Mapping southern resident killer whale high-probability feeding areas to inform marine spatial planning in San Juan County

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Executive Summary

Protected areas are widely accepted as an effective conservation tool for protecting biodiversity. In the case of Southern resident killer whales (SRKWs), protected areas may provide support to SRKW population recovery. SRKWs are more vulnerable to disturbance while they are feeding than in other activity states. To provide the most benefit, a transboundary network of protected areas in the Salish Sea selected to explicitly protect high-quality feeding habitat than if they were placed at random or for other activity states (e.g., travel) within the whales' range. In 2010, we conducted a study to identify key feeding areas for SRKWs as the first step of a systematic conservation planning process to identifying protected areas that would confer the most conservation benefit to SRKWs while minimizing costs, impacts, and inconvenience on other ocean user communities. In 2019, we requested data from nine data holders of high-quality killer whale feeding data. Seven agreed to share their data for this project and ultimately data from six sources were collected, georeferenced, edited following a process of quality assurance and control, and mapped. Differences in field protocols prevented the use of one of the proffered datasets. From the six sources, a total of 19,436 observations over 15 years between 2003-2020 were shared. Of these, 18,558 were included in the analysis after quality assurance and control. This represents a 14-fold increase in sample size over previous analyses and increases the duration of observations from 1 season to 14 field seasons over an 18-year period. All 18,558 observations from 2003-2020 were plotted in the Salish Sea study area (i.e., Haro Strait and nearby waters). Next, observations by activity state (Rest, Travel, Forage, Socialize) were mapped and these observations categorized as a binary (feeding / not-feeding) variable. Of the total number of observations, it is clear when the observations are plotted by proportion of observations per grid cell that the vast majority took place along the west side of San Juan Island. Of these observations, a high number of observations were of foraging activity along the (south-) west side of San Juan Island. A high proportion of foraging activity also took place along Hein and Salmon Banks.

List of Figures

List of Tables

1 Background

Protected areas are widely accepted as an effective conservation tool for protecting biodiversity (Myers et al. 2000). For cetaceans, and in the case of Southern resident killer whales (SRKWs), protected areas may offer a protection to support SRKW population recovery (Cañadas et al.2005; Ashe et al. 2010). A transboundary network of protected areas in the Salish Sea will offer more benefit for the whales if sites are selected explicitly to protect high- quality feeding habitat than if they were placed at random within the whales' range. SRKWs are more vulnerable to disturbance while they are feeding than in other activity states (Williams et al. 2006; Lusseau et al. 2009). Land-based studies on northern and southern resident killer whales found an 18 and 25% reduction in time spent feeding, respectively, in the presence of boats than periods when no boats are around (Williams et al. 2006; Lusseau et al. 2009). While physical presence of boats plays a role in disturbance, noise disturbance can interfere with prey acquisition. On a typical day in Haro Strait, SRKWs may lose 62% of their opportunities to communicate over biologically meaningful ranges and on a busy day, 97% of their opportunities to communicate can be lost (Williams et al. 2014). Killer whales can adjust the volume of their communication calls to compensate, to some extent, for this masking effect, but we do not know if the whales can increase the source level of echolocation clicks they produce to locate the same number of salmon under noisy conditions that they would under quiet conditions (Holt, 2008).

In 2010, a study (Ashe et al. 2010) identified key feeding areas for SRKWs as the first step of a systematic conservation planning process (Margules and Pressey 2000) to identify protected areas that would confer the greatest benefit to SRKWs while minimizing costs, impacts, and inconvenience on other ocean user communities. Subsequent refinements on this paper explored advanced statistical approaches to mapping killer whale behavior and taking into account the complex coastline of the Salish Sea habitat (Scott-Hayward et al. 2014, 2015). The initial (Ashe et al. 2010) and subsequent (Scott- Hayward et al. 2014, 2015) analyses had identified that the whales feed preferentially in an area marked on nautical charts as Salmon Bank. Drawing from a body of work on marine protected areas (e.g., Wilson et al. 2004), it appears that stakeholder opposition can be minimized if we can show that the siting of a protected area is based on best available science and is designed explicitly to find a compromise between protecting the habitats that are most important to whales, while minimizing costs to human users of the habitat. Before implementing such a protected area (or network of protected areas), it is important to assess the persistence and variability of SRKW summer habitat use (Hauser et al. 2007, Noren and Hauser 2016) over time so that the location, size, and shape of any proposed protected area is based on current and best available science. By merging as many high-quality, spatially explicit SRKW behavioral datasets as possible, we improve the robustness of our spatial planning process and maximize stakeholder confidence in the data we are using to make any area-based management decisions.

