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Assessing the efficacy of ecological reserves: killer whale beach rubbing behaviour and vessel disturbance

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ABSTRACT: Area-based protection is an important tool for safeguarding key habitat. Reserves that focus on mitigation of specific threats are particularly effective and are more likely to support a measurable outcome. In the marine environment, reserves that limit vessel presence have the potential to reduce disturbance to marine mammals. However, assessing the efficacy of reserves has been an ongoing challenge. Physical and acoustic disturbance from vessels is recognized as a primary threat to recovery for the northern resident killer whale (NRKW) population in Canadian Pacific waters. The Robson Bight Michael Bigg Ecological Reserve (RBMBER) was developed to support the behaviour of beach rubbing, a culturally distinct and traditionally important activity. Beach rubbing provides a rare opportunity to quantify vessel disturbance of a behaviour associated with a fixed geographic location, identifiable by visual cues, and verifiable acoustically. Observations on vessel presence, NRKW rubbing frequency, and duration were collected from a beach inside the reserve and compared to a beach in proximity to, but outside of, the RBMBER. In 2019–2022, vessel counts near the RBMBER beach were significantly lower than near the unprotected beach, and overall, rubbing occurred more frequently inside the reserve (78% of visits) than outside (35%). However, outside the reserve, concurrent vessel presence did not predict the occurrence of rubbing activity, indicating that vessel presence may negatively affect beach rubbing through long-term learned avoidance of frequently impacted areas.

KEY WORDS: Marine reserve efficacy · Vessel impacts · Killer whales · *Orcinus orca* · Area-based management · Rubbing beach

1. INTRODUCTION

Physical and acoustic disturbance from vessels is recognized as a primary threat to recovery in killer whale (*Orcinus orca*) populations in the eastern North Pacific (Fisheries and Oceans Canada 2017). Studies on the southern resident killer whale (SRKW) population indicate that when vessels are close, whales spend less time foraging and more time travelling (Lusseau et al. 2009), are more likely to perform surface active behaviours (Noren et al. 2009), and have decreased rates of prey capture (Holt et al. 2021). Additionally, increases in vessel number and proximity correspond to changes in SRKW swimming paths that are consistent with vessel avoidance (Williams et al. 2009a). Northern resident killer whales (NRKWs) are also less likely to forage when vessels are nearby (Williams et al. 2006).

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The creation of marine reserves can be effective for mitigating anthropogenic impacts on cetaceans when the reserve encompasses areas where important life functions are carried out (Nelms et al. 2021). The Robson Bight Michael Bigg Ecological Reserve (RBMBER) is one such reserve that was established on June 17, 1982 to protect important core habitat for NRKWs by limiting public access (Ministry of Environment 2003). While the NRKW range extends throughout the northeast Pacific waters from Alaska to Washington State, part of the population spends a substantial portion of its time from July through October off the northeastern coast of Vancouver Island, an area with a high seasonal abundance of Chinook salmon *Oncorhynchus tshawytscha*, its primary prey species (Ford 2006).

Within this region are several locations at which NRKWs perform beach rubbing, a culturally distinct and traditionally important activity (Ford 1989, Ford et al. 2000, 2017). NRKWs selectively rub at specific, smooth-pebble beaches, including one within the bounds of the RBMBER and one 4 km beyond the reserve's western boundary. The proximity of these beaches presents an opportunity to assess the effectiveness of the RBMBER at reducing vessel presence and the subsequent benefit to NRKWs, as measured by the frequency and duration of beach rubbing. Adequate protection of beach rubbing sites is a conservation issue, given that preserving cultural continuity is a key component of the Species at Risk Act recovery strategy for this population (Fisheries and Oceans Canada 2011).

Here, we evaluated a distinct quantifiable behaviour (beach rubbing) associated with the presence of a geographic feature (rubbing beach) that occurs both inside and outside a reserve to examine the hypotheses that: (a) rubbing beaches within the RBMBER experience lower vessel presence, both in the presence and absence of whales, when compared to a rubbing beach outside the reserve; and (b) vessel presence is negatively correlated with frequency and duration of NRKW beach rubbing.

2. MATERIALS AND METHODS

2.1. Study area and visual data collection

In 2019–2022, vessel and whale data were collected from approximately July 1 to the first Monday in September (hereinafter referred to as summer), between 09:00 and 16:30 h Pacific Daylight Time from a land-based monitoring platform on West Cracroft Island (50.52453° N, 126.5974° W; approximately 50 m above sea level; Fig. 1). The study area consisted of the waters of Johnstone Strait that were visible from the observation platform and included 3 rubbing beaches (Strider, Main, and Kaizumi; Fig. 1). Encompassing these beaches, we defined 2 'beach vicinities' with 1440 m radii, the distance an NRKW would travel in a 15 min scan based on a swimming speed of 1.6 m s^{-1} (Williams & Noren 2009). A theodolite (TOPCON DT-205) was used to capture vertical and horizontal angles to a whale or vessel, and data were calibrated using angles to known reference locations and then converted to spatial coordinates using Mysticetus software (Mysticetus LLC 2022). To account for tidal changes in observer height above sea level, an updated altitude was calculated every 15 min using the vertical angle to a reference location at sea level.

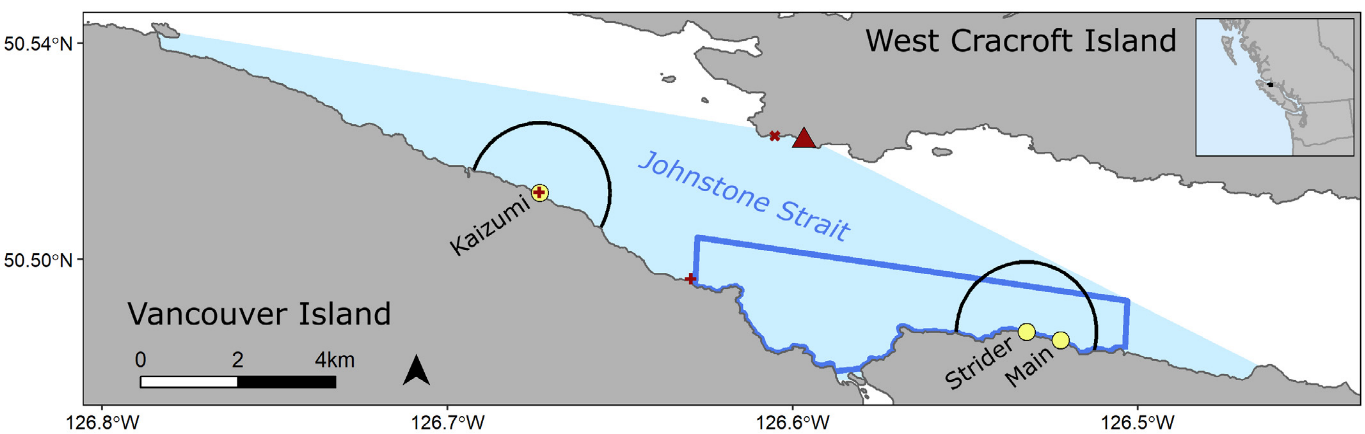

Fig. 1. Study area in Johnstone Strait. The visible area (light blue shading) for observers located at the observation platform (red triangle) included Robson Bight Michael Bigg Ecological Reserve (RBMBER; dark blue outline) and 3 rubbing beaches (yellow points). 'Beach vicinity' around Kaizumi and Strider Beaches indicated by black outlines (1440 m radius). Vertical (red 'x') and horizontal (red '+') reference points used to calibrate the theodolite are also indicated

