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Vessel-Based Marine Mammal Surveys in Puget Sound, Washington

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Alexandre N. Zerbini, Brenda K. Rone, Erin A. Falcone, Erin L. Keene, and Gregory S. Schorr

Foundation for Marine Ecology and Telemetry Research (MarEcoTel)
2468 Camp McKenzie Tr NW
Seabeck, WA 98380
(206) 931-4638
gschorr@marecotel.org

Dawn M. Grebner

Naval Undersea Warfare Center Division (NUWC), Keyport
610 Dowell Street
Keyport, WA 98345

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6. AUTHOR(S)
Alex Zerbini
Brenda K. Rone
Erin A. Falcone
Erin L. Keene
Gregory S. Schorr
Dawn M. Grebner

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Foundation for Marine Ecology and Telemetry Research (MarEcoTel)
2468 Camp McKenzie Tr NW, Seabeck, WA 98380
Naval Undersea Warfare Center Division (NUWC), Keyport
610 Dowell Street, Keyport, WA 98345

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander, U.S.Pacific Fleet, 250 Makalapa Dr. Pearl Harbor, HI

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14. ABSTRACT
The United States (U.S.) Navy conducts military training and testing in the Pacific Northwest. In order to obtain permits issued by the National Marine Fisheries Service to conduct these activities, a monitoring program is required to assess their impacts on protected species. The Dabob Bay Range Complex (DBRC), located within Hood Canal, is an area where both training and testing may occur. This is a region where marine mammals are exposed to a variety of anthropogenic sources including vessel traffic, fisheries, and underwater acoustic disturbance. In this study, we conducted line transect surveys to assess the seasonal distribution and abundance of marine mammals in Hood Canal (Washington), with emphasis on harbor porpoises (*Phocoena phocoena*) and killer whales (*Orcinus orca*). Vessel surveys were carried out during 37 days in all seasons from 09 February 2022 to 08 February 2023. Observers located on two independent platforms (an upper and lower deck of the same vessel) searched for species of interest during good weather conditions. Acoustic recordings were also made when feasible. A total of 2175.8 kilometers of on-effort trackline representing 691 lines were surveyed and 809 harbor porpoise groups (1,385 individuals) and four groups of transient killer whales were observed. In addition, 1,147 sightings of harbor seals (*Phoca vitulina*, 1,249 individuals), 4 sightings of Steller sea lions (*Eumetopias jubatus*, 4 individuals) and 23 sightings of California sea lions (*Zalophus californianus*, 57 individuals) were documented. Estimates of abundance showed a clear seasonal pattern in the occurrence of harbor porpoises in Hood Canal. The greatest abundance occurred in the fall totaling 1,336 individuals (CV=0.25) with the lowest, 308 porpoises (CV=0.25), occurring in the winter. These results indicate that harbor porpoises have increased

significantly in abundance from previous surveys (2013-2015), are most abundant in the summer/fall, leave the Canal in the winter, and begin returning in the spring. Density of porpoises was higher in the central region of Hood Canal, north of Hood Point, an area that coincides with DBRC.

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List of Acronyms

AIC	Akaike Information Criterion
CV	coefficient of variation
ESA	Endangered Species Act
DBRC	Dabob Bay Range Complex
dB	decibel
EIS	environmental impact statement
ft	feet
GLM	generalized linear model
GPS	Global Positioning System
HC	Hood Canal
Hz	hertz
kHz	kilohertz
km	kilometer
m	meter
MarEcoTel	Marine Ecology and Telemetry Research
min	minutes
MRDS	mark-recapture distance sampling
NAVSEA	Naval Sea Systems Command
nm	nautical mile
NUWC	Naval Undersea Warfare Center
NWTRC	Northwest Training Range Complex
NWTT	Northwest Training and Testing
RHIB	Rigid-hulled inflatable boat
SD	Standard deviation
sec	seconds
U.S.	United States
VHF	Very High Frequency
WA	Washington

Abstract

The United States (U.S.) Navy conducts military training and testing in the Pacific Northwest. In order to obtain permits issued by the National Marine Fisheries Service to conduct these activities, a monitoring program is required to assess their impacts on protected species. The Dabob Bay Range Complex (DBRC), located within Hood Canal, is an area where both training and testing may occur. This is a region where marine mammals are exposed to a variety of anthropogenic sources including vessel traffic, fisheries, and underwater acoustic disturbance. In this study, we conducted line transect surveys to assess the seasonal distribution and abundance of marine mammals in Hood Canal (Washington), with emphasis on harbor porpoises (*Phocoena phocoena*) and killer whales (*Orcinus orca*). Vessel surveys were carried out during 37 days in all seasons from 09 February 2022 to 08 February 2023. Observers located on two independent platforms (an upper and lower deck of the same vessel) searched for species of interest during good weather conditions. Acoustic recordings were also made when feasible. A total of 2175.8 kilometers of on-effort trackline representing 691 lines were surveyed and 809 harbor porpoise groups (1,385 individuals) and four groups of transient killer whales were observed. In addition, 1,147 sightings of harbor seals (*Phoca vitulina*, 1,249 individuals), 4 sightings of Steller sea lions (*Eumetopias jubatus,* 4 individuals) and 23 sightings of California sea lions (*Zalophus californianus*, 57 individuals) were documented. Estimates of abundance showed a clear seasonal pattern in the occurrence of harbor porpoises in Hood Canal. The greatest abundance occurred in the fall totaling 1,336 individuals (CV=0.25) with the lowest, 308 porpoises (CV=0.25), occurring in the winter. These results indicate that harbor porpoises have increased significantly in abundance from previous surveys (2013-2015), are most abundant in the summer/fall, leave the Canal in the winter, and begin returning in the spring. Density of porpoises was higher in the central region of Hood Canal, north of Hood Point, an area that coincides with DBRC.

Introduction

The Northwest Training and Testing (NWTT) study area (inset, Figure 1) in Washington State is comprised of multiple Navy ranges in both the offshore, nearshore, and inland waters. The NWTT study area provides an environment that ensures naval forces have the capabilities and readiness to complete assigned missions, and supports a variety of aerial, surface, and subsurface exercises. The Dabob Bay Range Complex (DBRC) is a training and testing area inside Hood Canal, a narrow fjord constituting the west side of Puget Sound within the greater Salish Sea. It is part of the Naval Sea Systems Command's (NAVSEA) Naval Undersea Warfare Center (NUWC) Keyport Range (Complex). Hood Canal is also home to Bangor Submarine Base which is part of Naval Base Kitsap (Figure 1).

All marine mammal species within Hood Canal are protected under the Marine Mammal Protection Act of 1972, with additional protection to some species under the Endangered Species Act of 1973. To conduct military activities, the U.S. Navy obtains a marine mammal permit issued by the National Marine Fisheries Service and is required to monitor the effects of its permitted activities on protected species (DoN 2020). When acquiring these permits, seasonal abundance, distribution, and density of these species are important considerations when assessing the overlap of activities and animal presence that may fluctuate throughout the year. While knowing these parameters are important for assigning takes, seasonal data are historically not well documented for species located in Hood Canal. Marine mammal species known to occur in Hood Canal include harbor porpoises (*Phoecoena phocoena*), killer whales (*Orcinus orca*), harbor seals (*Phoca vitulina*), California Sea Lions (*Zalophus californianus*), and Steller sea lions (*Eumetopias jubatus*). Both Southern Resident (Olson et al., 2018) and Transient (London et al., 2012) killer whales have been documented infrequently within the canal, though sightings of Transients are much more common than Residents.

Cetaceans, and harbor porpoises in particular, are susceptible to anthropogenic disturbance. Sources of disturbance may include vessels, fishing activities and underwater active acoustic devices, all of which can be found in Hood Canal. However, although porpoises may be impacted by all these activities to some degree, anthropogenic noise within the species' hearing range tend to be most disturbing (Noren et al., 2017). These include but are not limited to sonar (Parsons, 2017), pingers (Dawson et al., 2013), high-frequency vessel noise (Hermannsen et al., 2014; Dyndo et al., 2015), and sounds associated with construction and operation of wind turbines (Carstensen et al., 2006; Tougaard et al., 2014). A review by Noren et al. (2017) concluded that the most common reaction of odontocetes disturbed by an acoustic source was to cease echolocation and leave the area. This functional disruption of energy acquisition may have costly consequences for a species that has high foraging rates if it is prolonged or frequent (Wiśniewska et al., 2016).

In the past 20 years, some limited cetacean and pinniped research have been conducted in Hood Canal, including harbor seal haul-out behavior from tagging studies (2002-2006) (London et al., 2012), and harbor seal (Ampela et al., 2021) and harbor porpoise (Jefferson et al., 2016) abundance estimates obtained from aerial surveys (2013-2015). Within the inland waters of Washington, harbor porpoises are managed as a single stock ("Washington Inland Waters", Carretta et al., 2020). Pooled seasonal estimates for the entire Puget Sound region of the Salish Sea indicated potential seasonality in porpoise movements (Jefferson et al., 2016). Given that seven years have lapsed since these data were collected, existing estimates of abundance and distribution may no longer be representative.

In addition to being outdated, there are observational challenges with harbor porpoises that contribute to uncertainty in abundance estimates, including their small physical size, inconspicuous coloration, and cryptic surfacing behavior. Recent work suggests that vessel-based surveys detect 2-3 times the number of sightings per kilometer (km) than aerial surveys (Dahlheim et al., 2015; Jefferson et al., 2016), and thus have the potential to estimate abundance with higher confidence. This is particularly true in narrow bodies of water with high shorelines, such as Hood Canal, where viewing times from comparatively fast-moving aircrafts are limited. Aerial surveys may also struggle to detect animals that occur very near shore, which represents a much greater proportion of habitat in narrow waterways. Therefore, the goal of this project was to collect cetacean occurrence data within Hood Canal through vessel-based surveys, use these data to update existing estimates of harbor porpoise density and abundance, and to better describe their spatial distribution and habitat to inform management.

The scientific question addressed by this study is:

- *What is the seasonal occurrence, abundance, and density of harbor porpoises and killer whales within Hood Canal?*

Here, we present two components of this work:

- *Seasonal effort and sightings of marine mammals.*
- *Seasonal density and abundance estimates of harbor porpoises.*

Methods

Study Area and Survey Design

Located within the Salish Sea (a marginal sea of the Pacific Ocean that includes the Strait of Georgia, the Strait of Juan de Fuca, and Puget Sound), Hood Canal is a long and narrow fjord located in western Puget Sound, Washington (Figure 1. The 2022–2023 Hood Canal study area in Washington. ; it separates the Olympic and Kitsap peninsulas. It is 110 km long and covers an area of approximately 370 km^2, with an average width of 2.4 km. The average depth is 54 meters (m) with a maximum of 183 m.

The survey area was divided into six strata of varying geometry (Figure 1. The 2022–2023 Hood Canal study area in Washington. to facilitate allocation of survey effort and improve sampling efficiency (Strindberg and Buckland, 2004). Stratum 1 spanned an area of 40 km^2 (12.1% of the study area) and encompassed the entrance of Hood Canal, south to the Hood Canal Bridge, including Port Gamble Bay; Stratum 2 corresponded to an area of 73 km^2 (19.3% of the study area) spanning from the Hood Canal Bridge to just south of Naval Base Kitsap Bangor at Hazel Point; Stratum 3 spanned an area of 75 km^2 (19.8% of the study area) and encompassed all of Dabob Bay; Stratum 4 corresponded to an area of 50 km^2 (13.2% of the study area) encompassing the area from Hazel Point and the mouth of Dabob Bay and south to Hood Point; Stratum 5 corresponded to an area of 96 km^2 (25.3% of the study area) from Hood Point to Union; Stratum 6 corresponded to an area of 39 km^2 (10.3% of the study area) from Union to Belfair.

Each complete survey of the Canal was randomly created using custom-made functions and libraries developed for the open-source software *R* (version 4.2.1, R Core Team, 2021). These functions allowed us to evaluate survey design based on vessel speed, total survey duration each day (a function of daylight hours during the shortest survey), total survey area covered, and different line-type samplers (e.g., parallel tracklines, zig-zag tracklines). The approach used here provides statistically robust, defensible and comparable results across survey seasons. Survey lines were allocated using the package *dssd* (Marshall, 2021) in software *R.* After an exploratory analysis of the survey needs, an unequal spacing zig-zag design (Strindberg and Buckland, 2004) (Figure 1) was selected to efficiently sample the study area given the available survey platforms, survey logistics, and the complex characteristics (e.g., relatively narrow channels) of the habitats within the Canal (Strindberg and Buckland, 2004; Thomas et al., 2007). Systematic zig-zag tracklines were created with a random starting point. A slightly higher effort per unit of area was allocated to Strata 1-4 (Figure 1. The 2022–2023 Hood Canal study area in Washington. where the highest concentrations of harbor porpoises were expected to occur based on previous work (Jefferson et al., 2016), as well as to provide more coverage to areas that the U.S. Navy uses for testing and training. Strata 2-4 and the northern half of Stratum 5 contain the areas of naval operations, Dabob Bay Range Complex and Bangor (Figure 1. The 2022–2023 Hood Canal study area in Washington. . To capture seasonality within Hood Canal, it was estimated that effort would require a total of 40 days per year, with an estimated 10 days per season. Each stratum was surveyed twice per season (e.g., two unique, randomly-generated survey designs were completed) to ensure that relatively large sample sizes were collected in order to compute robust estimates of cetacean density within the study area.