We signed data sharing agreements with six researchers who hold fine-scale, spatially explicit behavioral data on SRKWs collected between 2003 and 2020. We used this combined dataset to conduct a sophisticated spatial model of foraging habitat use, which could be used in a stakeholder consultation process to identify protection zones for orcas and salmon. A longer time-series of data allows us to explore spatial and temporal patterns in SRKW habitat use, and to feed results into habitat protection processes that are robust to uncertainty and variability.

The objective of this study is to identify and map high probability SRKW feeding areas using SRKW behavioral observations pooled from multiple studies and an analytical framework from a previous study (Ashe et al. 2010) in order to guide a community-led effort to offer enhanced protection to SRKWs in key foraging areas. This activity is consistent with the first step of a systematic conservation plan, namely to compile data on the biodiversity of the planning region. By compiling and analyzing high-quality behavior and habitat-use data, the aim is to produce a map, predicted from a statistical model, of the probability that a whale present in an area will be engaged in feeding activity. The aim of the spatial analysis of SRKW feeding behavior is to inform protected area planning processes. Here we present the results of the conservation assessment (i.e., mapping key foraging areas) we conducted.

2 Methods

Data compilation

Researchers who have collected SRKW behavioral data from the waters near the San Juan Islands were identified and contacted. A formal data request was made to eleven data holders (Table 1). Of these, nine researchers agreed to share data. Permission was not required for the three of the data sets where EA and RW were listed as Principal Investigators.

Table 1: Record of data requests made for SRKW behavioral data and the response.

Record of Consultation	
Data Holders	**Status**
Dawn Noren	Included
Marla Holt	Included
Deborah Giles	Included
David Bain and Rob Williams	Included
Erin Ashe	Included
Oceans Initiative (Erin Ashe and Rob Williams)	Included
Jennifer Marsh	Provided, but methodology not compatible with proposed analysis
Brad Hanson	Declined
Sheila Thornton	Declined
Rich Osborne	Offered to share, but data unavailable in digital format
James Heimlich-Boran	Offered to share, but data unavailable in digital format
Russel Hoelzel	Offered to share, but data unavailable in digital format
Fred Felleman	Offered to share, but data unavailable in digital format

Table 2: Record of total observations and year from each study group included in the analysis.

Year	PI/Study Group	Number of Records
2003	David Bain, Rob Williams	949
2004	David Bain, Rob Williams	2,710
2005	David Bain, Rob Williams	1,736
2006	Dawn Noren	571
2006	Erin Ashe	763
2007	Marla Holt	123
2007	Deborah Giles	1,509
2008	Marla Holt	110
2008	Deborah Giles	3,289
2009	Marla Holt	140
2009	Deborah Giles	342
2010	Deborah Giles	1
2011	Deborah Giles	127
2012	Deborah Giles	304
2013	Deborah Giles	1
2014	Deborah Giles	166
2018	Deborah Giles	119
2018	Oceans Initiative	2,223
2019	Deborah Giles	46
2019	Oceans Initiative	1,983
2020	Oceans Initiative	2,224
Total Observations Provided		19,436
Total Observations Retained After Quality Control		18,558

Data quality and activity state definitions

Each dataset was rigorously assessed for data quality and compatibility with the analysis methods described in Ashe et al. (2010). First, behavioral observations and activity states from contributed datasets were categorized into the behavioral definitions described in Table 3 (after Williams et al. 2006 and Lusseau et al. 2009). These definitions were designed to be mutually exclusive and cumulatively inclusive of the entire behavioral repertoire of SRKWs. Due to some minor differences in terminology among researchers, the activity states were also collapsed to a binary (feeding/non-feeding) variable. Next, location data were assessed for accuracy by mapping all data, and investigating, editing, and removing any outliers that could not be resolved.