The present study focuses on Strider and Kazumi Beaches to mitigate the effects of differences in substrate quality. Strider and Kaizumi Beaches exhibit similar substrate characteristics, with moderately sized and relatively uniform pebbles with little to no sand, whereas the substrate at Main Beach consists of a sandy gravel mix with thin patches of pebbles (T. Millard pers. comm.). When killer whales were in either beach vicinity (Section S1.1 in the Supplement at www.int-res.com/articles/suppl/n053p555_supp/), scans were conducted every 5−15 min and positional data for whales were collected, beginning with the lead whale, followed by the last whale in a group. A group was defined as individuals within 10 body lengths of each other. The predominant behaviour of each group of whales was recorded, and behaviour was classified as beach rubbing if the whales were within 50 m of a beach and exhibited rubbing behaviour (indicated by independent surfacing and diving, bubbles, splashes or circling fins; behaviour classifications after Williams et al. 2006).

Immediately following whale data collection, vessel data were obtained, starting from the direction of whale travel (e.g. vessels were sighted from east to west, if the whales were easting). Vessel type was recorded (Table S1), and 2 positions were collected for each vessel, approximately 5 s apart, to allow the calculation of vessel speed. In 2022, vessel observations were also collected at the start of every hour when no NRKWs were present in the study area.

Environmental conditions were recorded at the start of each day and were updated when conditions changed (sea state, visibility, precipitation, and glare). In 2021 and 2022, the condition of 'sightability' was added as a subjective index (rated as 1 to 5, with 1 being very poor and 5 being very good) to summarize overall conditions for spotting whales. Scans in which sea state was >4 on the Beaufort scale, visibility was 'restricted' (significant portions of the Strait obscured) or 'poor' (<1 km visibility), and/or sightability was <3 were removed from the analysis.

2.2. Acoustic data collection

In 2020 and 2021, passive acoustic monitoring systems were deployed at the rubbing beaches. Hydrophones were elevated ~50 cm above the sea floor (Sea to Shore Systems mooring) and positioned within 100 m of the high tide mark to optimize acoustic detection of beach rubbing (Table 1). Continuous data were acquired at a sampling rate of 64 kHz with 24-bit resolution using icListen HF Smart Hydrophones SC2-ETH (Ocean Sonics), calibrated by the manufacturer, with a preamp gain of 36 dB. The data were transmitted to shore stations via a hydrophone cable (MacArtney Underwater Technology, Type 4700) and broadcast via Ubiquiti Sector 5GHz 25dBi AC Radio and Antenna (model no.: PBE-5AC-400-ISO-US) to a laboratory station for storage as waveform audio files.

Table 1. Parameters of acoustic recorders located at rubbing beaches during 2020 and 2021 summer season. Reported sensitivities are at 26 Hz, except Strider Beach in 2021, which is at 250 Hz. Depths are relative to chart datum, with an uncertainty of ±0.5 m

Beach	Year	Sensitivity (dB re V/µPa)	Depth (m)	Recording dates
Kaizumi	2020	−169.8	13	Jul 10−Aug 25
	2021	−169.8	13	Jul 1−Sep 6
Strider	2020	−170.4	17	Jul 10−Sep 1
	2021	−177	12	Jul 1−Sep 6

2.3. Data processing

2.3.1. Vessel presence and speed

Theodolite positional data were used to calculate the distance of each vessel from the rubbing beaches. Due to limitations in the precision of positional data (Lo et al. 2022), occasional geopositioned sightings were on land (4.8% of sightings), particularly those at greater distances from the theodolite. Land sightings were repositioned to the edge of the water, along the horizontal bearing angle of the sighting from the observation platform, prior to calculating distance from beach. Due to limitations in the precision of theodolite positions and for vessel movement occurring during the 15 min scan, vessels were assigned to 1 of 3 distance bins relative to the beach: within 1 km, between 1 and 2 km, and further than 2 km. For each distance bin, the number of vessels present from each vessel category was counted (Table S1).

Vessel speed was calculated using the distance travelled and time elapsed between subsequent positions taken for the same vessel. If multiple speed estimates existed for a given vessel during 1 scan (i.e. if 3 successive positions were recorded instead of 2), the speed values were averaged. Speeds were then classified into ordinal bins: <1 knot (stationary), 1−5 knots (slow), 5−10 knots (moderate), 10−15 knots (fast), and >15 knots (very fast). To correct likely erroneous speeds, adjustments were applied based on credible vessel speeds: any kayak or log barge speeds >5 knots were re-assigned to the 'slow' speed bin, any speeds >10 knots for tugs with tows were re-assigned to the 'moderate' speed bin, and any speeds >15 knots for tugs without tows were re-assigned to the 'fast' speed bin. For other vessels, any calculated speed >50 knots was assumed to be due to an error in data collection, and the speed bin was set as unknown.

For each scan, the median and maximum vessel speed bin was determined from all vessels within 2 km of the relevant beach(es). If speed was missing for any relevant vessels, the median and maximum speed bins were considered to be unknown. Kayaks were not included in these summaries, given that their speeds were relatively constant, and their presence was assessed separately from motorized vessels.

2.3.2. Vessel types

Vessel types were assigned to 1 of 3 categories, according to an assumed degree of disturbance (Table S1): (1) vessels likely to cause physical disturbance only (non-motorized vessels, i.e. 'kayaks'); (2) motorized vessels with a greater likelihood of proximity and/or extended duration of proximity to a whale or rubbing beach (e.g. research, ecotourism, recreational boater; hereinafter referred to as 'recreation, research, and monitoring'); and (3) vessels whose proximity to a whale or rubbing beach was incidental to the vessel's operation (e.g. commercial operations, tugs, cruise ships, etc.; hereinafter referred to as 'commercial or coast guard').

