while there are numerous lessons to be learned from captive and live-stranded animals, many diagnostic and treatment modalities are not directly transferable to assessing health or treating sick cetaceans in the wild. For example, efforts to diagnose and treat a sick 3-year-old SRKW calf, J50, were unsuccessful, largely due to the unprecedented use of, and therefore hesitation to apply, capture-and-release health assessment strategies, combined with a lack of remote tools available for diagnosing the cause of decline (Gaydos et al. 2019). More recently developed remote diagnostic tools for assessing health in free-ranging cetaceans like bottlenose dolphins (*Tursiops truncatus*) hold promise for informing management decisions and aiding in conservation and recovery (Barratclough et al. 2019). While a lot can be learned from these and other cetacean health assessment initiatives, adult killer whales are substantially larger than bottlenose dolphins, thereby discouraging their short-term capture for health evaluation. Their size also limits options for traditional hands-on veterinary assessment and treatment, requiring the development of innovative methods for remotely assessing the health status of, and for remotely treating, individual animals.

In addition to being able to promote recovery by improving health outcomes for individual animals, the collection of increasing amounts of diverse data on the health of SRKWs may allow for improved detection of how interactive stressors are affecting population recovery. Detailed health data may also have the potential to help understand how subtle population changes, or lack thereof, have been affected by novel management practices. For example, in human medicine, electronic health records have not only improved clinical decision making, the quality of care, and health outcomes for individuals, but—when designed correctly—they have been used to improve public health and health care disparities in populations (e.g., Birkhead et al. 2015, Kruse et al. 2018). In the case of wildlife and SRKWs specifically, health data and electronic health records should similarly provide the support tools needed for better population management and recovery.

Decades of work have enabled scientists and managers to understand health in free-ranging North Atlantic right whales (*Eubalaena glacialis*), which has focused recovery efforts on addressing anthropogenic causes of mortality (Moore et al. 2021). To arrive at this point where disease and mortality monitoring have been able to inform management, a dedicated effort was required to elucidate causes of mortality in stranded animals (Moore et al. 2004), and scientists had to develop a suite of reliable tools that permit visually assessing the health of living animals (Pettis et al. 2004, Rolland et al. 2016).

Developing a suite of qualitative and quantitative tools to evaluate the health of individual killer whales and the health of their population would benefit from a similar commitment of effort and resources to research and development. To be effective, on-water teams should be supported adequately to be able to acquire standardized health data and samples routinely and opportunistically throughout the year, and not only during pre-defined fieldwork periods. Test results are more useful to decision-makers if they are made available for review and evaluation by the collective subject-matter expertise of the SRKW recovery stakeholders, and not siloed in separate databases. For multiple years, researchers have been piloting metrics that could be used to evaluate killer whale health. In 2023, we convened a group of topic experts to evaluate existing and putative health metrics and tools for remotely evaluating killer whale health. Here we describe the outcomes of this workshop.

Materials and Methods

On 27–28 March 2023, 28 subject-matter experts participated in a two-day meeting to discuss the reliability, quality, and usefulness of putative remotely sensed health metrics and tools for measuring health in the SRKW population as well as in individual animals. A total of 52 potential metrics and tools were discussed that could help evaluate health in individual animals or at the level of the population. Topically, they were divided into behavior ($n = 13$), body condition ($n = 6$), fecal sample analyses ($n = 10$), inbreeding ($n = 1$), respiratory sample analyses ($n = 18$), skin condition ($n = 1$), mortality ($n = 2$), and medical records ($n = 1$). Using a collective genius approach (Hill et al. 2014), workshop participants qualitatively scored each proposed metric or tool using three criteria:

1. The effort and invasiveness of sample collection.
2. The reliability of findings.
3. Confidence in the ability to interpret results and their utility in evaluating a whale's health.

Ultimately, we collectively scored tools or metrics as:

- Currently ready to deploy for routinely assessing the health of individual animals or the Southern Resident killer whale population.
- Currently ready for use to understand health status in animals of concern (e.g., an animal suspected to be sick).
- Needing more research, data, or development.