Table 3: Description of activity state definitions used to translate observations across studies into a common currency.

1. Lusseau, D., Bain, D. E., Williams, R., & Smith, J. C. (2009). Vessel traffic disrupts the foraging behavior of southern resident killer whales Orcinus orca. *Endangered Species Research*, *6*(3), 211-221.
2. Williams, R., Lusseau, D., & Hammond, P. S. (2006). Estimating relative energetic costs of human disturbance to killer whales (Orcinus orca). *Biological conservation*, *133*(3), 301-311.

Activity State Subcategory	Activity State	Qualitative Speed	Definition[1]	Subcategory Detail[1]	Additional Detail[2]
1	Rest	Stationary or Very Slow	Characterized by prolonged surfacing in contrast to the rolling motion typically observed during travel	Deep rest, hanging, logging: whales do not progress through the water	Whales were swimming at slow speed with highly predictable sequences of several short (30 s) dives followed by a long dive of 3–5 min. This activity state was characterised by the absence of surface-active behaviour (e.g., breaching or tail-slapping)
2	Rest	Slow (<2 knots)	Characterized by prolonged surfacing in contrast to the rolling motion typically observed during travel	Resting travel, slow travel: whales progress through the water, although they may not make forward progress	Whales were swimming at slow speed with highly predictable sequences of several short (30 s) dives followed by a long dive of 3–5 min. This activity state was characterised by the absence of surface-active behaviour (e.g., breaching or tail-slapping)
3	Travel	Moderate (4 knots or less)	Characterized by a rolling motion at the surface, progress through the water, and membership in a	Moderate travel, medium travel: travel in which whales do not porpoise	
4	Travel	Fast, Porpoising (>6 knots)	Characterized by a rolling motion at the surface, progress through the water, and membership in a	Fast travel: travel which includes porpoising	
5	Foraging	Moderate-Fast (4-6 knots)	Characterized by progress through the water by lone individuals or while a member of a subgroup	Dispersed travel: foraging in a directional manner	Whales surfaced and dove independently but all whales in the group were heading in the same general direction. The dive sequences of individuals showed regular patterns of several short dives followed by a long one, and whales
6	Feeding	Fast, Irregular	Characterized by progress through the water by lone individuals or while a member of a subgroup	Milling, feeding, pursuit of prey: foraging involving changes in direction	Individuals spread out; individuals were surfacing and diving independently in irregular sequences of long and short dives; and individuals displayed fast, non-directional surfacings in the form of frequent directional changes
7	Socialize	Irregular	Touching	Tactile interactions: socializing that involves touching another whale, such as petting or nudging	Animals surfaced in tight groups with individuals engaged in tactile behaviour; whales showed irregular surfacing and diving sequences and swim speeds; irregular direction of movement; and high rates of surface- active behaviour
8	Socialize	Irregular	Not touching, Surface Active Behavior	Display: socializing that does not involve touching, but may include behaviors such as spy hops, tail slaps	Animals surfaced in tight groups; whales showed irregular surfacing and diving sequences and swim speeds; irregular direction of movement; and high rates of surface- active behaviour

Mapping the raw data

The compiled, quality checked data were mapped in the study area across a coarse grid for ease of interpretation.

Statistical analysis

Analyses were conducted in the package 'MRSea' for R (Scott-Hayward et al. 2020) which uses the Spatially Adaptive Local Smoothing Algorithm (SALSA) for modelling in regions with complex topography (Walker et al. 2011). Data were aggregated onto a 500m x 500m grid with each cell containing binary feeding and non-feeding observations. A generalized linear model with a binomial distribution and logit link was selected to express the relationship between a covariate of coordinate space s(x,y) and a response of mean probability of feeding. The spatial smooth used a gaussian basis function with geodesic distance. Model selection was performed based on minimizing Bayesian Information Criterion (BIC).