2.3.3. Beach rubbing

To address differences in scan timing of visual data across sampling years, we used the first scan of each 15 min interval for the analyses. For a given scan interval, visual and acoustic assessments were carried out independently to assess whether beach rubbing occurred. Visually, if any group's behaviour was recorded as beach rubbing, then beach rubbing was recorded as present. Acoustically, beach rubbing was recorded as present, absent, or unknown based on visual and aural assessment of recordings using Raven Pro (Cornell Lab of Ornithology 2022). Beach rubbing was identified as present for scan intervals with a broadband signal associated with substrate movement that occurred during beach rubbing. Identification of the beach rubbing signal was pioneered by OrcaLab through simultaneous acquisition of underwater video and audio recordings of rubbing events (H. Symonds, OrcaLab, July 2019, pers. comm.). A characteristic beach rubbing acoustic signal begins with a higher amplitude band caused by the whale's initial impact with the pebble beach, followed by a fading gradient to lower amplitude for approximately the same frequency band (Fig. 2; Section S1.2). For Kaizumi Beach in 2020, substrate sounds were identified aurally in real time. Intervals that contained only ambiguous acoustic signals (i.e.

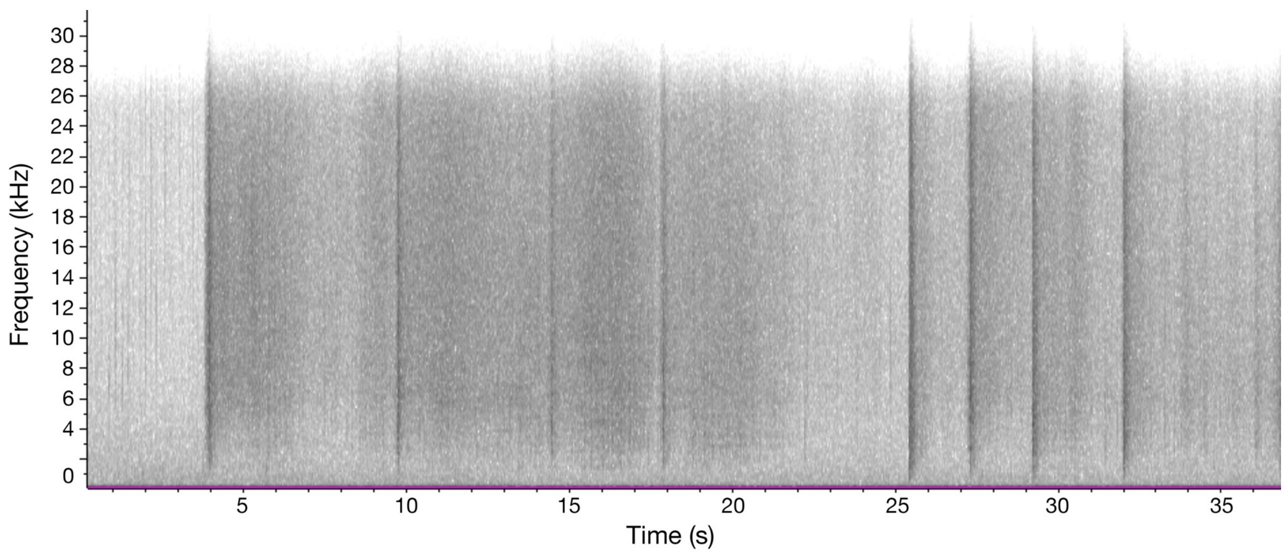

Fig. 2. A spectrogram of beach rubbing acoustic signals, recorded at Strider Beach, in RBMBER, on July 22, 2021. Higher amplitude indicated by darker shading. An accompanying acoustic file (Audio S1) is available at www.int-res.com/articles/suppl/n053p555_supp/

signal could be beach rubbing or from another sound source, such as wave action) were identified as unknown. If no beach rubbing or ambiguous signals were detected in a given scan interval, beach rubbing was recorded as absent. To examine the reliability of each method of assessing beach rubbing, the visual and acoustic detections of beach rubbing for each scan interval were compared.

Rubbing bouts were defined as consecutive 15 min scan intervals, wherein beach rubbing was detected visually and/or acoustically, during periods of visual observation.

2.4. Data analysis

2.4.1. Analysis parameters

All statistical analyses were performed in R, version 4.2 (R Core Team 2022). All analyses of vessel data and/or NRKW presence used all years of data (2019–2022). Analyses involving beach rubbing used only years for which both visual and acoustic rubbing data were available (2020 and 2021), unless otherwise stated.

2.4.2. Vessel presence

To compare mean seasonal vessel counts within 2 km of the beach per scan, 2-sided Wilcoxon rank sum tests (Mann & Whitney 1947) were performed for each pairwise combination of beach and year. The resulting significance values were adjusted using Holm's correction, to minimize the family-wise error rate (Holm 1979). Mean seasonal vessel counts in the study area as a whole were similarly examined. Vessel counts from each scan were treated as independent, as visual examination of differences between lagged vessel counts did not demonstrate a strong temporal autocorrelative signal.

Two-sided Wilcoxon rank sum tests were performed for each beach and vessel category, comparing the proportion of vessels in the study area within 2 km of the given beach each scan when no NRKWs were in the study area (collected in 2022 only) relative to when NRKWs were within the vicinity of the given beach (2019–2022). The resulting significance values were adjusted using Holm's correction. As the proportion of vessels within 2 km of a given beach did not vary significantly among study years (Wilcoxon rank sum test: Table S2), all years were pooled for this comparison.

2.4.3. Relationships between vessel and NRKW variables

Pearson's correlation coefficient was calculated using annual mean values at Kaizumi Beach for the number of vessels within 2 km each scan relative to NRKW beach visit duration and to the number of scans with visually observed beach rubbing each day of effort (2019–2022). Two-sided Spearman's rank correlation tests (Hollander & Wolfe 1973) were used to test for correlations between rubbing bout duration at Kaizumi Beach and 6 measures of mean vessel count: kayaks within 1 km of the beach, kayaks within 2 km, motor vessels within 1 km, motor vessels within 2 km, all vessels (kayaks and motor vessels) within 1 km, and all vessels within 2 km (2020–2021).

2.5. Modelling vessel impacts

2.5.1. Causal analysis and selection of variables

To inform causal inference, a directed acyclic graph (DAG; Fig. S1) was constructed (Shrier & Platt 2008) in the browser-based software DAGitty (Textor et al. 2016), to determine the variables that must be adjusted for (e.g. by including as a covariate in a model or filtering the dataset to 1 level of the variable; Section S1.3) to determine unbiased estimates of the variables of interest. Based on this DAG, adjusting each vessel variable (motor vessels presence, motor vessels speed, and kayak presence) by the other 2 vessel variables, as well as by tide height and beach quality, allowed for unbiased estimates of their effects on beach rubbing. For motor vessel presence and motor vessel speed, their estimated effects included the direct effect of the variable, as well as its indirect effect via underwater noise. For kayak presence, the effect estimated in the model is the unbiased direct effect on rubbing.