In summary, surveys were designed to meet the following objectives:

- Obtain an approximately uniform sampling coverage of the study area;
- Sample the entire Hood Canal, previously surveyed by Jefferson et al. (2016), for possible comparisons between these surveys and for future estimation of trends in abundance;
- Optimize survey effort within the allocated survey period.

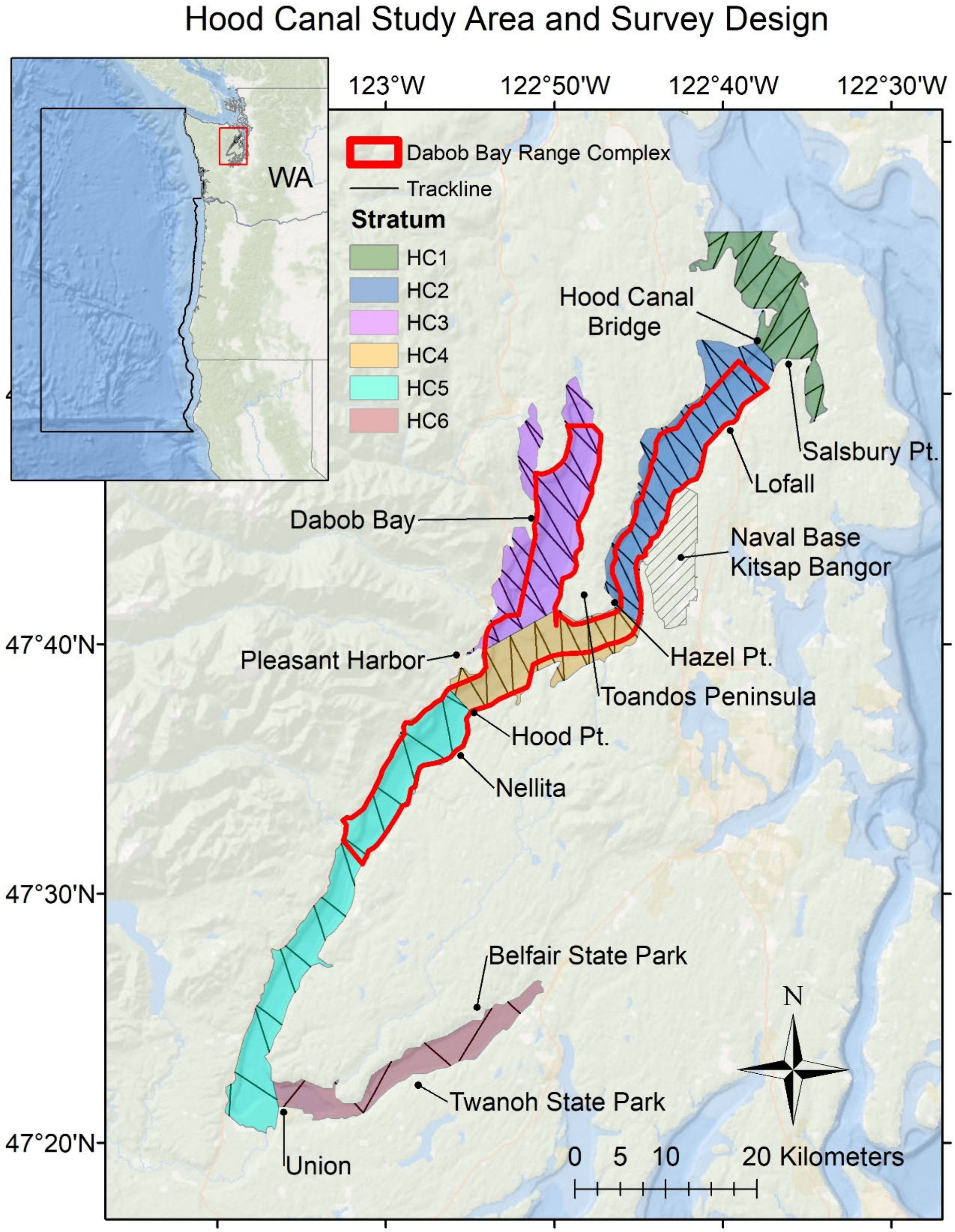

Figure 1. The 2022–2023 Hood Canal study area in Washington. This figure includes the inshore and offshore Northwest Training and Testing (NWTT) boundaries on the continental west coast (inset), the Dabob Bay Range Complex in Hood Canal, WA located within the NWTT, the six survey strata and an example of the randomized trackline design within each of the six strata. Prepared by B. Rone.

Field Methods

Visual Surveys

Vessel surveys were carried out in passing mode (i.e., the vessel did not divert from the trackline to close in on detected cetacean groups (Hiby and Hammond, 1989; Hammond et al., 2021), using the *R/V On Porpoise*, an 8.2 m double-decker research vessel (Figure 2).

Four observers rotated through three observation positions. Port and starboard primary observers were located on the upper deck, positioned with an average eye-height of 3.40 m above water, and one independent observer was positioned on the main deck with an average eye-height of 2.11 m above the water. Observers on upper and lower decks could not see or easily hear one another across platforms. Observations started no earlier than approximately 30 minutes (min) after sunrise, ended no later than 30 min before sunset, and were suspended in poor visibility conditions and/or a sustained sea state above 3 on the Beaufort scale. Port and starboard observers searched for marine mammals from the beam (90^o) of their respective side to approximately 10° on the opposite side of the survey line using the naked eye. The independent observer surveyed from -90^o to 90^o with the naked eye. The boat driver was responsible for recording environmental conditions and trackline effort, and was not involved in active searching.

Each observer used a clock, an angle board, and a voice recorder to document the distance and relative angle to all cetacean sightings. Any pinniped species that surfaced within approximately 100 m from the boat, a distance at which a rapid, accurate, species determination could be made quickly with the naked eye, was also documented. All clocks were calibrated to Global Positioning System (GPS) time prior to each survey. For each sighting, the observers recorded: time, species, angle (relative degrees to the bow), estimated radial distance (m), and minimum, best and maximum estimates of group size. Effort data were logged using a custom-built Microsoft *Access* (Microsoft, Redmond, WA) database on a ruggedized tablet with an integrated GPS. Vessel position information was automatically logged every 5 seconds (sec) using the vessel's GPS. Environmental information was entered at the start of each transect and when conditions changed. Information included: visibility (nautical mile, nm), precipitation/atmospheric conditions, cloud cover (%), Beaufort sea state, swell height (feet), glare angle (degrees relative to bow), glare severity (proportion of the field of view obscured by glare), and overall observational quality, a subjective score which takes into consideration the combined effects from all these factors. The time and position were logged at the start and end of each transect and anytime effort was paused/resumed during a transect due to navigational hazards or weather. Weather and visibility conditions changed frequently with the potential to influence the observer search pattern. To maximize data collection, the observers maintained search effort under light rain and under foggy conditions when the visibility was greater than ~1 km. Search effort ceased in sustained moderate to severe rain or if visibility in foggy conditions was less than 1 km.

Figure 2. R/V On Porpoise, the survey vessel used for Hood Canal surveys, with two observers seated on the upper deck, and one standing on the lower deck.

Distance Calibration Experiments

Because observers estimated the radial distance to sightings with the naked eye, experiments were conducted to assess distance estimation error for each observer under varying conditions and to use this information to correct field estimates *post hoc*. The experiment was repeated at least once per season for all observers. During these experiments, observers independently estimated distance to a moored object that resembled the dorsal fin and back of a harbor porpoise (aka the "Faux Po"). The boat was repositioned at various distances from the fixed Faux Po with the goal of collecting observer distance estimates across a range of circumstances encountered during a typical transect (e.g., close shoreline, land reflection, glare). Up to 20 estimations were obtained from each observer during each experiment, with trials split evenly between the lower and upper decks. The true distance to the object, as determined by the vessel GPS, was recorded by the driver and revealed to the observers in the first half of the trials from each level, but not for the second. In addition to the estimated distance, each observer recorded the visual conditions at the target as potential predictors of distance. A regression framework was used to derive a distance correction function for each observer (e.g., Williams et al., 2007). Exploratory analyses were conducted to assess the relationship of the response variable (true distance) and the various predictors and to evaluate covariance among predictors (Figure 3, Appendix 1).

Generalized linear models (GLMs) were used to model true distance as a function of five numerical and two factor predictor variables (Table 1). Models included all combinations of these variables in an additive fashion. True and estimated distances were log-transformed before analysis to maximize normality of model residuals, which were confirmed after model fitting using a Shapiro-Wilk normality test. The Akaike Information Criterion (AIC) was used for model selection and the model with the lowest AIC score (the "most supported" model) was used for computing the predicted "true" radial distances from those estimated or sightings detected by the observers during the actual surveys. All analyses were conducted in the software *R*.

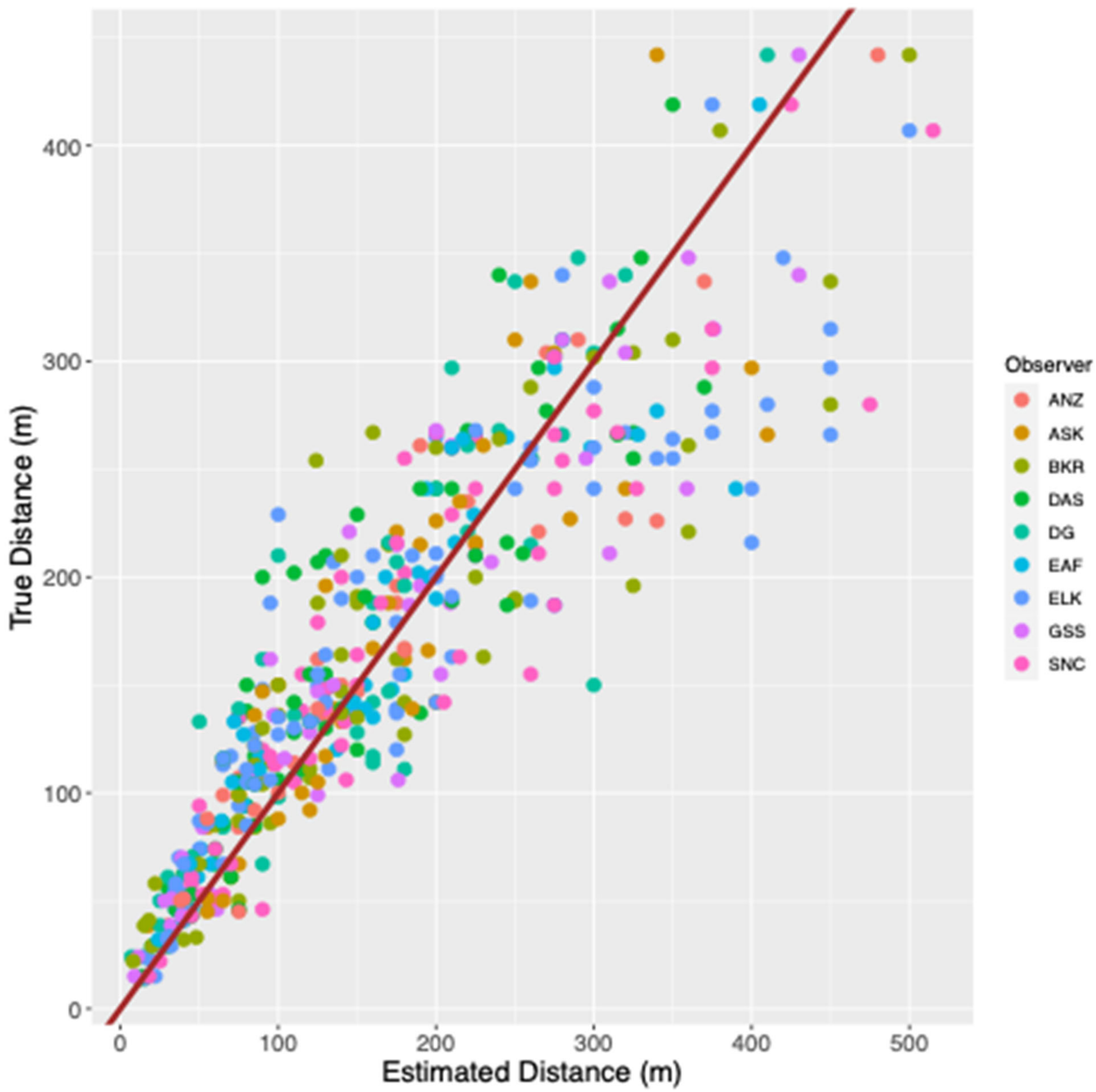

Figure 3. Visual exploratory analysis to assess variable relationships and correlations in calibration experiments to correct for distance estimation in Hood Canal marine mammal surveys.