Using the example developed by the Washington Department of Fish and Wildlife to better understand bat health, workshop participants discussed the pros and cons of developing a conceptual model for SRKW determinants of health, similar to Wittrock et al. (2019; Figure 1). Specifically, Wittrock et al. (2019) identified that, as a concept, wildlife health is more than the absence of pathogens or disease. As with human health, SRKW health is an aspirational capacity that is the cumulative state of physical health and personal, social, and environmental factors, rather than a dichotomous state in which an individual or population is binomially classified as healthy or unhealthy. Wittrock et al. (2019) demonstrated that a "determinants of health" model as developed for humans can be applied to wildlife species, and that such a model better reflects wildlife health for resource management decisions. Specifically, they called out six themes that should be included:

1. The biologic endowment of the individual and population.
2. The animal's social environment.
3. The quality and abundance of the animal's needs for daily living.
4. The abiotic environment in which the animal lives.
5. Sources of direct mortality.
6. Changing human expectations.

Figure 1. Determinants of fish and wildlife health, adapted from Wittrock et al. (2019).

The goal in developing a determinants of health framework for SRKWs is to have a tool that can be used for planning, developing policy, and guiding research. In turn, this health framework will support the development and implementation of health protection priorities and promote conservation actions.

At the workshop closing, we asked participants to identify top needs for improving our understanding of killer whale health.

Results

Twenty-eight subject experts (Table 1) collectively identified 20 existing tools that are ready for use for routine health assessment of Southern Resident killer whales. Of these, eight were behavioral, five were associated with body condition, four required breath samples, and three used fecal samples (Table 2, labeled *Yes* in Column 6).

They also identified 40 tools that are ready to be deployed to better understand the health status and diagnose cause of disease in SRKW of concern. Of these, ten were behavioral, five were related to body condition, 13 required breath samples, ten required fecal samples, one had to do with inbreeding coefficient, and one was related to skin lesions (Table 2, labeled *Yes* in Column 7). Tools that were identified as helping to provide value in diagnosing a pathogen and etiology for measuring health (e.g., fecal aerobic and anaerobic bacterial culture) were considered useful when diagnosing disease in animals of concern (Table 2, Column 7), but do not provide the resolution and detail required for understanding or managing health at the population level.

Table 1. Wild killer whale health workshop participants.

Name	Organization
Lynne M. Barre	NMFS West Coast Region
Christopher Dold	United Parks & Resorts, Inc.
Dave Ellifrit	Center for Whale Research
Candice K. Emmons	NMFS Northwest Fisheries Science Center
Tara Galuska	Office of the Governor, Washington State
Joseph K. Gaydos	The SeaDoc Society/UC Davis Wildlife Health Center
Deborah Giles	Wild Orca
Frances M. D. Gulland	Marine Mammal Commission
Katherine Haman	Washington Department of Fish and Wildlife
M. Bradley Hanson	NMFS Northwest Fisheries Science Center
Martin Haulena	Vancouver Aquarium
Marla M. Holt	NMFS Northwest Fisheries Science Center
Catherine F. Lo	The SeaDoc Society/UC Davis Wildlife Health Center
James McBain	United Parks & Resorts, Inc. (retired)
Hendrik H. Nollens	San Diego Zoo Wildlife Alliance
Dawn P. Noren	NMFS Northwest Fisheries Science Center
Stephanie A. Norman	Marine-Med
Linda D. Rhodes	NMFS Northwest Fisheries Science Center
Todd R. Robeck	United Parks & Resorts, Inc.
Kyle Ross	National Marine Mammal Foundation
Mark Sears	Independent
Maya Sears	The SeaDoc Society/UC Davis Wildlife Health Center
James K. Sheppard	San Diego Zoo Wildlife Alliance
Jessica J. Stocking	Washington Department of Fish and Wildlife
Jennifer Tennessen	University of Washington
Sheila J. Thornton	Fisheries and Oceans Canada
Megan M. Wallen	NMFS West Coast Region
Michael Weiss	Center for Whale Research

Table 2. Putative killer whale health tools and metrics. In Column 5, *B* = boat, *U* = UAV. Metrics that are ready for use for routine health assessment are labeled *Yes* in Column 6; those ready for diagnosing disease in an animal of concern are labeled *Yes* in Column 7.