Making predictions

Probability of feeding was predicted for grid cells with ≥5 observations. Output from the analysis was exported for mapping in QGIS 3.10 (QGIS Development Team, 2020).

3 Results

Data compilation

Data from six sources were collected, georeferenced, edited following a process of quality assurance and control, and mapped. Differences in field protocols prevented the use of one of the proffered datasets (Table 1). From the six sources, a total of 19,436 observations over 15 years between 2003-2020 were shared. Of these, 18,558 were included in the analysis after quality assurance and control (Table 2). This represents a 14-fold increase in sample size over previous analyses and increases the duration of observations from 1 season to 14 field seasons over a 19-year period (cf. Ashe et al. 2010 and Table 2).

Mapping

First, all 18,558 observations from 2003-2020 were plotted in the study area (Figure 1). Next, observations by activity state (Rest, Travel, Forage, Socialize) were mapped with color indicating each activity state (Figure 2). Figure 3 shows these observations categorized as a binary (feeding=green, not-feeding=blue) variable. Of the total number of observations, it is clear when the observations are plotted by proportion of observations per grid cell that the vast majority took place along the west side of San Juan Island (Figure 2). Of these observations, a high number of observations were of foraging activity along the (south-) west side of San Juan Island. A high proportion of foraging activity also took place along Hein and Salmon Banks.