Table 1. Variables considered in the observer distance calibration analysis for marine mammal surveys in Hood Canal.

Variable	Variable type	Description	Mean	Min	Max	Levels
True distance	Numeric	Distance determined by the GPS location of the target and the vessel	162.9	14	442	-
Estimated distance	Numeric	Distance estimated by the observer				-
Observer	Factor	Observer estimating distance	-	-	-	9 different observers
Beaufort	Numeric	Sea state in the Beaufort Scale				-
Cloud cover	Numeric	Percentage of cloud cover in the survey area	69.31	0	100	-
Visibility Conditions	Numeric	Visible distance (km)	3.51	0	3	-
Background Conditions	Factor	Description of current background conditions at the target	-	-	-	5 levels (Land-Distant, Land-Medium, Land-near, Water-Horizon, Water-no horizon)
Glare	Numeric	Quantitative description of glare intensity at the target	1.35	1	4	-

Acoustic Recordings

Acoustic deployments were a leveraged, collaborative opportunity for the Navy to collect underwater recordings of harbor porpoises around Hood Canal. This acoustic effort was funded separately and was not a requirement of this contract. Acoustic deployments occurred in all four seasons. An anchored, vertical acoustic array was used on visual transect survey days, when feasible. Due to last minute survey scheduling changes in strata and/or dynamic weather changes, hydrophone deployment locations did not always overlap in space and time with the visual survey efforts. In addition, the highly directional, very high frequency (VHF) characteristics of the harbor porpoise sounds (Au et al., 1999) make detecting their clicks problematic due to reduced sound levels at the receiver (e.g., due to head turning, short propagation distances of VHF sounds in seawater, etc.). Signal quality at the receiver can also impede detector algorithm performance.

The recording system was comprised of two HTI-99-UHF hydrophones (High Tech, Inc., U.S.) connected to a SoundTrap 4300 high frequency (HF) 4-channel digital sound recorder (Ocean Instruments, New Zealand). Each channel on the 4300 HF recorder had a maximum sampling rate of 384 kilohertz (kHz) with a bandwidth from 20 hertz (Hz) to 150 kHz ± 3 decibels (dB) (higher frequencies observed). The HTI hydrophones had flat frequency responses from 2 Hz to 200 kHz, which were chosen to cover the upper frequency range of harbor porpoise clicks. Hydrophone pre-amp sensitivities were -165 dB re 1 V/µPa ± 3 dB. The SoundTrap recorder was attached to 30 m of line at 14 m from the surface buoy. Hydrophone 1 was positioned in the upper 3 m of the water column while Hydrophone 2 was 7 m vertically below the surface (depths were tide dependent).

The vessel-based marine mammal survey effort provided opportunities for deployments in multiple locations and seasons that varied in ambient conditions and the collection of data to assess the acoustic presence of these porpoises in the greater Hood Canal area. Prior to use during vessel surveys, the SoundTrap array was deployed only in Dabob Bay (Figure 1) over four days to test the recording system's capability to capture harbor porpoise clicks.

The overall goal of this portion of the project was to help identify harbor porpoise 'hot spots' in Hood Canal that may have potential spatial and temporal overlap with Navy activities in order to inform management.

Sound files were post-processed using a matched filter click detector designed using *Matlab* (version R2014a, MathWorks, Inc.) where the full-bandwidth 'generalized click' was low-pass filtered and down-sampled to the sampling frequency of the SoundTrap recorder. Probability of detection and false positives for this matched filter were 77.6 % and 14.4 %, respectively.

Estimates of Density and Abundance

Line-transect analytical methods are relatively well developed for estimating density and abundance of marine mammals using visual sighting data (Buckland et al., 2001, 2004). One of the main assumptions of this method is that all objects (a group of marine mammals in this study) are detected with certainty on the survey line. This is often known as the "g(0)=1" assumption. Because of their elusive behavior, marine mammals, especially harbor porpoises, are often missed by observers and the g(0)=1 assumption is not met (e.g., Laake et al., 1997). One of the goals of this study is to compute estimates of the proportion of groups of animals missed on the trackline (perception bias) by treating sighting data from the upper and lower observation positions as independent platforms.

To identify duplicate sightings between the upper and lower observers, we compared the time, angle, radial distance, linear distance (as calculated from the corrected radial distances), and group size estimates among all harbor porpoise sightings on the same day (e.g., Palka, 2000; Sucunza et al., 2020). We considered all upper-lower sighting pairs that were recorded within 90 sec and within 300 m linear distance of each other as potential matches; there could be multiple potential matches for a single sighting in areas of high sighting density. This resulted in 391 sighting pairs that were then manually evaluated by a single analyst to identify which were likely to be the same group of animals and which were not. While the offset data were seldom identical across observers due to factors such as the use of visual estimates, the potential for human error, and animal behavior, a sighting by the lower observer was considered a match to a sighting by an upper observer when the differences among all offsets were plausible, e.g., where the first observer to record the sighting had a shallower angle than the second, the sighting was on the same side of the track line, and the difference in the radial distance estimates were within expected levels for estimation error and the time lag between the two records.

To record matches, the lower sighting was associated with the sighting number from the corresponding upper sighting, and this was used to exclude the lower sighting from the reconciled data set for analysis and also to flag the upper sighting as having been recorded by the lower. The exception was a small number of cases where multiple upper sightings were recorded as a single, larger sighting by the lower observer- in this case the additional matching sightings from the upper observers were associated with corresponding lower sighting number to flag them as sighted by the lower. We then conducted a secondary review of the mapped sightings to identify any additional matches that may have been missed in the initial screening using offset data.

Data analysis was performed using mark-recapture distance sampling methods (MRDS, Laake and Borchers, 2004), which is an extension of standard line-transect analysis. In MRDS, the probability of sighting a cetacean group is the product of two components. The distance sampling component specifies the probability of an observer detecting a cetacean group as a function of its distance from the survey line (with the probability of detection declining as distance from the trackline increases) or of other covariates (e.g., group size, visibility conditions). The mark-recapture component corresponds to a conditional detection function and is defined as the probability of one team of observers (e.g., primary) detecting the animal group, given the other team (secondary) has detected it and given the group's distance from the survey line. MRDS methods allow for estimation of the proportion of the detection probability on the trackline (g[0]) and also allow for the use of environmental or biological covariates in the estimation of detection probabilities.

Data analysis was conducted using custom-made functions and libraries (e.g., package *mrds*, Laake et al., 2020) in software *R* (version 4.1.2, R Core Team, 2021). Detection probability was estimated using the point independence approach (Laake, 1999; Laake and Borchers, 2004; Borchers et al., 2006). Sighting data from the upper and lower platforms were used in the mark-recapture models for the estimation of the probability of detection on the trackline. Because observers in these two positions were independent (they were visually and acoustically isolated), "capture histories" were developed based on sightings made only by the upper or the lower platform, or by both platforms (Laake and Borchers, 2004). All models proposed for the mark-recapture component of the model included distance from the trackline as a covariate. Other environmental or biological covariates considered included conditions of glare, harbor porpoise group size, sea state (Beaufort scale), season, and visibility conditions. These covariates were included in the models in an additive fashion to model heterogeneity in detection probability. Once the most supported mark-recapture model was selected, the distance sampling model (the detection function) was estimated by fitting a half-normal or a hazard rate model with and without covariates (cloud cover, glare, group size, sea state and visibility conditions) similarly to what was performed for the mark-recapture models. Detection functions were fit to unbinned perpendicular distance data truncated at 200 m. Model selection for both the mark-recapture and the distance sampling components was performed using AIC and inference was based on the most supported model.

Estimates of density and abundance of harbor porpoises were computed by pooling data across each of the two completed survey designs within each season. Stratum-specific estimates of density and abundance, corrected for perception bias, were estimated using the Horvitz-Thompson estimator (Borchers and Burnham, 2004). Expected mean group size was obtained as specified by Innes et al. (2002) and Marques and Buckland (2003). Variance of the quantities of interest and 95% confidence intervals (CI) were estimated as described by Buckland et al. (2001) and Innes et al. (2002) as implemented in package *mrds*.

Seasonal density was computed for each survey stratum in each season. Overall density in the whole study area was estimated as the average density across all strata, weighted by their areas. Abundance in each stratum was computed by multiplying the estimated density by the area of each stratum. The overall abundance in the study area (Hood Canal) was calculated as the sum of the stratum-specific abundances.

Results and Discussion

Survey Effort and Sightings

There was a total of 691 lines totaling 2175.8 km of trackline completed in 37 days between 09 February 2022 and 08 February 2023 (Table 2, Figure 5). The Canal was surveyed twice in each of the four seasons. A total of 809 on-effort sightings of harbor porpoises were recorded, totaling 1,385 individuals across all four seasons (Table 2, Figure 4, Figure 6). An additional four sightings (two on-effort, two off-effort) of transient killer whales totaling 18 individuals were documented from 12-14 July 2022 (Figure 7). These sightings were of the same 7-8 individuals, with individual identity confirmed by opportunistic reports from Orca Network volunteers. Harbor seals were the dominant pinniped sighted, as expected based on previous studies (Ampela et al., 2021; London et al., 2012; Jefferson et al., 2016), with 1,147 on-effort sightings totaling 1,249 individuals (Figure 7). There were 4 on-effort single sightings of Steller sea lions and 23 on-effort sightings of California sea lions totaling 57 individuals (Figure 7).

Spatial and seasonal variation in harbor porpoise sightings were readily evident (Table 2, Figure 6). Most harbor porpoise sightings occurred in Strata 1-4. The lower part of Stratum 2 and all of Stratum 4 were particularly important in the spring and summer. Stratum 3 in Dabob Bay contained many sightings in the fall, when there were fewer sightings in lower Stratum 2 and Stratum 4. Sightings in Stratum 1 were highest during the summer and lowest in the fall. Sightings in the southern half of Hood Canal, Strata 5 and 6, were least common, but appeared to increase as the year progressed with the highest numbers occurring in the fall.

Table 2. Trackline surveyed (km), lines completed, and on-effort harbor porpoise sightings summary by season used to calculate seasonal density and abundance of in Hood Canal, 08 February 2022–09 February 2023 (n = sample size, ind. = number of individuals).