Tool focus	Health metric	Rationale	Comments and relevant publications	Platform	Routine health assessment?	Animal of concern?
Behavior	Behavioral budget	Changes in health can lead to changes in behavioral budget (travel, rest, forage, play).		B/U	No	No
	Buoyancy	Decreases in lung volume due to edema, phlegm, inflammatory infiltrate, or pleural effusion can negatively affect buoyancy and cause listing while at rest; reduction in blubber can also affect buoyancy and swimming kinematics.		B/U	Yes	Yes
	Change in buoyancy with respirations at rest	Changes in total lung volume or tidal volume may decrease changes in buoyancy with respirations; reduction in blubber can also affect buoyancy and swimming kinematics.		B/U	No	Yes
	Character of movement	General weakness and decreases in body condition and buoyancy can result in less fluid surfacing motion.	This metric may be useful with a compromised whale.	B/U	Yes	Yes
	Feeding/foraging	Suboptimal health can negatively affect appetite and food drive.		B/U	Yes	Yes
	Foraging bout time	Lusseau et al. 2004	Northern Resident killer whales will feed longer when prey abundance is higher.	B/U	No	No
	Individual's social interactions	Foster et al. 2012, Ellis et al. 2017, Nattrass et al. 2019		B/U	Yes	Yes
	Inter-whale distance during foraging	Not well developed or proven; Parsons et al. 2009		U	No	No
	Lone whales			B/U	Yes	Yes
	Proximity of older calves to mothers	Changes in social grouping may reflect weakening health.	Noren and Hauser 2016	B/U	Yes	Yes
	Social cohesion of pods	Whales in suboptimal health may spend increased amounts of time in close proximity to specific individuals. Estrus affects proximity.	Noren and Hauser 2016	B/U	Yes	Yes
	Speed of movement relative to pod	Whales in compromised health may show decreased swim speed relative to the pod members. Entire pods may decrease their swim speed to allow weaker animals to keep up.	Williams et al. 2024b	B/U	Yes	Yes

Table 2 (continued). Putative killer whale health tools and metrics.

Tool focus	Health metric	Rationale	Comments and relevant publications	Platform	Routine health assessment?	Animal of concern?
Behavior (cont'd)	Synchrony of surfacing young and older animals			B/U	No	Yes
Body condition	Body condition of individual	Inanition, poor nutrition, or chronic health issues can lead to poor body condition.	Higher confidence in UAV-based than boat-based body condition evaluation; see Fearnbach et al. (2018) for objective body condition scoring.	U	Yes	Yes
	Body condition of pod members	Changes in body condition of pod members can provide a background for distinguishing generalized weight loss (e.g., ecosystem influences) from individual animal weight loss (e.g., during illness).	Higher confidence in UAV-based than boat-based body condition evaluation; see Fearnbach et al. (2018) for objective body condition scoring.	U	Yes	Yes
	Change in body condition (since last sighting)	Positive or negative trends in body condition can help differentiate acuteness or chronicity of the underlying cause.	Higher confidence in UAV-based than boat-based body condition evaluation; see Fearnbach et al. (2018) for objective body condition scoring.	U	Yes	Yes
	Individual growth curve	The measurement of individual growth over time is widely used to assess health and nutrition of humans and animals. For example, WHO publishes Child Growth Standards as a reference for healthy growth in children and adolescents. Growth suppression is also a fundamental part of the generalized stress response in all vertebrates.	This metric is best assessed from historical records. Size at age was only subjectively evaluated during this effort. Defer to Fearnbach et al. (2018) for objective measures. This metric would greatly benefit from compiling historical growth curves for all individual SRKWs.	U	Yes	No
	Pregnancy	When is birth expected? Is it based on body condition vs. progesterone levels, or both?	Need to know how many abortions or successes females have. When during pregnancy are losses occurring?	B/U	Yes	Yes
	Size at age	Chronic or congenital health issues can lead to decreased size at age in growing animals.	This metric is best assessed from historical records. Size at age was only subjectively evaluated during this effort. Defer to Fearnbach et al. (2018) for objective measures. This metric would greatly benefit from compiling historical growth curves for all individual SRKWs.	U	No	Yes
Feces	Defecation character	Changes in diet and changes in gastrointestinal health can affect the gross appearance of defecations.	Fecal virus screen, fecal parasite screen, and fecal algal biotoxin-level analyses are pending.	B/U	No	Yes

Table 2 (continued). Putative killer whale health tools and metrics.