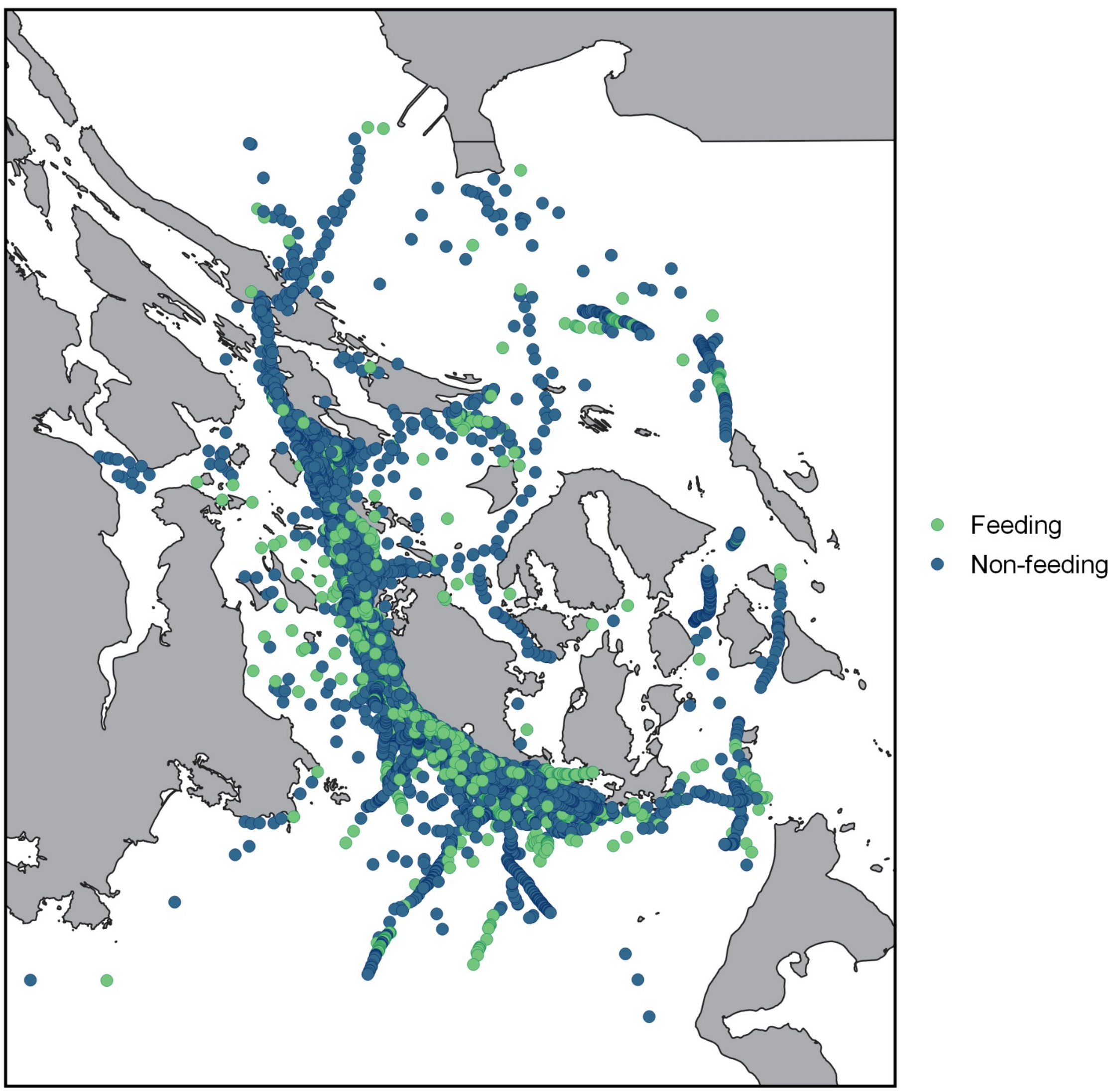

Figure 1: Binary feeding and non-feeding observations recorded in shared datasets from 2003-2020.

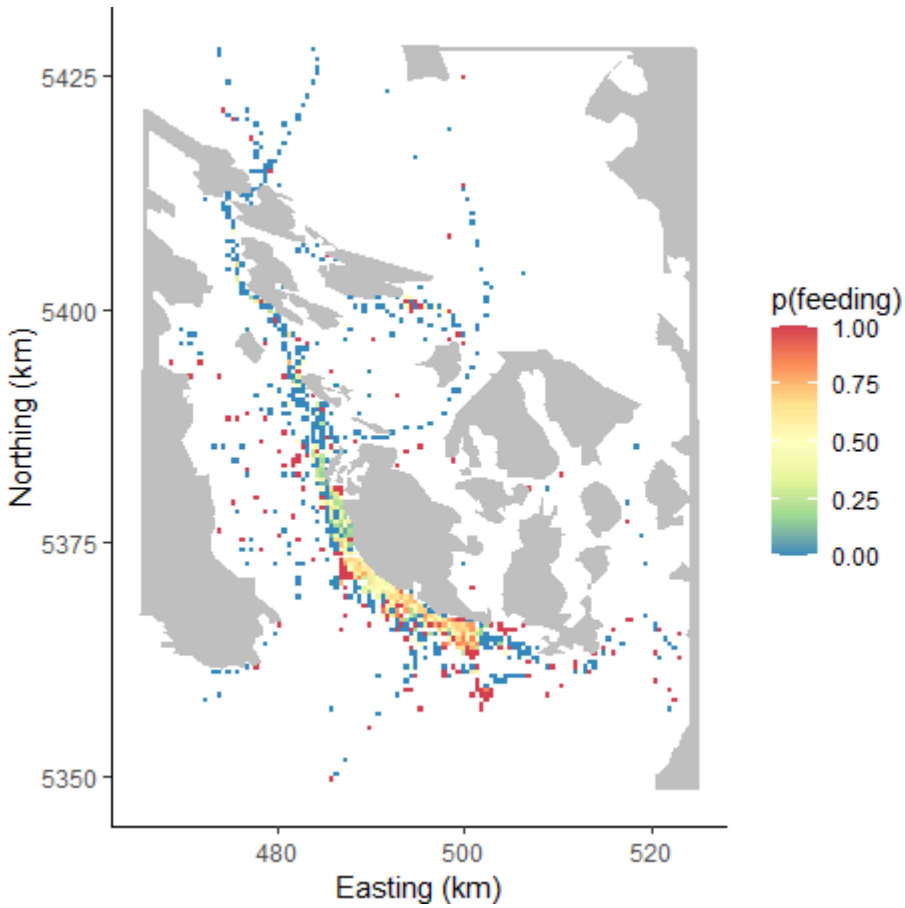

Figure 2: Proportion of observations in the foraging activity state for all SRKW raw data prior to full analysis.