Stratum	Spring			Summer			Fall			Winter			All Seasons		
	Effort (km)	n lines	Sightings groups (ind.)	Effort (km)	n lines	Sightings groups (ind.)	Effort (km)	n lines	Sightings groups (ind.)	Effort (km)	n lines	Sightings groups (ind.)	Effort (km)	n lines	Sightings groups (ind.)
1	82.03	29	15(27)	71.14	25	33(55)	77.52	26	5(8)	74.70	26	14(26)	304.39	*106*	*67(116)*
2	129.72	41	89(143)	129.58	40	142(192)	131.16	41	51(101)	122.09	42	19(31)	*512.79*	*164*	*301(467)*
3	135.33	34	6(14)	128.04	33	37(59)	136.16	34	93(186)	127.22	33	3(7)	*526.75*	*134*	*139(266)*
4	98.14	29	94(157)	89.98	28	80(138)	92.10	30	29(51)	99.11	29	45(106)	*379.33*	*116*	*248(452)*
5	88.08	31	1(2)	86.27	31	11(12)	92.27	32	32(55)	87.17	32	5(8)	*353.79*	*126*	*49(77)*
6	25.44	12	0	24.06	12	1(1)	25.12	11	4(6)	24.12	10	0	*98.74*	*45*	*5(7)*
Total	**557.74**	**176**	**205(343)**	**529.07**	**169**	**304(457)**	**554.57**	**174**	**214(407)**	**534.41**	**172**	**86(178)**	**2175.79**	**691**	**809 (1,385)**

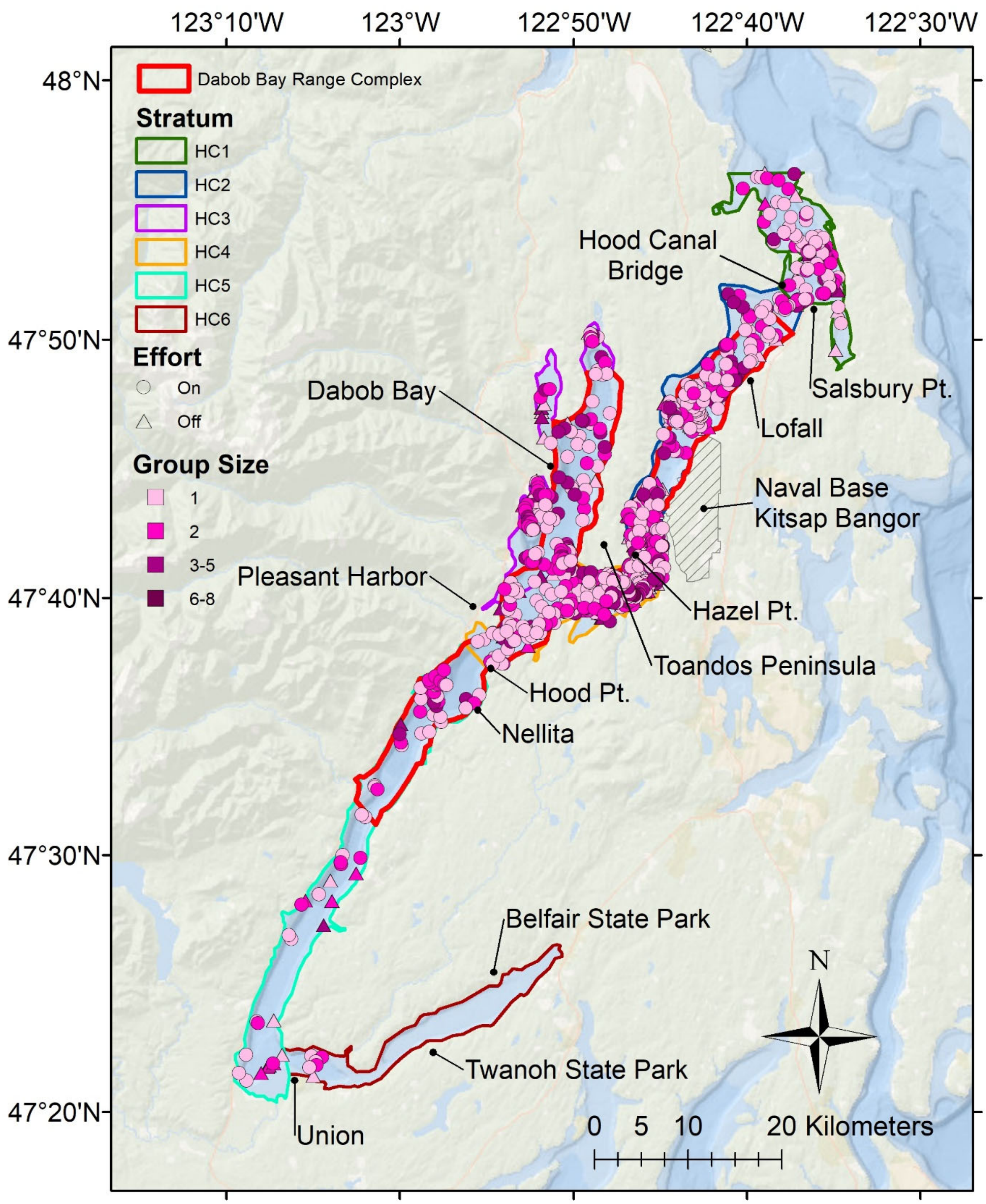

Figure 4. All harbor porpoises sighted in Hood Canal, WA, across the entire survey effort, 2022–2023. Prepared by B. Rone.

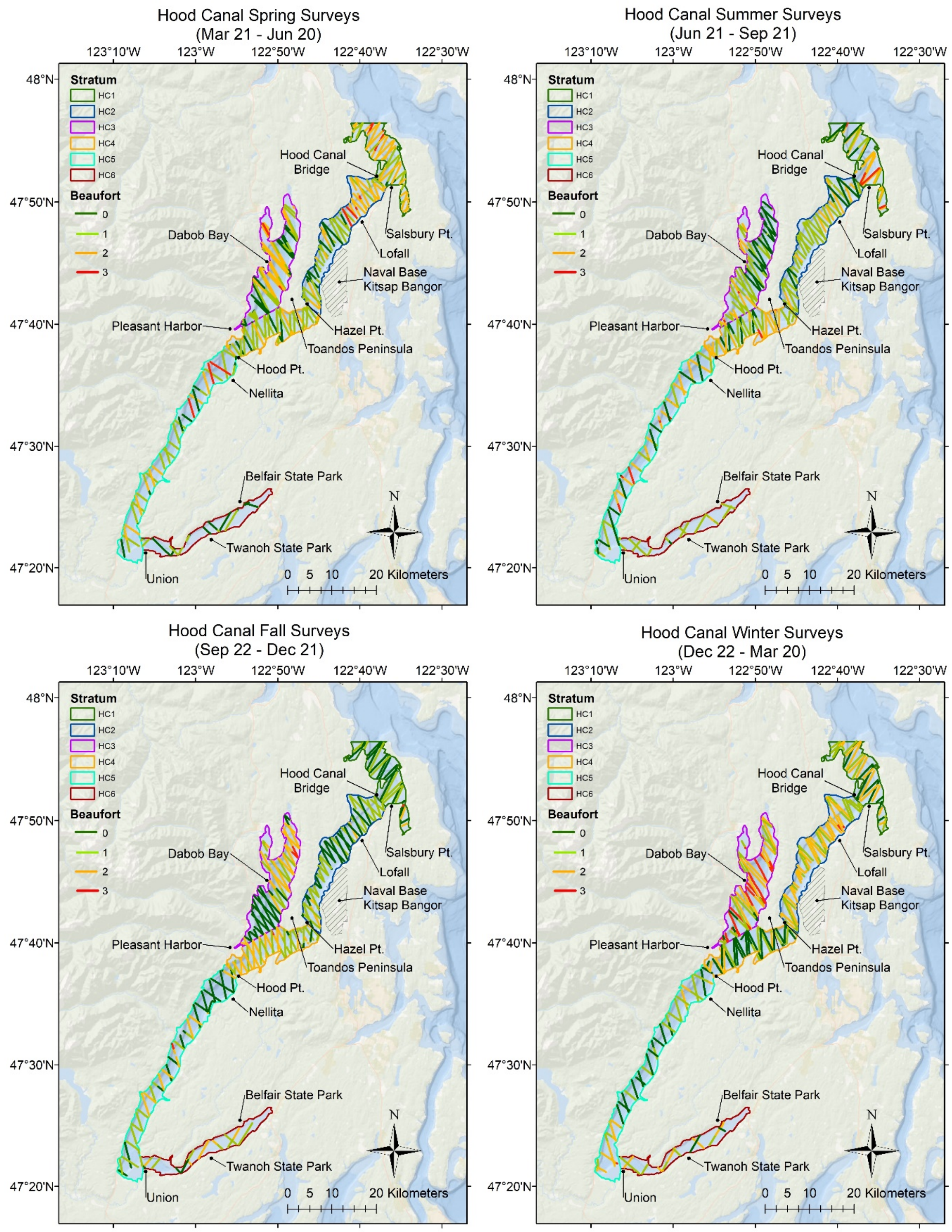

Figure 5. Seasonal survey effort conducted in Hood Canal, WA, 2022–2023. Prepared by B. Rone.

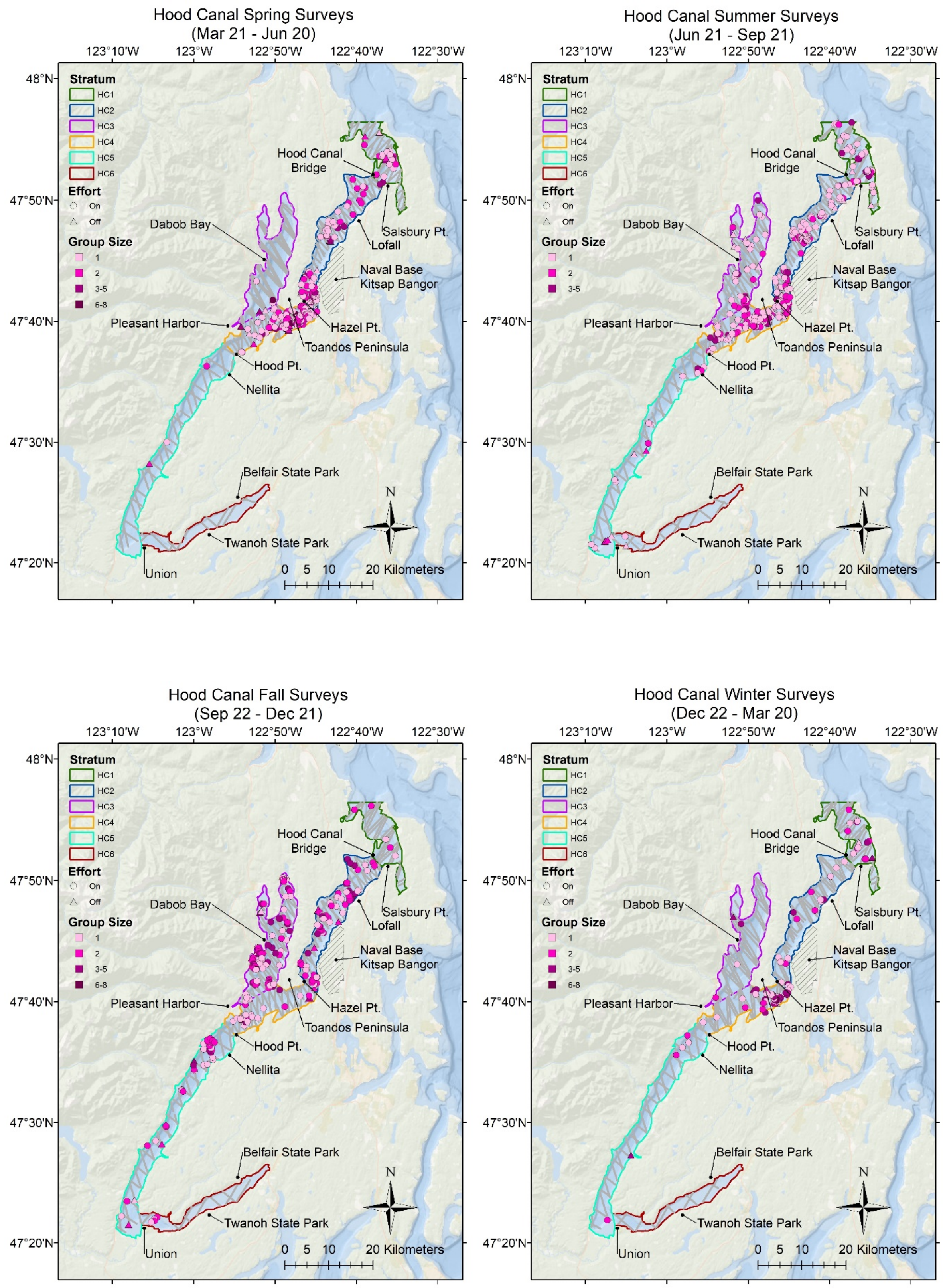

Figure 6. Seasonal harbor porpoise sightings in Hood Canal, WA, 2022–2023*. Prepared by B. Rone.*