Tool focus	Health metric	Rationale	Comments and relevant publications	Platform	Routine health assessment?	Animal of concern?
Feces (cont'd)	Defecation frequency	Cetaceans have a fast gastrointestinal transit time. Recent feeding triggers defecations. Diarrhea in cetaceans manifests as increased frequency of defecations. Feeding frequency also affects defecation.	Boat-based observations of feeding and foraging are less reliable than UAV-based observations. The contribution of observations of defecations to health evaluations is still limited due to the lack of historical observations from a UAV platform and due to the short observation times.	B/U	No	Yes
	Fecal algal biotoxin levels	Presence of domoic acid or saxitoxin in feces would indicate recent exposure to algal biotoxins.		B/U	Yes	Yes
	Fecal bacterial culture	Presence of known enteric pathogens (*Salmonella* spp., *Campylobacter* spp., some *E. coli*) can indicate gastrointestinal infection.		B/U	No	Yes
	Fecal cytology	Inflammation, infection, and parasitism of the gastrointestinal tract can result in the presence of host immune cells in feces.		B/U	Yes	Yes
	Fecal gram stain	Inflammation, infection, and parasitism of the gastrointestinal tract can result in imbalances of the bacterial flora in feces.		B/U	Yes	Yes
	Fecal parasite screen	Presence of unusual parasites in the feces can indicate compromised gastrointestinal health.	Protozoal assay also picks up nematodes.	B/U	No	Yes
	Fecal virus screen (NEM)	Presence of virus groups that are known enteric pathogens in other mammals can indicate gastrointestinal infection.		B/U	No	Yes
	Metabalomics	Comparison to known disease syndromes.		B/U	No	Yes
	Proteonomics	Comparison to known disease syndromes.		B/U	No	Yes
Inbreeding	Inbreeding coefficient	See Kardos et al. (2023). Consider having a coefficient for each SRKW individual.		n/a	No	Yes

Table 2 (continued). Putative killer whale health tools and metrics.

Tool focus	Health metric	Rationale	Comments and relevant publications	Platform	Routine health assessment?	Animal of concern?
Respiratory	Breath smell character	Disease in the respiratory tract or even potentially metabolic disease can often cause a change in the breath odor.		B	Yes	Yes
	Respiratory character	Discomfort and compromised lung health can result in changes in respiratory character.	Respiratory character could be evaluated in real time.	B/U	Yes	Yes
	Respiratory pitch and duration using a directional microphone	Compromised lung health can result in changes in respiratory pitch and sounds.	Respiratory character could be evaluated in real time. Respiratory character was also documented using a directional microphone for future review.	B/U	No	Yes
	Respiratory rate (at travel)	Decreased fitness and compromised lung health can trigger increased respiratory rate while exercising.	Williams and Noren 2009, McRae et al. 2024, Williams et al. 2024b	B/U	No	Yes
	Respiratory rate (at rest)	Discomfort and compromised lung health can trigger increased respiratory rate at rest/increased respiratory interval.	Can be challenging to find animals at rest.	B/U	No	Yes
	Vapor bacterial culture	Compromised respiratory health can result in the presence of bacterial pathogens in exhaled breath samples.		B/U	No	Yes
	Vapor *Brucella* spp. PCR	Active infection with *Brucella ceti* can result in the presence of *Brucella* spp. DNA in exhaled breath.		B/U	No	Yes
	Vapor cytology	Inflammation, infection, and parasitism of the upper and lower respiratory tract can result in the presence of host immune cells in exhaled breath condensate.	The vapor, when captured, was diagnostically useful. UAVs were flown over the course of two separate weeks. The investigator team continues to optimize sample-collecting methodology.	B/U	Yes	Yes
	Vapor fungal culture	Compromised respiratory health can result in the presence of fungi in exhaled breath samples.		B/U	No	Yes
	Vapor gas analysis	Gas composition of exhale can change with metabolic changes in some species.		B/U	No	No

Table 2 (continued). Putative killer whale health tools and metrics.

Tool focus	Health metric	Rationale	Comments and relevant publications	Platform	Routine health assessment?	Animal of concern?
Respiratory (cont'd)	Vapor gram stain	Inflammation, infection, and parasitism of the upper and lower respiratory tract can result in changes in the presence and makeup of bacteria in exhaled breath condensate.		B/U	Yes	Yes
	Vapor metabolomics		Need to compare syndromes or etiologies to findings.	U	No	No
	Vapor microbiome	Compromised respiratory health can result in changes in the presence and makeup of bacteria in exhaled breath condensate.		B/U	No	Yes
	Vapor panbacterial PCR	Compromised respiratory health can result in the presence of bacterial pathogens in exhaled breath samples that may not grow on in-vitro culture.		B/U	No	Yes
	Vapor panfungal PCR	Compromised respiratory health can result in the presence of fungi in exhaled breath samples that may not grow on in-vitro culture.		B/U	No	Yes
	Vapor plume height (FLIR)	Compromised lung health can result in changes in tidal (exhaled) breath volume and may be measurable as changes in the height of the exhaled breath column.	The vapor plume was successfully imaged, but equipment failure interfered with evaluating this health metric.	B/U	No	No
	Vapor plume height (ratio to dorsal)	Compromised lung health can result in changes in tidal (exhaled) breath volume and may be measurable as changes in the height of the exhaled breath column.	The vapor plume was successfully imaged, but equipment failure interfered with evaluating this health metric.	B/U	No	No
	Vapor proteonomics		Need to compare syndromes or etiologies to findings.	U	No	No
Skin	Amount of gray patches and target lesions	Point prevalence of these two lesions is increasing annually; could be related to body condition and/or immune status.	Gaydos et al. 2023; increasing over years, not tied to etiology, but could be metric of immune health.	B/U	No	Yes