Statistical Analysis

Figure 3 shows our best estimate of the average probability of being in the feeding activity state throughout the study area over the time period, 2003-2020. Figure 4 shows the upper and lower 95% confidence intervals on that surface, which represents a measure of variability and uncertainty around that estimate.

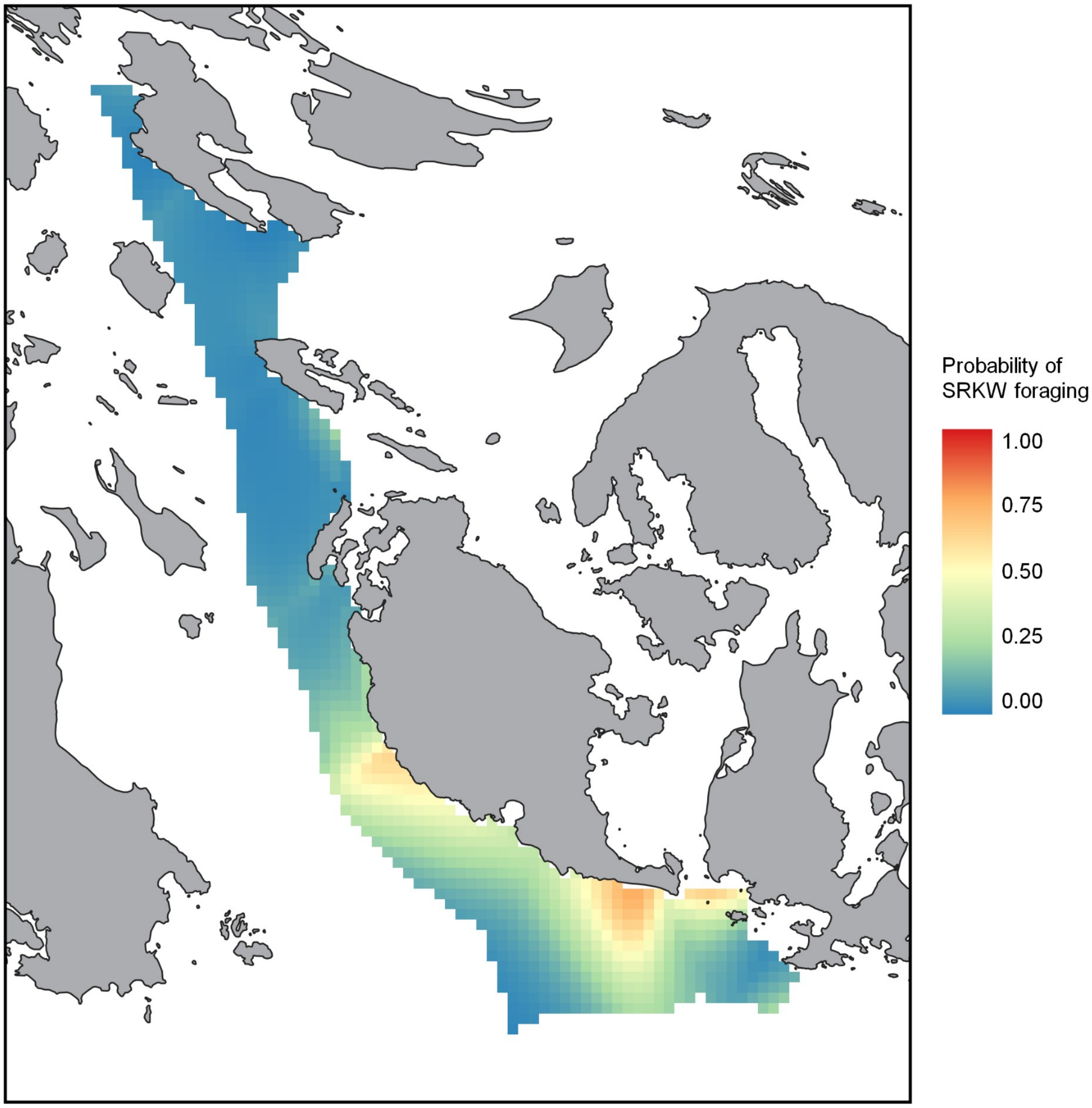

Figure 3: Mean probability of feeding predicted across the study area.