As we did not have direct estimates of beach properties that contribute to beach quality (e.g. beach area, substrate quality, slope), we used beach identity as a proxy. As a relative measure of tide height, altitude values derived from theodolite measurements were used.

2.5.2. Model development

Generalized additive mixed models (GAMMs) were used to evaluate the relative impacts of motor vessel presence, kayak presence, and motor vessel speed on the likelihood of NRKW beach rubbing, using years with both visual and acoustic beach rubbing data (2020 and 2021). To eliminate a bias introduced by beach identity, models were built for Kaizumi Beach only. This approach was chosen because only Kaizumi Beach provided reasonable variation in the vessel variables of interest (i.e. there was very little vessel presence near Strider Beaches) and imbalances in these variables between the beaches would complicate the effects of beach quality and vessel impacts in a multi-beach model. Our response variable was binary, indicating whether beach rubbing was visually and/or aurally observed (1) or not (0) in a given scan. Vessel variables were evaluated at a time lag of 1 scan.

Median and maximum speed bins were the only highly collinear variables (variance inflation factor [VIF] > 2; Zuur et al. 2009). Maximum speed bin was removed from the model. Median speed bin was consolidated to 3 levels: stationary (<1 knot), slow (1–5 knots), and moderate to very fast (>5 knots). To assess vessel presence and type, vessel counts were determined separately for kayaks and for motor vessels at 3 distance thresholds: within 1 km, within 2 km, or all vessels observed in the study area. A binary factor for vessel presence was also determined, as the presence or absence of motor vessels and kayaks within 2 km.

Models were built using tide height and each combination of vessel presence by vessel type, as well as 2 variations of a null model (see Table S8). The top-ranked models were selected using Akaike information criterion, corrected for small sample sizes (AICc; Hurvich & Tsai 1989). Models with score differences <4 (when compared to the score of the top-ranked model) were considered among the top model set, and the top-ranked model of this set would be considered the single best model if its weight was >0.9 (Burnham & Anderson 2002).

We fit candidate models (n = 12) with a binomial error distribution (logit link function) using restricted maximum likelihood, using the 'gam' function in the R package 'mgcv' (Wood 2011). To account for daily variation in uncontrolled variables, day was included as a random effect in all models. Cubic spline shrinkage smoothers were used to model the effects of continuous variables, to avoid overfitting (Marra & Wood 2011). Model residuals were examined to determine whether there was any outstanding autocorrelation. Second-order residual autocorrelation was identified in the model results, which was consequently mitigated by including the presence or absence of rubbing at Kaizumi Beach in the previous scan as a binary factor.

3. RESULTS

3.1. Vessel presence

Vessel presence within the RBMBER was lower than in surrounding waters (Fig. 3), resulting in significantly lower vessel counts in the proximity of Strider Beach than Kaizumi Beach in all years (Fig. 4; Wilcoxon rank sum test: Table S3). Vessels from all 3 categories were observed in the reserve (Fig. 3), but vessels from the 'kayak' category and the 'recreation, research, or monitoring' category were typically only observed near the reserve boundaries (Fig. 3). Kayaks and recreation, research, or monitoring vessels concentrated significantly in proximity to Kaizumi Beach when NRKWs were present at the beach relative to when NRKWs were absent from the study area, but vessels in the 'commercial or coast guard', category did not (Figs. 3 & 5). Proportions of recreation, research or monitoring vessels near Strider Beach also significantly increased when NRKWs were present in the beach vicinity (Fig. 5), with increased vessel presence near the reserve boundary (Fig. 3). Vessel counts varied across years at Kaizumi Beach and for the study area as a whole, but did not differ significantly at Strider Beach (Fig. 4, Table S3). Vessel counts near Kaizumi Beach were higher in 2019 relative to 2020 and 2021 (Fig. 4, Table S3). Similarly, in the study area as a whole, vessel counts were significantly greater in 2019 and 2022 than in 2020 (Table S4; daily mean vessel count per scan: 9.4, 3.2, 5.1, and 7.9 in 2019, 2020, 2021, and 2022, respectively).

3.2. NRKW beach visits

The number of days and the number of 15 min scans that NRKWs were observed in the vicinity of each beach increased across the study period, while the number of days of observer effort was similar across the 3 yr (Table 2). In all years, NRKWs were observed on more days in the vicinity of Kaizumi Beach than Strider Beach (inside the RBMBER), but whether NRKWs spent a greater total duration (measured in number of scans) at Kaizumi or Strider Beach varied among years (Table 2). There was statistically significant inter-annual variation in visit durations at Kaizumi Beach, with visits in 2019 and 2022 being shorter than in 2020 and 2021, but not at Strider Beach (Table S6). Beach visit duration did not vary significantly between beaches (Table S6).