Table 2 (continued). Putative killer whale health tools and metrics.

Tool focus	Health metric	Rationale	Comments and relevant publications	Platform	Routine health assessment?	Animal of concern?
Mortality	Loss of calves under five years old in a pod over a set time frame	Recruitment in pod provides a background for interpreting changes in individuals. Lack of post-weaning survival to > 5 yr due to factors other than age structure would negatively affect assessment.		n/a	n/a	n/a
	Number of mortalities in a pod over the last three years	Mortalities in pod provides a background for interpreting changes in individuals. Recent mortalities may negatively affect assessment.		n/a	n/a	n/a
Records	Electronic medical records	Need to share findings with managers, not for research purposes, but for management.	Password protected. Enter health assessment findings in real time. Complete annually.	n/a	n/a	n/a

Figure 2. Draft determinants of killer whale health framework, including the six themes associated with health. This framework needs to be more thoroughly developed, workshopped by experts, and ultimately submitted for peer review.

Although not ready for field use, eight additional tools were identified as putatively having promise for use for routine health assessment or for diagnosis in an animal of concern, but needing further research and development (Table 2; labeled *No* in Columns 6 and 7). In some instances, tool use and data collection were fully functional, but the health metric required more data to determine their usefulness in distinguishing normal from abnormal.

At the workshop, there was consensus that developing a conceptual model for SRKW determinants of health using the framework by Wittrock et al. (2019) should be formally completed. One participant (KH) sketched out a starting point (Figure 2), recognizing that a finalized model needs to be more thoroughly developed, workshopped by experts, and ultimately submitted for peer review.

Electronic health records were identified as the top need for advancing our understanding of SRKW health. Participants were clear that electronic records were not a tool as discussed above, but rather a critical platform for integrating and interpreting health data collected with the tools discussed.

While there was not an in-depth discussion on the level of funding that might be needed to complete research and development of nascent health metrics and to operate a year-round health assessment team, there was general participant acknowledgement that insufficient funding was a current hindrance and needed to be addressed at some point in the near future if health assessment is to be adequately incorporated into recovery-related decision-making.

Discussion

Assessment of wildlife population health has immense management and conservation merit, especially if health can be holistically and measurably defined. For example, successful management of white-tailed deer (*Odocoileus virginianus*), arguably one of the most important game species in North America, can include using parasite counts and body condition scoring to determine when populations are at carrying capacity (Gaydos 2005). Such information can enable managers to increase harvest levels well before deer overpopulation can be detected by overbrowse and other visible vegetation alterations that occur secondary to deer numbers exceeding available forage. In a very different scenario, conservation medicine that included health assessment and intervention was responsible for 50% of the population growth seen in endangered habituated mountain gorillas (Robbins et al. 2011). Evaluations of mortality and health have also played an important role in the recovery of the Florida manatee through a program often referenced as an "open system" that permits continuous change and adaptation while accounting for uncertainties, limited resources, numerous participants, and intense public scrutiny and involvement (Wallace 1994). For the highly endangered SRKW population, understanding health by using remotely sensed methods can provide both types of benefits. Routine health assessments of SRKWs provide a more timely mechanism for monitoring population health, inform decisions on management actions that benefit the population, and provide means for assessing the efficacy of management actions. Additionally, remotely evaluating the health of individual animals can identify animals of concern, pinpoint an underlying cause and etiology, and permit treatment of individuals. These recommendations are consistent with priorities previously identified by NMFS (see NMFS 2021, Trego et al. 2025). In addition, as shown by Williams et al. (2024a), the SRKW population is at such a low number that successful intervention and mortality prevention in just a few females could mean the difference between a population that grows or one that continues to decline into extinction.