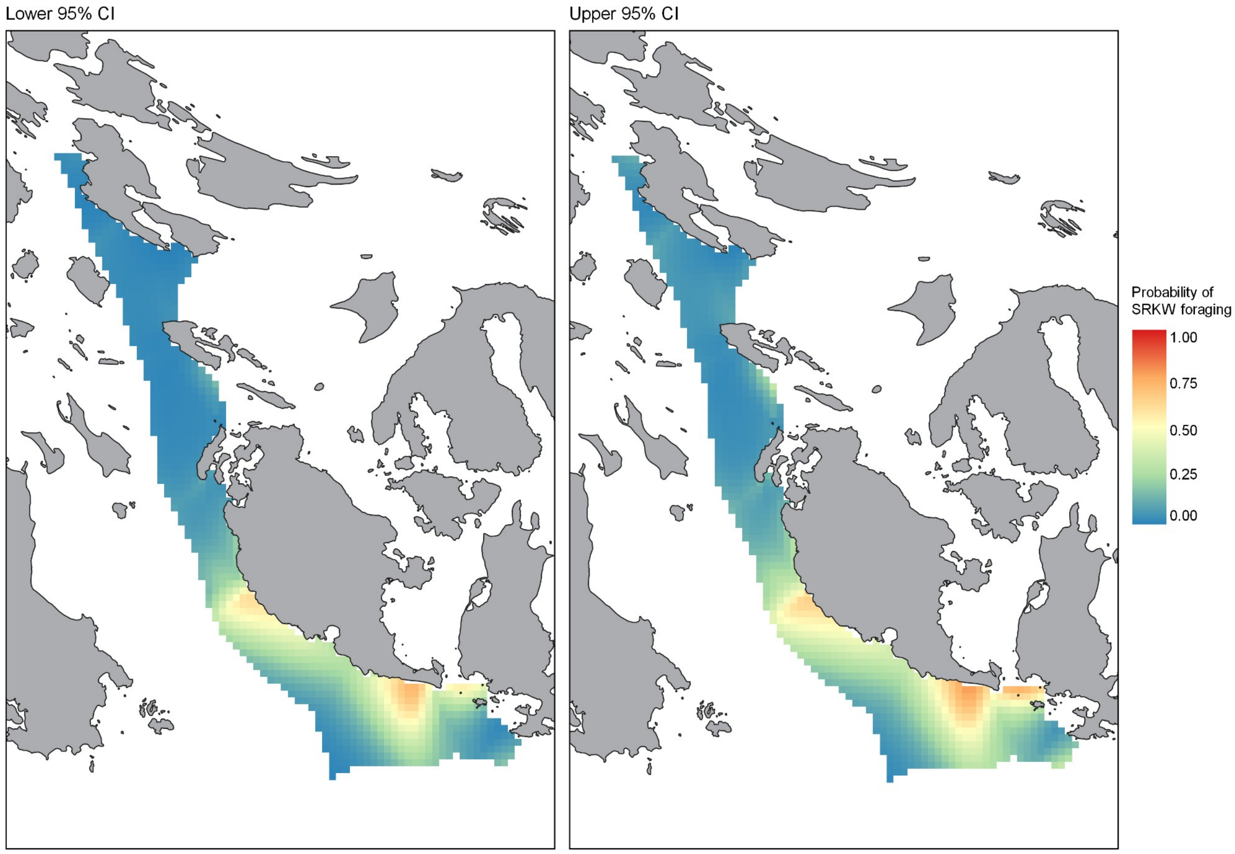

Figure 4: Lower (left) and upper (right) 95% confidence intervals of predicted feeding across the study area.