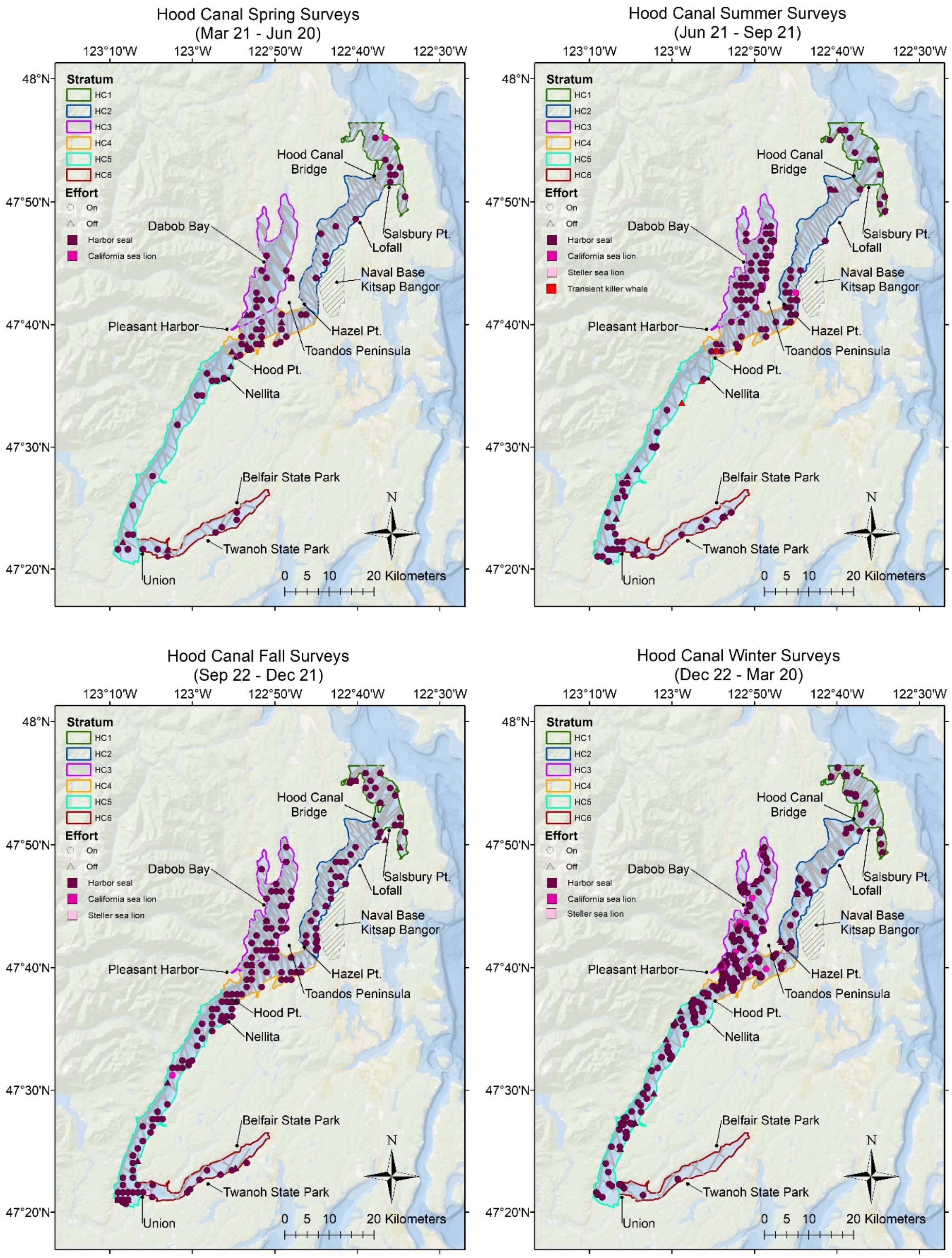

Figure 7. Seasonal killer whale and pinniped sightings in Hood Canal, WA, 2022–2023*. Prepared by B. Rone.*

Calibration Experiments

The most supported model of the calibration experiments suggested that *estimated distance* and *target contrast* were the only significant predictors of true distance, indicating that observers were unable to accurately estimate true distance and that distance estimation was influenced by target contrast. However, because target contrast is not consistently recorded during the actual surveys, this model was not used to compute the predicted true distance for sightings. Instead, the next best model was used, which only included estimated distance as a covariate (Table 3). Interestingly, no difference in distance estimation was detected for the different observers.

Table 3. Parameter estimates for the model selected to correct sighting distances estimated by observers during marine mammal surveys in Hood Canal.

Variable	Estimate	SE	t-value	p-value
Intercept	1.016	0.065	15.628	<0.001
log(Estimated Distance)	0.807	0.013	60.264	<0.001

Acoustic Recordings

A total of 15,531 harbor porpoise clicks were detected during the 131.3 recording hours collected across the 17 days of SoundTrap deployments, including 2 overnights. The first objective was to validate a visual sighting with an acoustic detection. This occurred in May within Stratum 5 during an off-effort encounter occurring just prior to the start of that day's survey. Figure 8 shows a sound file (spectrogram and waveform) of 2 click trains produced by 2 harbor porpoises that were visually observed traveling toward the acoustic array on 21 May 2022 between 07:48 - 07:49 AM. A summary of the acoustic recording data collection effort during each deployment for each Stratum (1-5), and the resulting matched filter click detections, are shown in Table 4 (no recorders were deployed in Stratum 6). Table 5 shows a summary of the Stratum-specific totals for click detection count and recording time sampled during the surveys, along with several measures of acoustic "effort" for each stratum sampled.

The preliminary results presented here focus only on acoustic detections. Analysis of any overlaps of visual sightings and acoustic recordings is still under investigation.

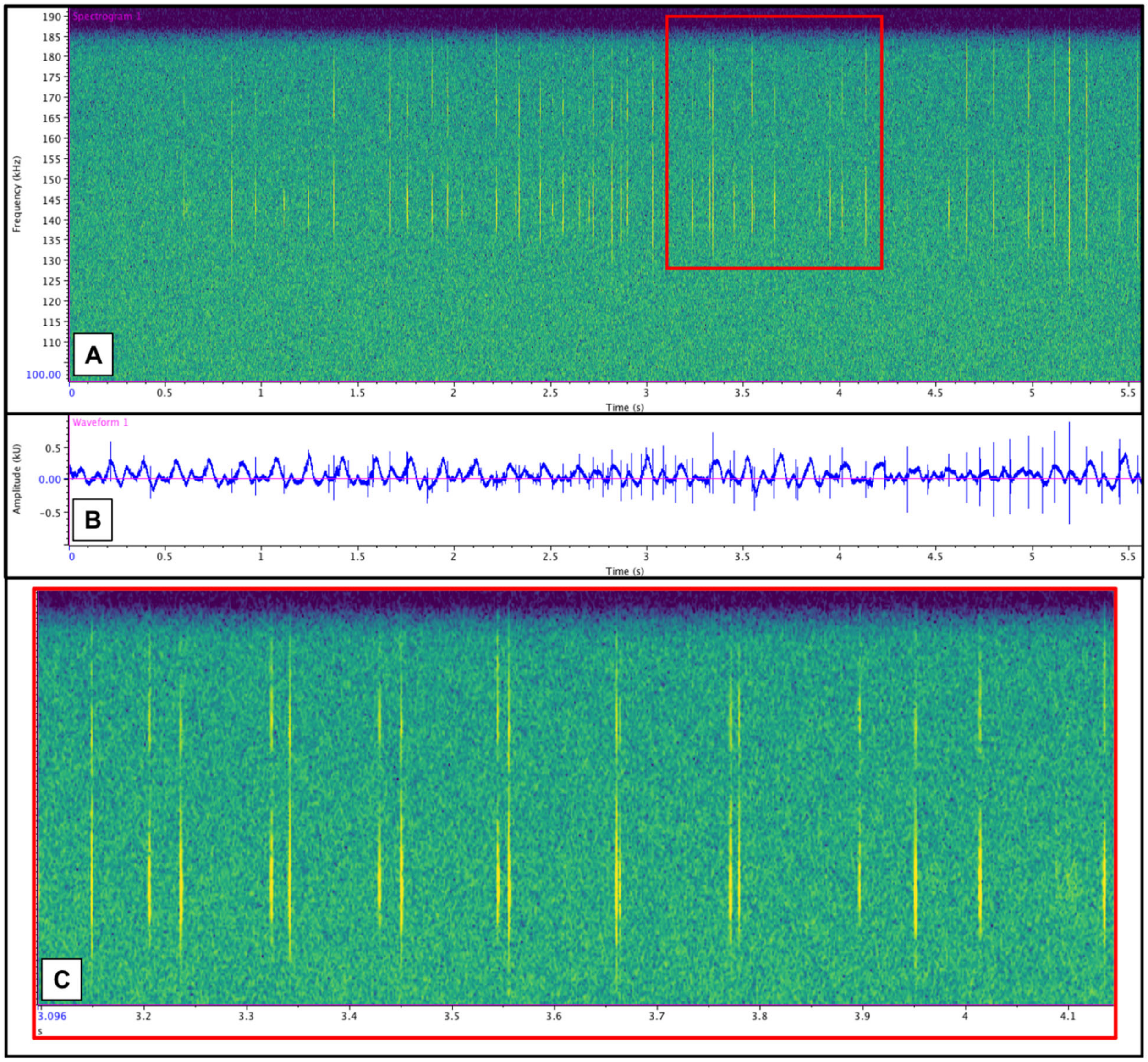

Figure 8. Acoustic and visual confirmation of echolocating harbor porpoises. Two animals were visually observed (off-effort) swimming towards the acoustic array. Clicks train features are shown in A) a spectrogram and B) a waveform; C) is a close-up of 2 click trains emitted by the 2 porpoises (spectral settings: Fs =384 kHz, window size = 512, hanning window).

*Table 4. Summary of the preliminary results from the acoustic recording effort and matched filter click detection processing. The sample sizes of acoustic recordings collected with the SoundTrap are shown in the top section (in hours) for each deployment site (9 total), number (3 max), and corresponding Stratum (1-5). Total recording hours are summarized in bold (e.g., "**S1 Total**" corresponds to the total recording time collected in Stratum 1). The positive detections of harbor porpoise VHF clicks identified by the matched filter algorithm are shown in the bottom section (detection count) for the corresponding recordings collected during each SoundTrap deployment. Total click detection counts for each Stratum are summarized in bold.*

		SoundTrap Recording Time (hours)			
Stratum	**Deployment Site**	**Deployment 1**	**Deployment 2**	**Deployment 3**	**Total**
1	HC Bridge NE	6.6	5.9	-	12.5
	HC Bridge NW	8.1	6.7	5.6	20.4
				S1 Total	**32.9**
2	Lofall N	5.2	7.4	-	12.6
				S2 Total	**12.6**
3	Toandos W Dabob	4.1	6.4	-	10.5
				S3 Total	**10.5**
4	Pleasant Harbor	6.1	-	-	6.1
	Toandos	4.9	-	-	4.9
	Hazel Pt	28.6	-	-	28.6
				S4 Total	**39.6**
5	Nellita	7.1	23.0	-	30
	Union N	5.6	-	-	5.6
				S5 Total	**35.7**
		Matched Filter Detection Counts of Harbor Porpoise Clicks			
1	HC Bridge NE	53	0	-	53
	HC Bridge NW	4976	1521	541	7038
				S1 Total	**7091**
2	Lofall N	349	1072	-	1421
				S2 Total	**1421**
3	Toandos W Dabob	96	576	-	672
				S3 Total	**672**
4	Pleasant Harbor	0	-	-	0
	Toandos	2062	-	-	2062
	Hazel Pt	3378	-	-	3378
				S4 Total	**5440**
5	Nellita	0	608	-	608
	Union N	299	-	-	299
				S5 Total	**907**

Table 5. The total number of harbor porpoise VHF click detections are shown with the total number of recording hours collected within each Stratum sampled. Also shown for each Stratum are the detection counts by acoustic "effort" (number of detections per hour of recording time). The click detection counts identified within each Stratum were calculated as a percent of the total number of detections across Stratums 1-5, and are shown below. This corresponding metric was also calculated for recording time in each Stratum (as percent of total time across Stratums 1-5) and is shown below.

	Stratum				
	1	**2**	**3**	**4**	**5**
Detection Count	7091	1421	672	5440	907
Recording Time (hours)	32.9	12.6	10.5	39.6	35.7
Detections by Effort (count/hour)	216	113	64	137	25
Percent of Total Detections	45.7%	9.1%	4.3%	35.0%	5.8%
Percent of Total Time	25.1%	9.6%	8.0%	30.2%	27.2%

Estimation of Detection Probability, Density, and Abundance

The total number of sightings used to estimate detection probability after truncating the perpendicular distance data at 200 m was 624. Of these, 484 sightings were seen by the primary ("upper") platform, 290 were seen by the secondary ("lower") platform and 150 sightings seen by both platform (duplicate sightings).

The most supported detection probability model according to AIC included distance, group size and season in the mark-recapture component and the hazard rate function without covariates for the distance sampling model. Parameter estimates for this model are presented in Table 6 and the fit of the model to sighting data is provided in Figure 9. Model selection and AIC values for all detection probability models are summarized in Appendix 2 and Appendix 3. The most supported model suggested that detection probability decreases with distance and increases as group size increases. It also indicated that detection probability varied by season (*Table 6*).

Details of stratum-specific effort information for each season are provided in Table 2. Seasonal estimates of harbor porpoise encounter rate, group size, density, and abundance and their respective CVs for the whole study area and for each stratum are summarized in Table 7 and Appendix 4, respectively. Seasonal estimates of harbor porpoise abundance for Hood Canal and for each stratum are illustrated in Figure 10 and Figure 11, respectively.