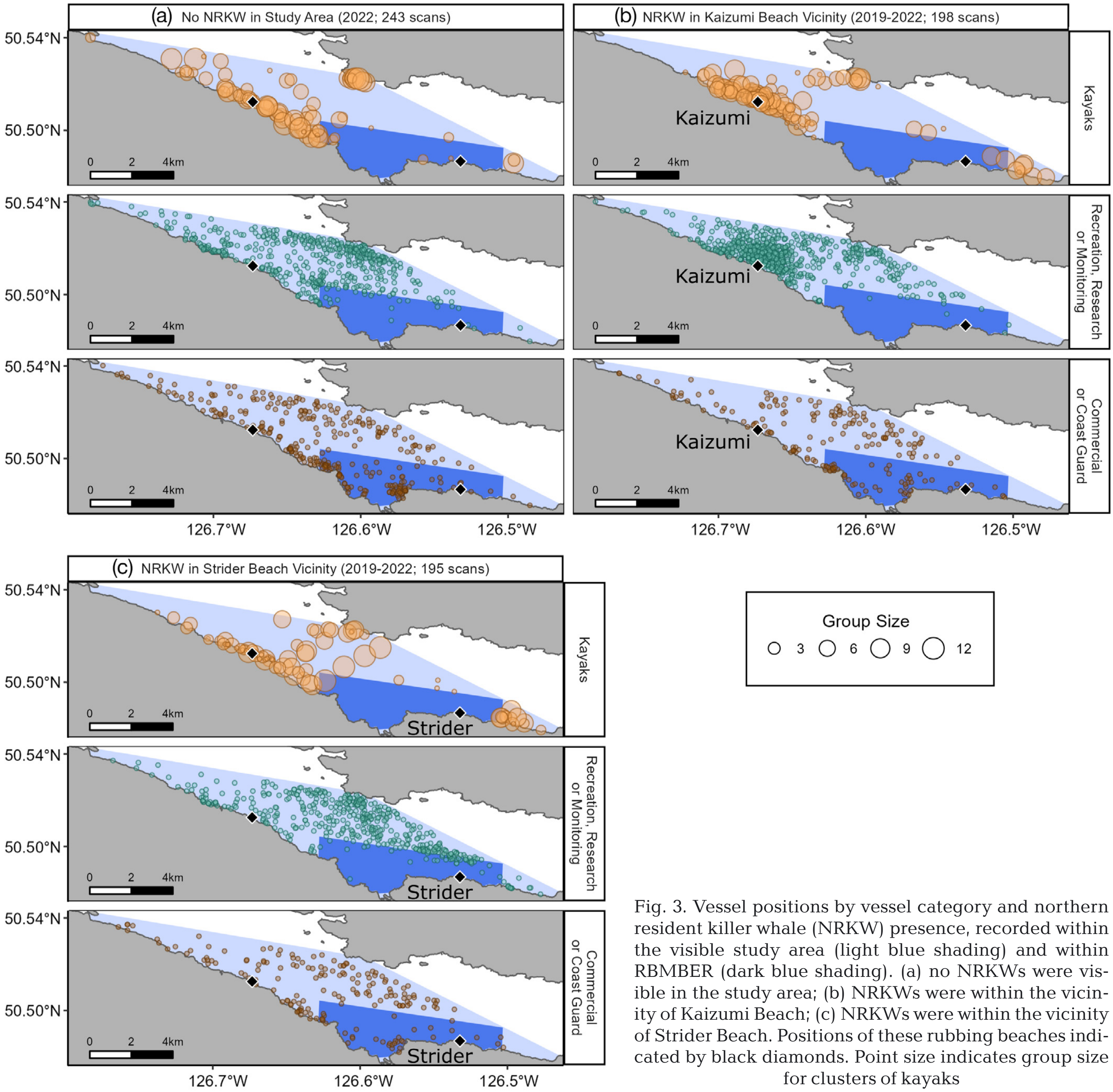

Fig. 3. Vessel positions by vessel category and northern resident killer whale (NRKW) presence, recorded within the visible study area (light blue shading) and within RBMBER (dark blue shading). (a) no NRKWs were visible in the study area; (b) NRKWs were within the vicinity of Kaizumi Beach; (c) NRKWs were within the vicinity of Strider Beach. Positions of these rubbing beaches indicated by black diamonds. Point size indicates group size for clusters of kayaks

3.3. Beach rubbing

By several measures, beach rubbing occurred more often at Strider Beach (inside the RBMBER) than at Kaizumi Beach. Once whales entered the vicinity of a rubbing beach, they were more likely to rub if they were at Strider Beach (78% of visits) than if they were at Kaizumi Beach (35% of visits), and whales at Strider Beach spent a greater proportion of their time rubbing relative to Kaizumi Beach (Fig. 6). Additionally, beach rubbing occurred on a greater number of days at Strider Beach than at Kaizumi Beach (Kaizumi: $n_{2020} = 7$, $n_{2021} = 8$; Strider: $n_{2020} = 9$, $n_{2021} = 13$). Observed rub durations did not differ significantly between beaches ($W = 192$, $p = 0.13$), but were longer on average at Strider Beach compared to Kaizumi Beach (44.5 and 30 min, respectively).

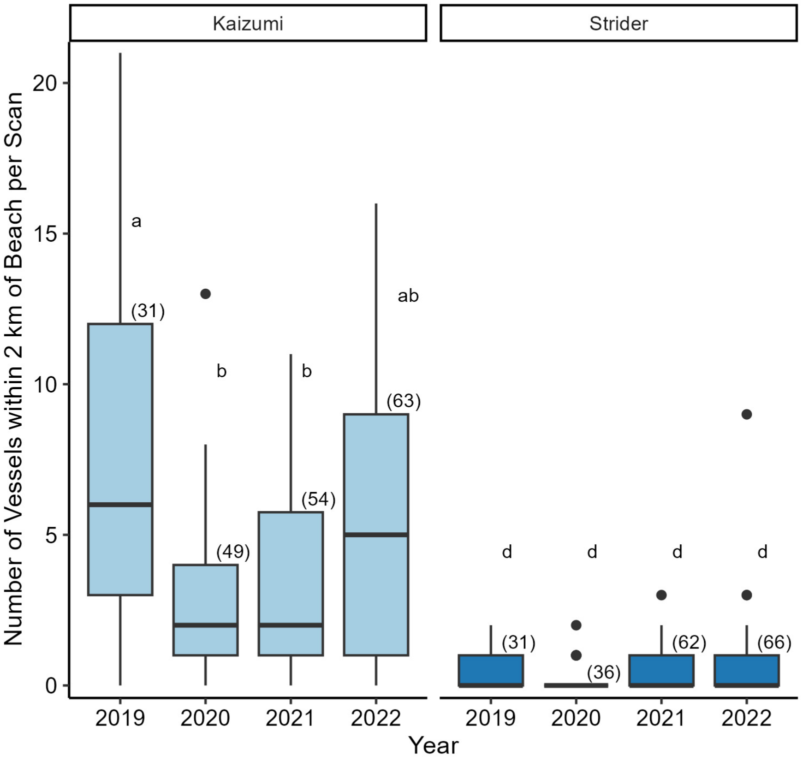

Fig. 4. Vessel counts by beach and year, indicating the variation in the number of vessels within 2 km of the beach, while NRKWs were within the vicinity of the beach. Lower and upper hinges correspond to the first and third quartiles; whiskers extend to the largest and smallest values no further than 1.5× the interquartile range; and black points are outliers. Sample size (number of scans) indicated in parentheses. Statistically significant differences ($p < 0.05$, after Holm's correction; Wilcoxon rank sum test: Table S3) indicated by different letters (a–d)