While this workshop identified remotely sensed health metrics that have been trialed and are ready to be used to routinely provide information on certain aspects of SRKW population health, and others that are ready to provide data on individual animal health, in reality, some metrics can be valuable for both. For example, UAV-collected photogrammetry and body condition scoring can serve as a population-level health tool (e.g., more animals are thin than in prior years) as well as an individual animal health assessment tool (e.g., an individual of concern continues to lose body condition). Other tools are not as widely useful. For example, aerobic and anaerobic bacteriology of fecal samples is unlikely to tell us much about the health of the SRKW population overall, but in the case of an animal of concern, it could help us identify a bacterial gastrointestinal pathogen responsible for making an animal sick (e.g., *Salmonella* spp. infection). However, it is crucial to recognize that no single tool can be relied upon to unequivocally identify or categorize an animal as healthy or not. This is especially true if the goal is to identify animals of concern before their disease or health issues progress toward irreversible pathology. Therefore, continuing to develop a diverse range of diagnostic tools, each of which can help identify or narrow down potential etiologies behind each disease state (Trego et al. 2025), will help to improve the potential for appropriate response. A continuous assessment of data collected, information learned, and priorities identified is essential to ensure the usefulness of health-monitoring efforts.

Determinants of health encompass a wide range of factors that influence an individual's overall wellbeing, extending far beyond mere infections or diseases. These factors encompass biological, individual, social, and environmental elements. To best understand both population and individual animal wellbeing in SRKWs, we need to develop a conceptual model for their determinants of health. This can then be applied to management decisions, including a wide range of options from fisheries management measures to veterinary intervention on ailing animals.

The consistent and increasing occurrence of Bigg's killer whales (BKWs) in the Salish Sea allows ready access to this non-endangered and growing population, presenting an ideal opportunity for further development of remotely sensed health metrics. Routinely collecting and monitoring health in this sympatric killer whale population can serve as a comparative baseline for SRKWs (NMFS 2021) and will improve techniques and team efficiency for collecting health data (technique development and validation) from SRKWs. Additionally, it will ensure efficiency and operational flow for health team members. Scientists need to recognize that while techniques can be developed on BKWs and adapted to SRKWs, they are distinct populations with different diets and different behaviors, so BKWs cannot be used as a direct proxy for SRKWs. A recent example of this was slight differences detected in the BKW response to UAV collection of breath compared to the SRKW response to the same technique (Lo et al. 2024).

Fielding an effective, routine, year-round, and transnational killer whale health assessment initiative in the Salish Sea will require multi-institutional collaboration and coordination, as well as dedicated funding and support. A centralized electronic health records system—highly recommended for collating these independently collected health data—will be essential to ensure that data collected by numerous individuals, agencies, and organizations will translate into efficient health monitoring. Any electronic medical records system will need to be easily accessed by managers, easy for scientists to upload data to, and secure, so that scientists and managers can provide data with set reassurances and expectations regarding data sharing. The North Atlantic Right Whale consortium that collectively provides health monitoring that is integrated through an electronic health records system is a good model to emulate (Rolland et al. 2016).

The vision of workshop participants for a well organized health effort for SRKW recovery included an organizational structure that is collaborative and integrated, and funded at a level that permits integration of metrics, routine evaluation of findings, and continual improvement of the process. Workshop participants also recommended periodic overarching programmatic evaluations.

Next Steps

There was consensus among workshop participants that SRKW population recovery efforts would be enhanced if:

1. A community of experts worked together to continually assess known and putative health metrics (Table 2) and refine them as more funding and data are available. For example, Williams et al. (2024b) was published after the 2023 workshop. Now that it is published, a small group of experts on this metric could work with biologists to identify how swim speed and respiratory rate measured from land or by boat can be an active part of population or individual health monitoring.
2. Putative health metrics that have high potential value were prioritized for investment.
3. Long-term funding was secured to develop and support management and maintenance of a shared killer whale electronic health records database hosted by the Center for Whale Research. *Note*: As of January 2026, the Center for Whale Research and the SeaDoc Society received a grant from the National Fish and Wildlife Foundation for further developing a Southern Resident killer whale health monitoring database; a collaborator workshop was hosted in October 2024; and a prototype database was rolled out in December 2025.
4. A model for the determinants of killer whale health was developed, linked to remotely sensed health metrics, and used to identify areas for most impactful management actions.
5. A strategy was created to develop and seek funding for a comprehensive killer whale health monitoring program that will inform management action and SRKW recovery.

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