Table 6. Parameter estimate of the most supported detection probability model for harbor porpoise sightings in Hood Canal.

Parameter	Estimate	SE	CV
Mark-recapture model			
Intercept	-0.626	0.301	
Distance	-4.522	1.892	
Group size	0.398	0.099	
Season (summer)	0.315	0.236	
Season (fall)	-1.281	0.326	
Season (winter)	-0.232	0.352	
Average *p(0)*	0.618	0.063	0.10
Distance Sampling model			
Scale coefficient	-1.932	0.076	
Shape coefficient	0.783	0.281	
Average *p(0)*	0.802	0.034	0.04
Average *p*	0.496	0.054	0.11

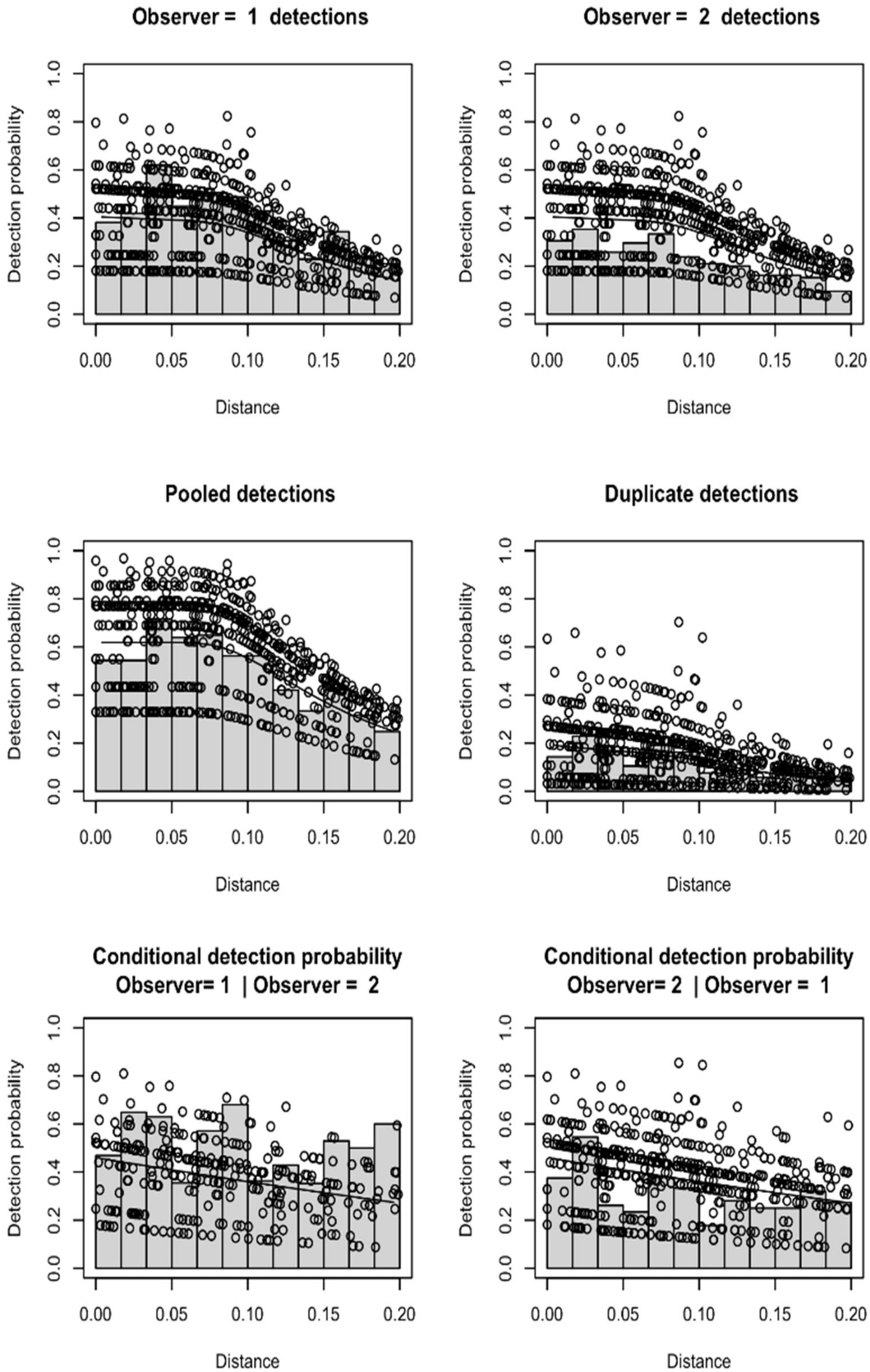

Figure 9. Fit of the AIC-most supported detection probability model to fit harbor porpoise perpendicular distance data (Observer 1 = upper platform, Observer 2 = lower platform).

Table 7. Quantities of interest for seasonal estimation of abundance of harbor porpoises in Hood Canal.

(n = number of groups seen by the upper observation platform, ER = encounter rate, ES = expected group size, D = density of individuals per km2, N = number of individuals, N_LCL = 95% lower confidence interval for the abundance estimate, N_UCL = 95% upper confidence interval for the abundance estimate, CV = coefficient of variation of the relevant estimates).

Season	n	ER	CV(ER)	ES	CV(ES)	D	N	CV(D/N)	N_LCL	N_UCL
Spring	152	0.07	0.21	1.59	0.05	2.444	547	0.19	375	796
Summer	245	0.113	0.15	1.43	0.03	2.152	815	0.14	623	1066
Fall	161	0.074	0.16	1.62	0.04	3.524	1336	0.25	826	2160
Winter	66	0.03	0.24	1.77	0.06	0.812	308	0.25	189	503

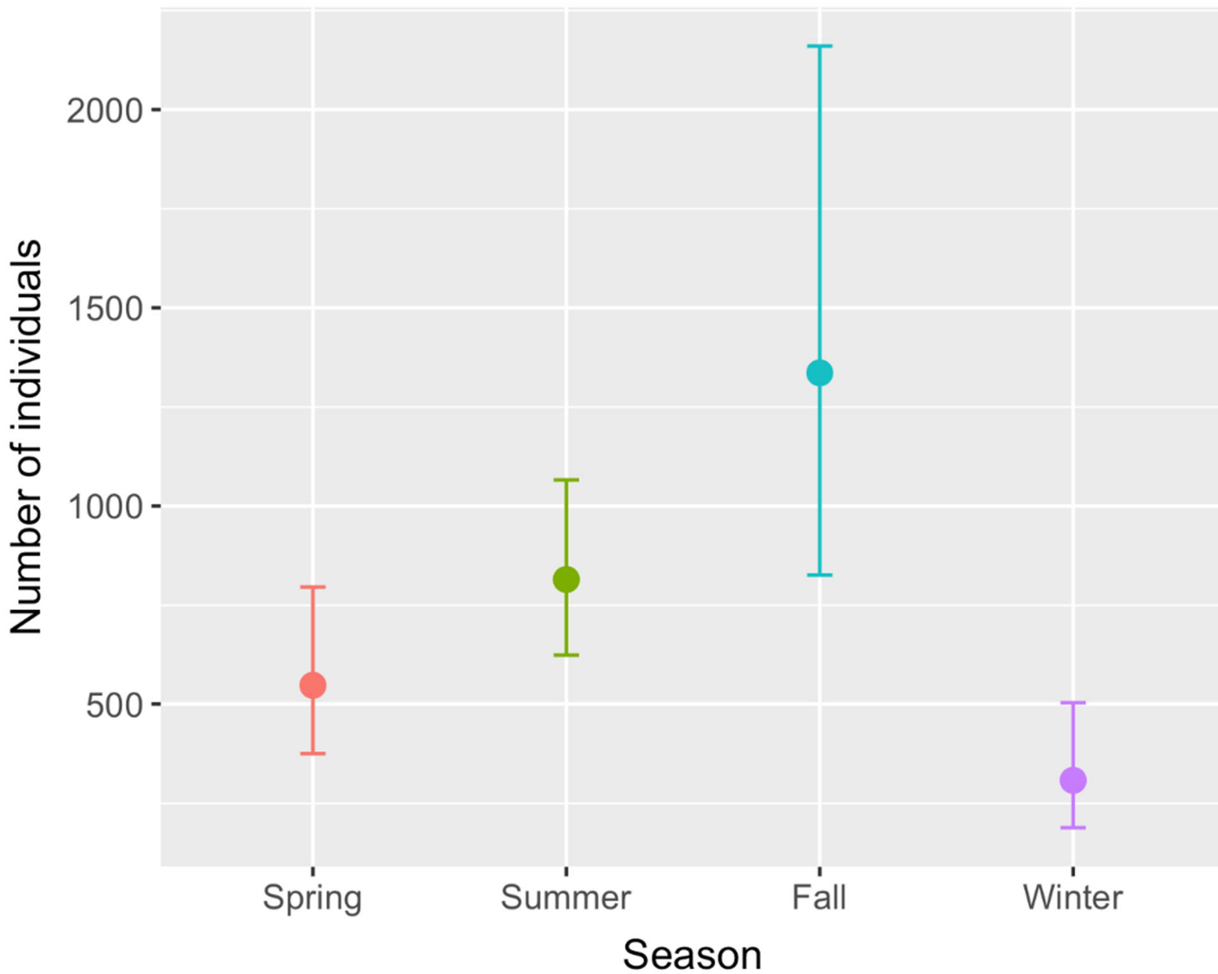

Figure 10. Seasonal estimates of abundance of harbor porpoises in Hood Canal and their respective confidence intervals.

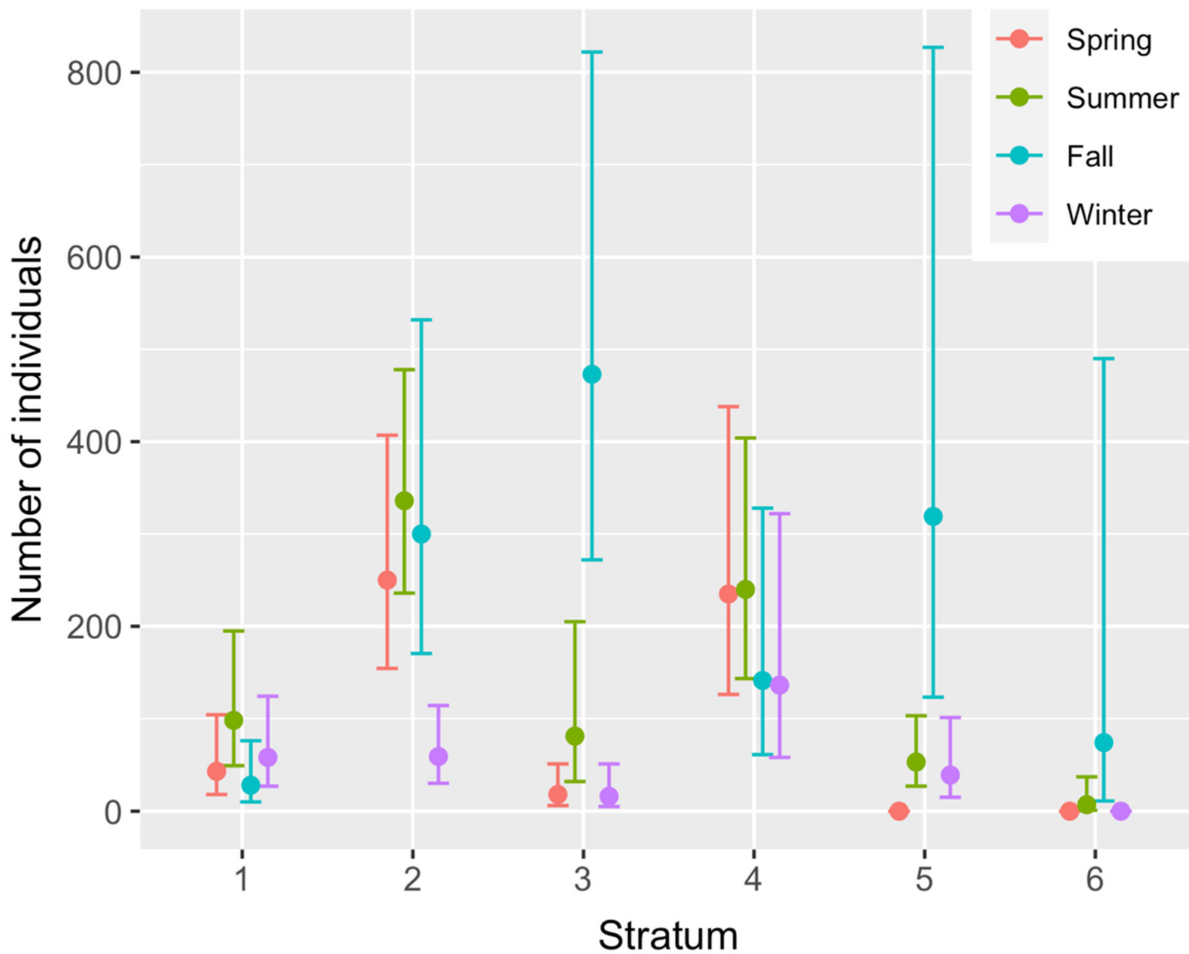

Figure 11. Seasonal estimates of abundance (and confidence intervals) of harbor porpoises in each survey stratum in Hood Canal.