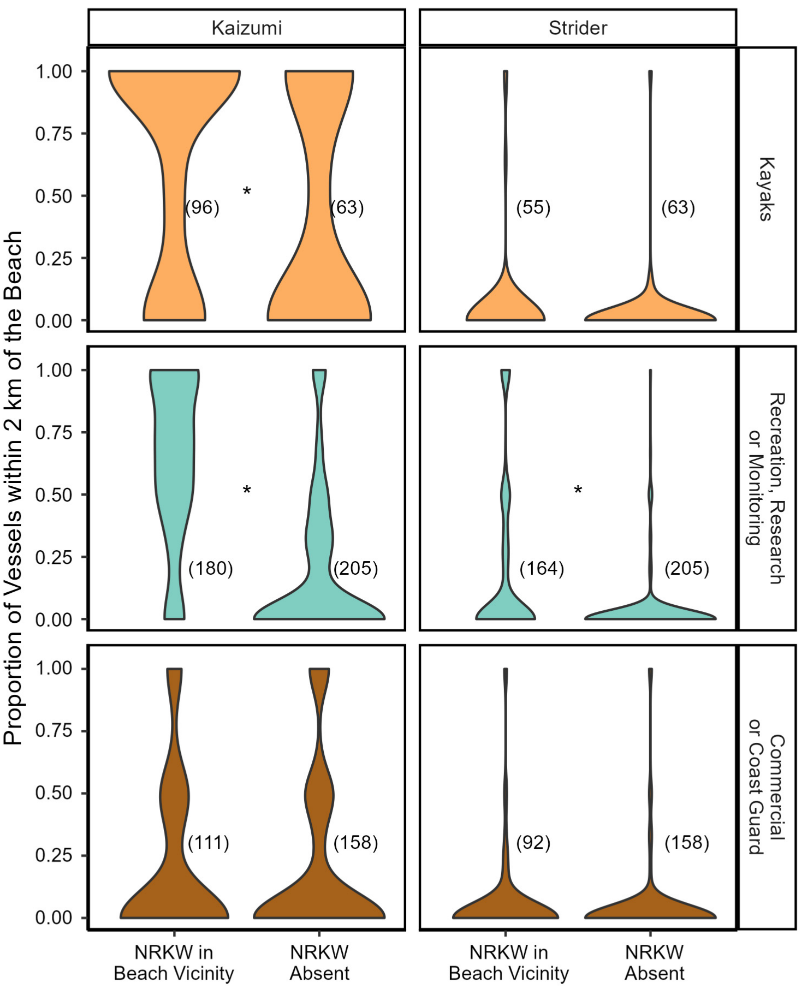

Fig. 5. Proportions of vessels near Kaizumi and Strider Beaches in relation to NRKW presence and vessel category. Within each panel, proportions are compared for while NRKWs were within the vicinity of the beach (2019–2022) and while no NRKWs were visible in the study area (2022). Data shown as a mirrored density plot. *Significant difference between proportions (Wilcoxon rank sum test: Table S5). Sample size indicated in parentheses

Table 2. Study effort and sample size by year and beach. Total number of days with observation effort includes days when no NRKWs were observed. Number of scans and days enumerated only when NRKWs were in the beach vicinity

Year	Total effort days	Kaizumi Beach Scans	Kaizumi Beach Days	Strider Beach Scans	Strider Beach Days
2019	56	31	17	31	9
2020	57	49	19	36	12
2021	58	54	20	62	16
2022	60	66	33	67	21

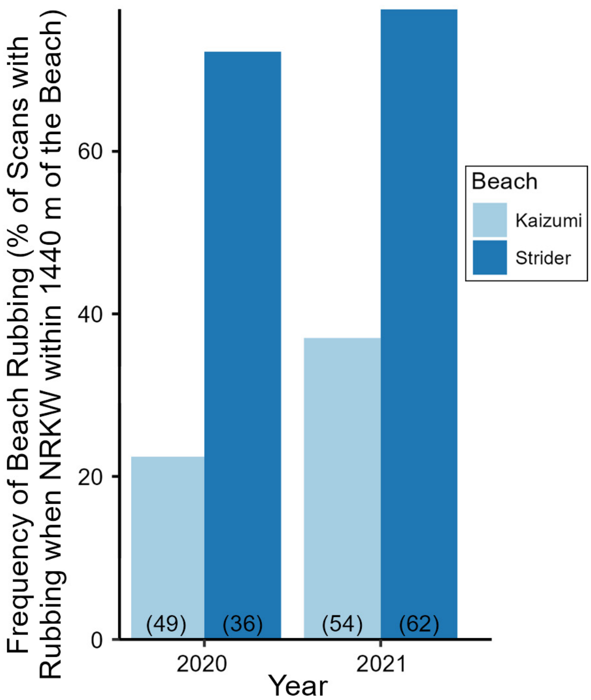

Fig. 6. Percentage of scans with beach rubbing detected (visually and/or acoustically), by beach and year. Sample size (number of scans for which NRKWs were within the proximity of the given beach) indicated in parentheses

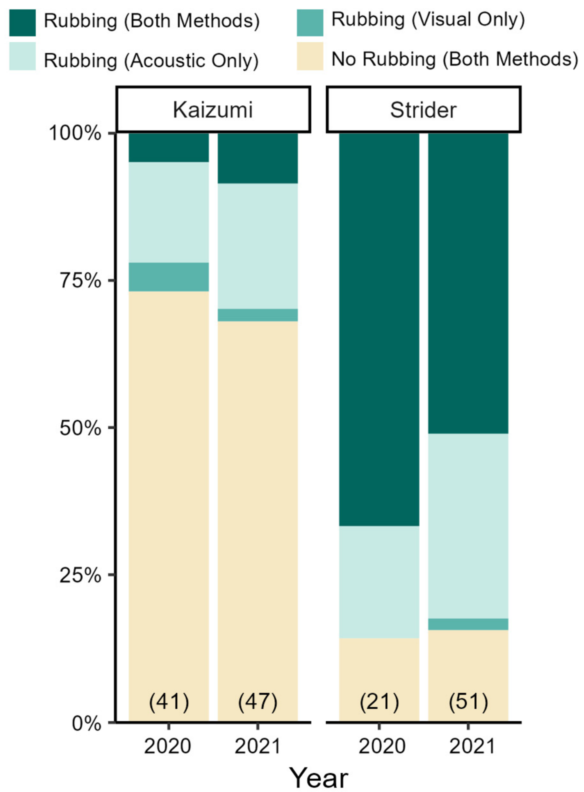

Fig. 7. Percentage of scans with beach rubbing detected acoustically, visually, or by both methods. Sample size (number of scans for which NRKWs were within the proximity of the given beach and both visual and acoustic data were available) indicated in parentheses

In the absence of close vessels (within 2 km of the beach), NRKW preference for rubbing at Strider Beach remained: Strider Beach had a higher rate of rubbing than Kaizumi Beach, considering both the proportion of time near the beach spent rubbing and the proportion of beach visits for which the whales decided to rub (Fig. S2).

3.4. Comparison of beach rubbing assessment methods

Acoustic and visual methods of assessing the presence or absence of beach rubbing agreed 77.3% of the time at Kaizumi Beach and 70.8% of the time at Strider Beach (Fig. 7). However, due to a high visual false negative rate, a non-negligible amount of the rubbing detected at each beach was detected only acoustically, and thus would be missed if relying on visual data only, particularly at Kaizumi Beach (63.6% of detected rubbing in 2020 and 66.6% in 2021; Fig. 7). For both beaches and both years, a smaller proportion of beach rubbing was missed acoustically than visually (Fig. 7).