4 Discussion

The analyses we completed successfully identified key foraging areas for SRKWs. There was little support from the data for a model that allowed feeding locations to change over time, but this may be because the spatial distribution of search effort was itself highly variable over the duration of the study. Figure 3 shows the average feeding probability over the 18-year period, and Figure 4 shows the uncertainty around that probability surface. There are two high-probability feeding areas that stand out, namely an area off Lime Kiln, and another, wider patch of feeding habitat that stretches offshore from South Beach to Salmon Bank (Figure 3). This foraging habitat map can serve as the first step in a systematic conservation plan, namely to compile data on the valued biodiversity component(s) in the planning region (Margules and Pressey 2000). The next step is for managers and policy-makers to identify their conservation goals for the region (Margules and Pressey 2000).

Although no quantitative conservation targets have been set yet, qualitatively, managers and policy-makers on both sides of the border have articulated a desire to enhance protection of key foraging habitats of SRKWs. This conservation objective is grounded in science. It has been established for more than a decade that resident killer whales (a) are more vulnerable to boat-based noise and disturbance when they are feeding than when they are engaged in other activities (Williams et al. 2006, Lusseau et al. 2009), and (b) experience lowered survival and reproductive rates in years of reduced prey abundance (Ward et al. 2009, Ford et al. 2010). Marine protected areas offer a robust tool to resolve some of that conflict between endangered species and human uses of the ocean (Agardy 2000). Setting clear conservation goals for the region is essential, but this requires making challenging and potentially contentious decisions about how much foraging habitat to protect, what size and shape of habitat to set aside for conservation, and what level of protection to offer (Agardy et al. 2003). A number of spatial conservation prioritization and decision support tools are available to "solve" mathematically for the size and shape of protected areas to accomplish a given conservation objective, but they all require explicit articulation of conservation targets from the outset that to our knowledge have not yet been set for SRKW foraging habitat (Moilanen et al. 2009).

The Government of Canada[1] recently concluded "that SRKW are likely facing imminent threat to survival. Unless mitigated, the current threats may make survival of the population unlikely or impossible." Put simply, the population has little resilience to tolerate any

[1] https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/related-information/southern-resident-killer-whale-imminent-threat-assessment.html

additional reductions in accessibility of prey, either through vessel disruption of foraging success from vessel noise and disturbance or through localized competition with fisheries (Williams et al. 2016). Given the dire status of the population, the precautionary principle would suggest we should err on the side of protecting more habitat rather than less, and offering stricter levels of protection rather than permissiveness (Harwood 2000). In the case of protecting SRKW foraging habitat, this suggests that it would be more precautionary to incorporate scientific uncertainty in our decision-making by using the upper 95% confidence intervals in area-based management actions (e.g., Figure 4, right). The overall pattern of SRKWs feeding in areas off the southwest side of San Juan Island are remarkably consistent with the results from a simpler analysis of data collected in 2006 alone (Ashe et al. 2010). When trying to protect important habitats of highly mobile cetaceans, there is ongoing concern that animals may shift their distribution before protected areas can be put in place (Wilson et al. 2004). It is reassuring in this instance that, although SRKWs are less commonly seen in the waters near the San Juan Islands in summer months than they have in previous years, their average foraging habitat use has been consistent since 2003 (Figure 3). This long-term consistent use of habitat lends itself to area-based management tools, including marine protected area and other spatial zoning techniques.

This study accomplished its primary objective, which was to compile data on SRKW foraging habitat using data that span more than a killer whale generation. Identifying key foraging areas will be an essential first step to any spatial planning process to spatially separate human activities (e.g., vessel-based noise and disturbance) from a valued ecological component (i.e., SRKW foraging habitat). It is vital in any systematic conservation planning process to be explicit about the ecological component to be protected, and what level of risk we are willing to live with if we fail to provide adequate protection (Duffus and Dearden 1992).

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