Average seasonal estimates of harbor porpoise group size ranged from 1.43 to 1.77 individuals (Table 7), but these numbers are not statistically different. Overall, group size for this species was estimated at 1.6 individuals per group, which is consistent with estimates of group sizes of this species in this and other regions (e.g., Dahlheim et al., 2015; Jefferson et al., 2016; Zerbini et al., 2022).

Density and abundance estimates indicate a seasonal pattern in the occurrence of harbor porpoises in Hood Canal. The highest abundance was observed in the fall (D = 0.881 ind/km^2, N = 1336 individuals, CV = 0.25, Table 7, Figure 10), followed by the summer (D = 0.538 ind/km^2, N = 815 individuals, CV = 0.14) and then spring (D = 0.361 ind/km^2, N = 547 porpoises, CV = 0.19). Abundance in the winter was the lowest (D = 0.203 ind/km^2, N = 308 individuals, CV = 0.25). The estimates between fall and summer and spring and winter are not statistically different due to overlapping confidence intervals. The estimates proposed here suggest that harbor porpoises are more abundant in the summer/fall and leave Hood Canal in the winter, possibly returning in the spring.

Stratum-specific estimates (Figure 11) suggest that harbor porpoise abundance is higher in Strata 2 and 4, which corresponds to middle Hood Canal within the DBRC and includes the section of the Canal adjacent to Naval Base Kitsap Bangor (Figure 12), though there is a marked absence of harbor porpoise sightings directly adjacent to the in-water physical structures associated with the base. The only exception is Stratum 3 in the fall, which presented the highest abundance of all strata across all seasons. In general, abundance is substantially lower in the northern (Stratum 1) and southern ends (Strata 5 and 6). However, fall abundance in Strata 5 and 6 are higher than any other season, but the confidence intervals are wide suggesting that, at least for Stratum 6, the fall estimate is not significantly different than the estimates for other seasons.

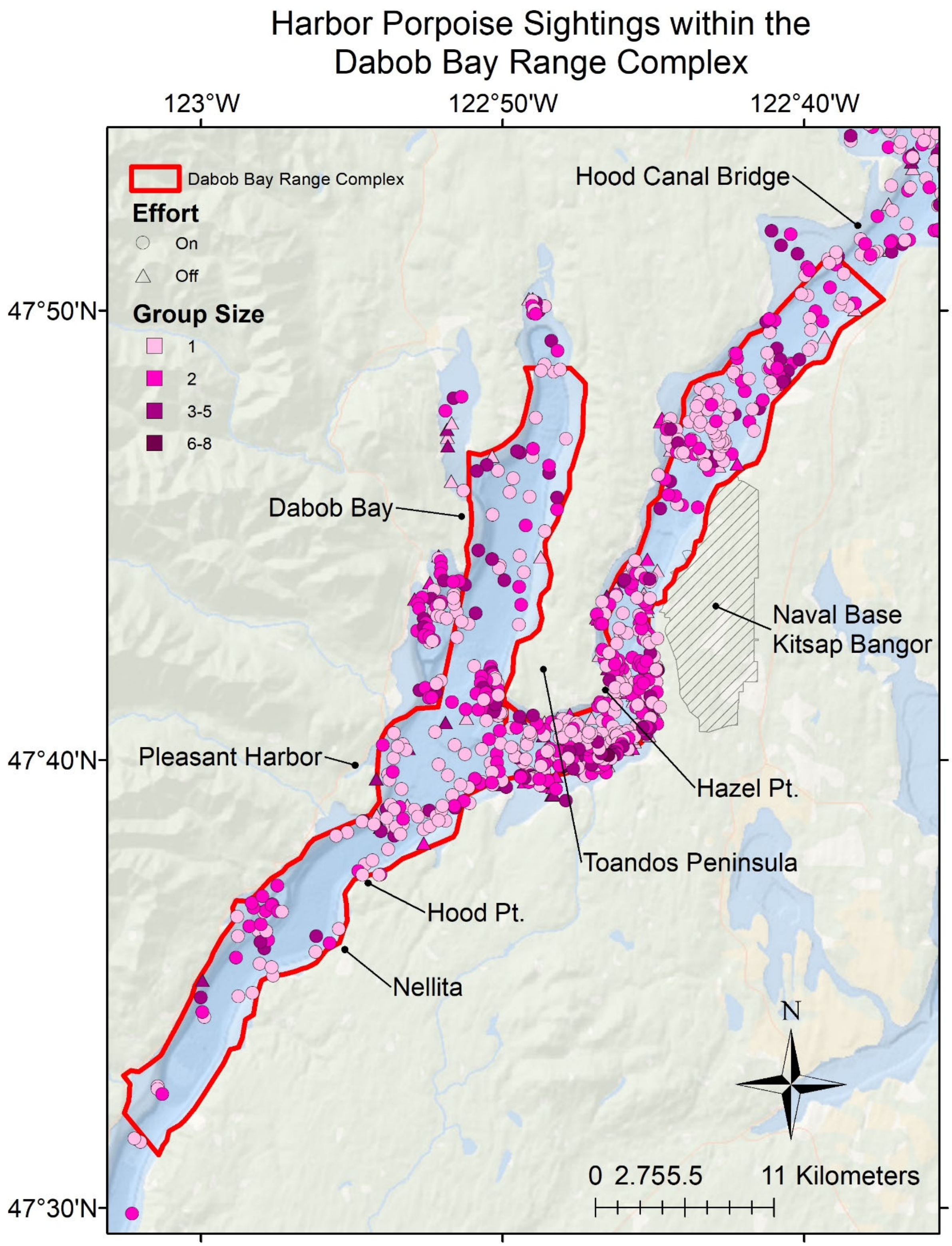

Figure 12. Harbor porpoise sightings within the Dabob Bay Range Complex located in Hood Canal, WA, 2022–2023.

Estimates of abundance provided in this study suggest that a relatively large number of harbor porpoises inhabit Hood Canal, especially in the summer-fall period, and that most porpoises leave Hood Canal in the winter. The fall estimate is substantially higher than in the other seasons and that is mainly caused by the small number of matches between the upper and the lower platform (Figure 13). The proportion of groups seen by both platforms is much greater (ranging from 0.17 to 0.23) in the spring, summer and winter when compared to the fall (0.09). Because detection probability is computed as a function of these matches, a low matching rate indicates that a high proportion of animals is missed by the upper observer (that is g(0) is much lower). Abundance is inversely proportional to detection probability; a low detection rate will result in a high estimate of individuals.

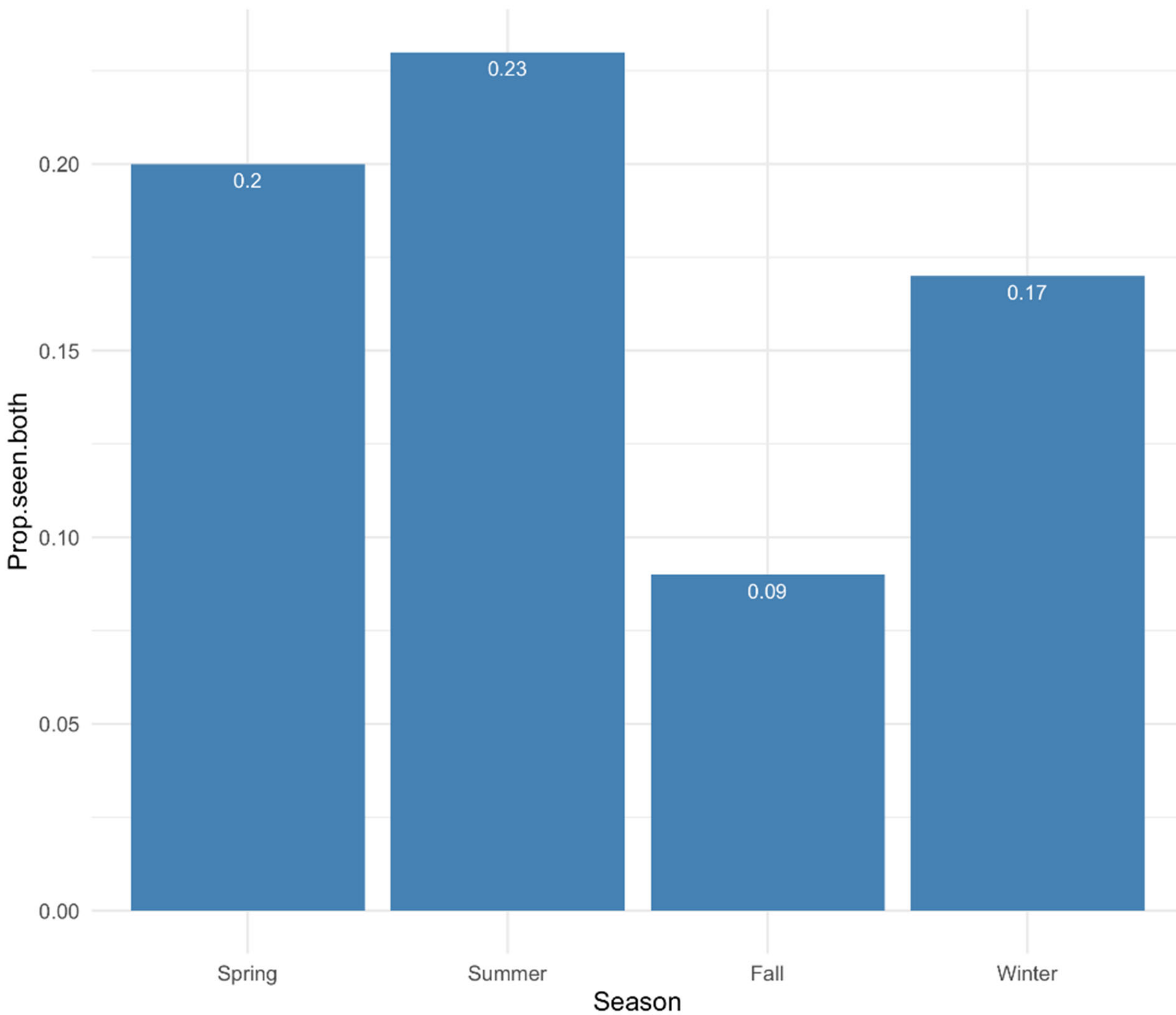

Figure 13. Proportion of sightings seen by both observation platforms (upper and lower) during harbor porpoise surveys in Hood Canal, WA, 2022 and 2023.

Currently, it is unclear why the proportion of sightings seen by both observation platforms is lower in the fall. Observers were consistently used in all seasons and because they rotated across all observation positions, we expected the relative number of matches to be somewhat consistent across seasons. It is conceivable that there are seasonal changes in harbor porpoise behavior that may explain these differences. If animals in the fall display social or feeding behavior that is different from those displayed in other seasons, it is possible that this could affect detectability by the observers, resulting in lower matching rates across platforms. Visual evaluation of spatial distribution along the trackline suggested that porpoises were more clustered in other seasons versus the fall. This difference alone could contribute to a reduction in upper and lower matches as a result of distance estimation error (i.e., there may have been increased error in distance estimation in the fall because sightings appeared to occur further from the trackline versus other seasons). Additionally, general observations suggested that animal availability may have decreased in the fall as it was observed several times that animals appeared to spend less time at the surface when initially sighted (e.g., surfacing only once) making it less likely for both upper and lower observers to catch a single surfacing of a porpoise. Further studies are needed to better understand seasonal behavior of harbor porpoises and the potential implications for detectability of this species in visual surveys in Hood Canal.