3.5. Relationships between vessel and NRKW variables

3.5.1. Rub duration versus vessel presence

Among years, mean vessel counts within 2 km of Kaizumi Beach were negatively correlated with the mean length of each NRKW visit to the rubbing beach and mean amount of time spent beach rubbing each day (Fig. 8). However, when examining relationships at a finer temporal resolution, among beach rubbing bouts at Kaizumi Beach in 2020 and 2021, there was no significant correlation between mean motor vessel count, kayak count, or the combined count of all vessels within 1 or 2 km and observed rub duration (2-sided Spearman's rank correlation test: Table S7).

3.5.2. GAMMs

According to AICc scoring, the model that excluded all vessel variables (while including tide height, day, and prior rubbing) was the top-ranked model. It was the only model considered to be in the top model set (ΔAICc > 4 for all other models), though its model weight was < 0.9. All models with vessel variables were not among the top model set (ΔAICc > 4; Table S8) and detected no effect of vessel count at any distance threshold, though the second ranked model estimated a not statistically significant negative effect of higher motor vessel speeds on the probability of beach rubbing (Fig. S3).

4. DISCUSSION

The RBMBER was established in 1982 under the province of British Columbia's Ecological Reserve Act with the intent to reduce vessel presence and protect NRKW resting, socializing, foraging, and rubbing behaviour relative to the surrounding waters (Johnstone Strait Killer Whale Committee 1991, Ministry of Environment 2003). To evaluate the efficacy of the reserve, we first quantified the reduction in an anthropogenic threat (vessel presence) to NRKWs. Our data indicate that for the study duration (July and August), the reserve significantly reduced vessel presence near Strider Beach relative to Kaizumi Beach, both in the presence and absence of whales. This is largely due to the efforts by BC Parks and the Robson Bight Marine Warden Program, where each summer, on-water patrols discourage unauthorized vessel entry into the RBMBER and educate recreational users about the impacts of vessels on whales. As the RBMBER includes marine waters under federal jurisdiction, the provincial agency does not have the authority to enforce the marine boundaries of the reserve, but instead relies on education to achieve the mandate of the ecological reserve and reduce vessel transits. Incorporation of the RBMBER reserve boundaries on Canadian Hydrographic Service charts and chart plotter software serves to inform vessel operators of the presence of the reserve, and the significant on-water efforts of the Warden Program (established in 1987) have resulted in heightened awareness and general compliance from recreational and ecotourism vessels. However, increased protection has progressed slowly across years, as restrictions have increased and compliance has improved (Johnstone Strait Killer Whale Committee 1991). Presently, commercial fishers are still authorized to operate in the reserve, and commercial vessel transits (e.g. tug and tows) are not restricted

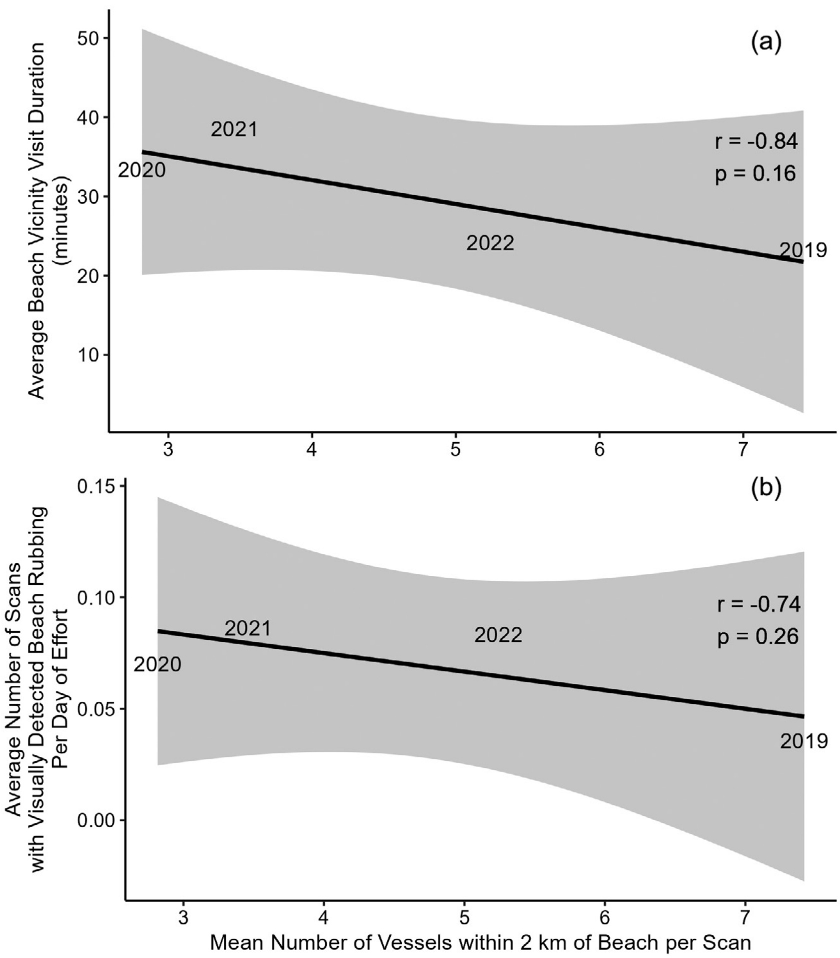

Fig. 8. At Kaizumi Beach, inter-annual trends in (a) mean NRKW beach visit duration and (b) mean number of scans with visually observed beach rubbing per day of effort relative to vessel presence. Linear model fit and Pearson's correlation are shown. Grey shading indicates 95% confidence interval. Reduced vessel presence in 2020 and 2021 corresponds to restrictions related to the COVID-19 pandemic

from entry. As this BC Parks-funded on-water program is costly and labour-intensive, and the Ecological Reserve Act has limited power with respect to the marine portion of the reserve, ongoing protection for this important killer whale habitat is not secure. Reserves and protected areas have the potential to support survival and recovery of species at risk (Cazalis et al. 2020, Rodrigues & Cazalis 2020), and heightened awareness of anthropogenic impacts to marine species has led to an increase in marine protected areas around the world. However, they can be ineffective 'paper parks' if resources are insufficient for ongoing monitoring, management, education, and enforcement (Duffus & Dearden 1993, Rife et al. 2013, Iacarella et al. 2021).

As the intent of the reserve is to protect NRKW beach rubbing behaviour, we examined the likelihood to initiate a rub, the frequency of rubbing, and duration of rubbing bouts on each of the beaches. One of the greatest challenges in assessing marine mammal behaviour is the difficulty in extrapolating visual data from the surface, which may account for only a small percentage of an individuals' overall activity, to the events that occur subsurface (Mann 1999). The selection of beach rubbing as a measure of reserve efficacy provided a rare opportunity to examine and quantify a behaviour that was associated with a fixed geographic location, identifiable by visual cues and able to be confirmed acoustically.

For both beaches, the majority of visual assessments indicating the presence or absence of beach rubbing behaviour were confirmed acoustically. However, a substantial number of rubbing events were detected acoustically with no visual confirmation. This incongruence between visual and acoustic detection rates was greater at Kaizumi Beach, where >50% of rubbing was detected by acoustic cues alone and a small number of beach rubbing events were detected visually but not acoustically. This may be due to the trend of shorter rubs at Kaizumi Beach, which may increase the likelihood of missed visual detections. As the beaches demonstrated differing rates of success with visual detection of rubbing, caution should be exercised using visual observations alone to compare rubbing among beaches. Overall, acoustic detection had a much higher success rate (lower false-negative rate) than visual detection, suggesting that the use of visual detection alone would likely underestimate true rubbing frequencies. Our study is the first to formally assess and quantify beach rubbing acoustically and establishes this method as a more effective means of detection.

By all measures assessed, NRKWs rubbed more at Strider Beach than at Kaizumi Beach in terms of likelihood to initiate a rub, the frequency of rubbing, and duration of rubbing bouts. Interestingly, while there was a negative correlation between annual mean vessel presence and rubbing behaviour on Kaizumi Beach, the model outputs did not identify a direct causal relationship between NRKW rubbing behaviour and the presence or proximity of vessels. Even in the absence of vessels, NRKWs were less likely to exhibit rubbing behaviour at Kaizumi Beach than at Strider Beach. There are several possible explanations for this persistent preference that are not mutually exclusive. As the reserve was established >40 yr ago, with protection increasing over the intervening years, whales may have learned that disturbance from vessels is more likely at Kaizumi Beach and instead favour Strider Beach for rubbing. In addition, although Kaizumi and Strider Beaches were used in this study due to their proximity, similarities in beach substrate, tidal flow, and currents, uncaptured beach properties could affect beach preference, such as beach surface area or kelp growth.

Significant variation in vessel presence among years and was negatively correlated with beach visit durations and beach rubbing; this supports the idea that NRKW beach preference is influenced by learned patterns of vessel presence. Travel restrictions and precautions related to the COVID-19 pandemic, which resulted in reductions in vessel traffic around the globe (March et al. 2021, Millefiori et al. 2021), were likely drivers for the observed decreases in vessel presence in 2020 and 2021, with 2022 vessel numbers approaching the 2019 pre-pandemic levels. At Kaizumi Beach, observed decreases in vessel presence were accompanied by increases in both beach visit durations and rubbing behaviour.

Aligned with our findings, past studies also reported that NRKWs were more likely to rub on the beaches inside the reserve than outside, and that location (i.e. beach identity) was a more important predictor of rubbing than vessel presence (Williams et al. 2006, 2009b). However, in contrast to our findings, Williams et al. (2006) reported that NRKWs were less likely to beach rub when vessels were immediately nearby. This may be due to methodological differences between the studies or a change in NRKW response to vessel presence over time. Given that vessel presence and rubbing are confounded by location, it is also unclear whether the observed negative vessel effect was due to vessel presence directly or a preference for a specific beach. Alternatively, several limitations may have affected our ability to detect a direct causal effect of vessel presence on beach rubbing. Our model results did not demonstrate an effect of vessel presence on beach rubbing at the spatiotemporal resolution we had available. This does not disqualify the possibility that momentary interactions and brief approaches missed in our 15 min resolution could negatively affect rubbing, or that vessel presence could influence long-term preferences, as discussed above. Additionally, Williams et al. (2006), by focusing on behaviour transitions of specific individuals and groups, including those within RBMBER, may have detected an effect missed by our model that assessed the overall presence or absence of rubbing at Kaizumi Beach. It is also noteworthy that our model included only data from 2020 and 2021, which had significantly lower vessel traffic than adjacent years. As there is some evidence that vessel impacts may only be noticeable once a certain threshold of vessel density is reached (Williams et al. 2009a), the threshold may not have been achieved in the seasons affected by COVID-19 restrictions (2020 and 2021). Additionally, the model outputs suggest that increased speed may have a negative effect on the probability of rubbing, but this analysis was limited by its temporal resolution and low sample size of vessels moving at high speeds. The variations in behaviour among years and between studies emphasizes the need for an adaptive management approach that can accommodate changes in rubbing behaviour over time.

While NRKWs rubbed more often at Strider Beach than Kaizumi Beach, NRKWs visited the Kaizumi Beach vicinity on more days in all years, and in 2020, when vessel traffic was lowest, spent more time there cumulatively than at Strider Beach. NRKW visits to Strider Beach that were longer than a single scan (15 min) always included rubbing, implying this is a key activity when visiting Strider Beach. In contrast, NRKWs sometimes had long visits (30–75 min) to Kaizumi Beach that did not include rubbing. Longer durations spent in the vicinity of Kaizumi Beach without rubbing may indicate that NRKWs are more hesitant to undertake beach rubbing, due to frequent vessel presence when compared to Strider. Alternatively, the area around Kaizumi Beach may be important to NRKWs for other behaviours in addition to rubbing. In either case, use of the area may increase with decreased vessel presence, as demonstrated by the trend of longer beach visits on average in years with lower vessel presence.

While this study examined the physical presence of all vessel types and the correlation with rubbing beach behaviour, it did not explicitly take into account the acoustic impacts from motorized vessels. Analysis of the ambient acoustic environment and the relationship with rubbing behaviour is currently underway, and the addition of acoustic data into the causal analysis may provide further insights into the mechanism of vessel disturbance to NRKW behaviour.

5. CONCLUSIONS

In this evaluation of reserve efficacy for the threatened NRKW population, we found a negative correlation between chronic vessel presence and NRKW rubbing behaviour, and reduction in vessel presence provided by the RBMBER is an effective means of mitigating disturbance of this behaviour. However, given the jurisdictional challenges regarding protection of the marine portion of a provincial reserve, and the selective application of the boundaries to various categories of users, there are concerns over the support for ongoing successful mitigation. In addition, the frequency and duration of beach visits to Kaizumi Beach indicate that this is a preferred habitat that is not currently afforded protection. Consideration should be given to this area when evaluating killer whale habitat protection, and opportunities to both strengthen protection and expand the spatial coverage will provide additional benefits to this threatened population of killer whales. The increased understanding of the link between vessel presence and killer whale behaviours will provide further information for mitigation efforts in support of the endangered SRKW population, whose critical habitat experiences substantial vessel traffic from both commercial and recreational users. These data contribute to the growing body of literature documenting vessel impacts on cetaceans and lend strength to the need for effective mitigation strategies to protect cetaceans from disturbance.

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