This study has resulted in the most up-to-date and comprehensive assessment of harbor porpoises in Hood Canal. Preliminary findings have demonstrated a markedly higher abundance estimate since the last study undertaken by Jefferson et al. (2016) in 2013-2015, where aerial survey-based pooled data from spring-summer-fall resulted in an estimated abundance of 185 individuals (95% CI = 116-291); winter estimates were not obtained due to inclement weather. The estimates presented here suggest that the number of porpoises in Hood Canal in 2022/2023 is approximately an order of magnitude higher and significantly different than those estimated by Jefferson et al. (2016). Differences in abundance across the survey period may occur because of different sampling protocols (e.g., aerial versus vessel surveys), true differences in density of porpoises across years or a combination of factors. Aerial surveys are widely used to estimate abundance of cetaceans, including harbor porpoises. Because of the speed of travel, the proportion of animals missed by an observer (perception bias) in an aerial platform is relatively high (Laake et al., 1997 estimated this proportion to range from about 20 to 80% of porpoise groups depending on the experience of the observer). In addition, groups of animals are missed because they are submerged (availability bias) for the entire time an airplane flies over. Jefferson et al. (2016) applied a correction factor to account for both perception and availability bias developed for harbor porpoises by Laake et al. (1997). However, correction factors are often observer-specific and may vary regionally or depending on the behavior of the animals. If that is the case, the correction factor by Laake et al. (1997) may not be the most applicable to the aerial surveys of Jefferson et al. (2016). This observation is not meant to be a criticism to the latter authors. Their approach was appropriate (i.e., they attempted to account for perception and availability bias in their surveys), but if the correction factor is not applicable to the survey, the estimate produced during their study could be biased. Searching for porpoise from a slower surface platform such as the vessel used in this study minimizes bias due to availability bias because porpoise groups are more likely to surface one or more times in the observer's field of view as the vessel slowly moves through the transect. In addition, estimating perception bias from the double platform observer ensured that the estimates produced here accounted for survey-specific bias due to animals missed during the present research.

Discrepancies in the estimates of abundance in Hood Canal between the Jefferson et al. (2016) study and this study may also occur because of true differences in density in the region. The movement dynamics of harbor porpoises in the Canal, as well as in the broader Salish Sea region, are not well known. Harbor porpoise abundance in the Salish Sea has varied over a period of several decades (Evenson et al., 2016). According to these authors, the species used to be relatively common in the 1940s but nearly disappeared from the Puget Sound in the 1970s and their numbers were greatly reduced in the Straits of Juan de Fuca, Straits of Georgia and around the San Juan Islands. Since the early 1990s, an increase in harbor porpoise abundance has been documented (Evenson et al., 2016) and higher numbers in Hood Canal today than in the mid-2010s may be a result of this increase. It is also possible that the use of Hood Canal by harbor porpoises varies on some regular basis with the influx of animals from the greater Salish Sea being greater in certain years (e.g., regional habitat suitability was greater in 2022/2023 when compared to the mid-2010s). Clearly, additional studies are needed to better understand movement dynamics and habitat use of harbor porpoises in this region.

Next Steps

The next steps for these data are to explore possible explanations for the low detection rate during the fall season. We are currently reconciling the pinniped sightings between the upper and lower observers as previously described in the Methods section. This may provide two additional key pieces of information: 1) it will help inform upper and lower observer sighting performance. For example, when there was the presence of "hotspot" areas containing aggregations of both porpoise and pinniped sightings, we may be able to evaluate whether pinnipeds (typically recorded within ~100 m of the vessel) were distracting observers from porpoise detections, and 2) this may further describe the seasonal landscape of marine mammal sightings. The outcome of this additional analysis may provide recommendations on future survey designs (e.g., certain species should be ignored depending on the objective and target species of a given study).

We will continue our exploration into potential tidal influence on porpoise distribution within Hood Canal and may include results of this analysis in the upcoming publication. The relationship between tidal activity and harbor porpoise presence has been demonstrated in other regions (e.g., Johnston et al., 2005; IJsseldijk et al., 2015), and understanding how ecosystem dynamics may influence porpoise presence in the Canal may further inform EIS and management strategies.

However, given the relatively limited sampling of this project, with just one year of effort instead of the three originally proposed, these more detailed analyses may be inconclusive.

Recommendations

Although this work was successful in achieving the goal of this project, it should be stressed that multi-year surveys to assess inter-annual changes in numbers, distribution and overall trends would benefit the Navy for future permit acquisition and monitoring. Given the limited research in this area and the changing environment of today, it is crucial to invest money in time series studies in order to draw defensible conclusions.

Throughout the course of this past year, it became clear that this project would have benefitted from the proposed drone work. Drones have proven useful in generating surface availability and group size estimates, body condition, and in documenting behaviors of small odontocetes that are not apparent from lateral, surface-based platforms (e.g., Brown et al., 2022). Obtaining regional data on harbor porpoise surface availability, group spread and dynamics, foraging and other behaviors which appeared to vary throughout 2022/2023 (e.g., less surfacing time and groups more spread out in the fall), would likely have provided quantifiable data to refine these estimates. This variability we observed in behavior most likely influenced sighting rates and g(0) calculations and should be quantified. Finally, collecting pinniped sightings may have contributed to missing harbor porpoise sightings in areas of high density. We suggest that future surveys in this area focused on cetaceans should ignore pinniped sightings, as at-sea data collection for pinnipeds needs concurrent data collection at haul out sites in order to be truly relevant.

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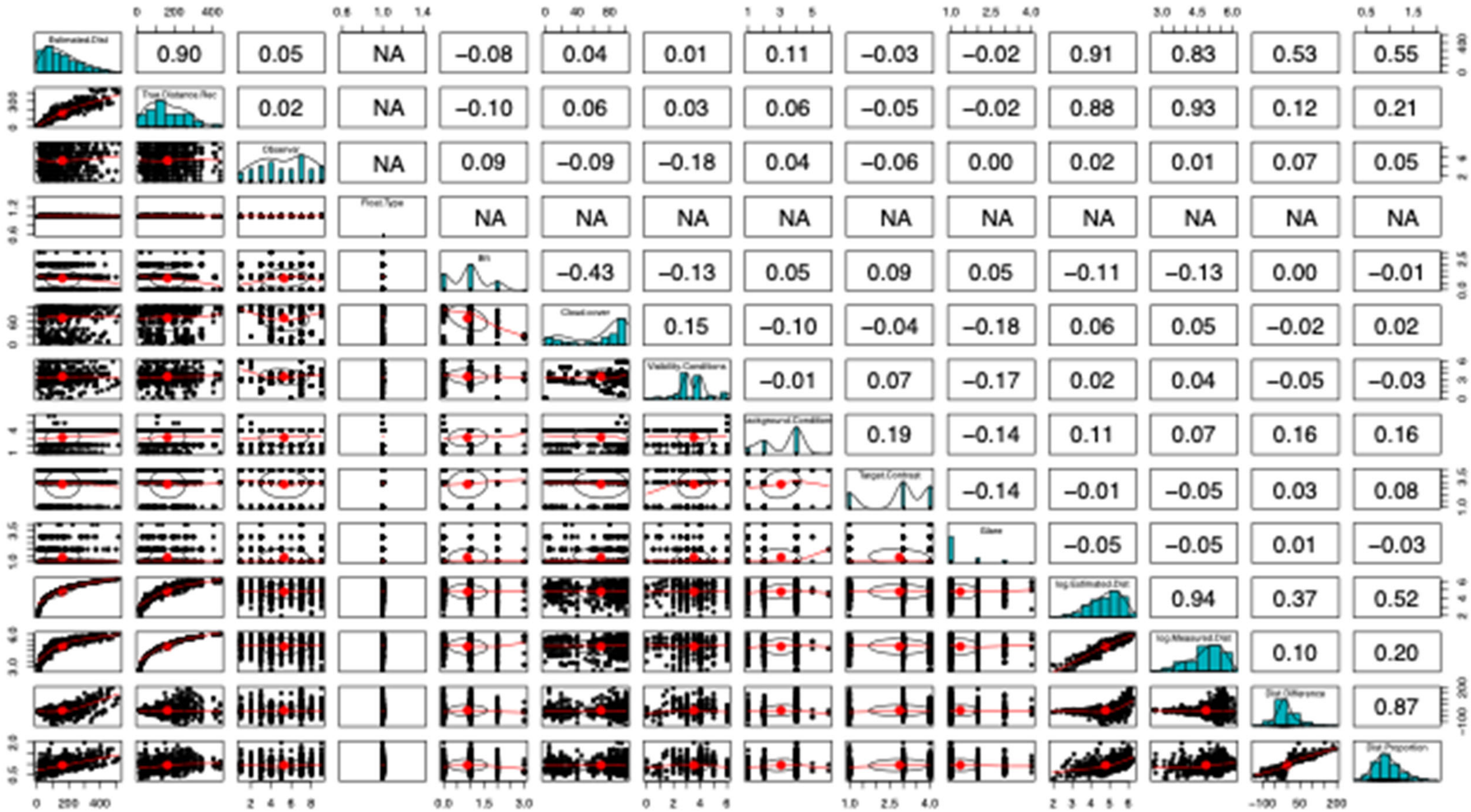
Appendix 1. Exploratory scatter plot of matrices (SPLOM) showing bivariate scatter plots below the diagonal, histograms on the diagonal, and the Pearson correlation coefficients above the diagonal (correlation ellipses are also shown).



Appendix 2. Model selection table for the mark-recapture component of the detection probability model.

(MR = mark-recapture, AIC = Akaike Information Criterion)

MR_Model	AIC	deltaAIC
~distance+size+Season	-741.174	0.000
~distance+size+Visibility.Conditions+Season	-739.729	1.445
~distance+size+Visibility.Conditions+Glare.Conditions+Season	-737.738	3.436
~size+Season	-737.311	3.864
~size+Visibility.Conditions+Season	-735.995	5.179
~distance+size+Visibility.Conditions+Glare.Conditions+Sea.State+Season	-735.995	5.179
~size+Visibility.Conditions+Glare.Conditions+Season	-734.004	7.171
~size+Visibility.Conditions+Glare.Conditions+Sea.State+Season	-732.179	8.996
~distance+Season	-727.152	14.023
~distance+Visibility.Conditions+Season	-725.965	15.210
~distance+Visibility.Conditions+Glare.Conditions+Season	-724.059	17.115
~Season	-723.765	17.409
~distance+Glare.Conditions+Sea.State+Season	-723.293	17.882
~Visibility.Conditions+Season	-722.737	18.437
~Glare.Conditions+Season	-721.879	19.296
~Visibility.Conditions+Glare.Conditions+Season	-720.864	20.311
~Visibility.Conditions+Glare.Conditions+Sea.State+Season	-718.949	22.226
~distance+size+Visibility.Conditions	-715.285	25.890
~distance+size+Visibility.Conditions+Sea.State	-714.232	26.942
~distance+size+Visibility.Conditions+Glare.Conditions	-713.673	27.501
~size+Visibility.Conditions	-713.519	27.655
~distance+size+Sea.State	-712.889	28.285
~distance+size+Visibility.Conditions+Glare.Conditions+Sea.State	-712.778	28.396
~distance+size	-712.674	28.501
~size+Visibility.Conditions+Sea.State	-712.511	28.663
~size+Visibility.Conditions+Glare.Conditions	-711.884	29.291
~distance+size+Glare.Conditions	-711.247	29.928
~size+Sea.State	-711.226	29.948
~size+Visibility.Conditions+Glare.Conditions+Sea.State	-711.026	30.149
~size	-710.956	30.218
~size+Glare.Conditions	-709.500	31.675
~distance+Visibility.Conditions	-707.786	33.389
~distance+Visibility.Conditions+Sea.State	-706.698	34.476
~Visibility.Conditions	-706.320	34.854

~distance+Visibility.Conditions+Glare.Conditions	-705.896	35.278
~Visibility.Conditions+Sea.State	-705.310	35.865
~distance+Sea.State	-705.057	36.118
~distance+Visibility.Conditions+Glare.Conditions+Sea.State	-704.885	36.289
~distance	-704.810	36.364
~Visibility.Conditions+Glare.Conditions	-704.404	36.771
~Sea.State	-703.729	37.446
~Visibility.Conditions+Glare.Conditions+Sea.State	-703.461	37.714
~distance+Glare.Conditions	-703.034	38.141
~Glare.Conditions	-701.558	39.616

Appendix 3. Model selection table for the distance sampling component of the detection probability model.

(DS = distance sampling, AIC = Akaike Information Criterion)

DSKey	DS_Model	AIC	deltaAIC
hr	~1	-742.387	0.000
hn	~1	-741.174	1.213
hr	~Sea.State	-740.850	1.537
hr	~Glare.Conditions	-740.835	1.552
hr	~Visibility.Conditions	-740.639	1.748
hr	~size	-740.421	1.966
hr	~Cloud.Cover	-740.400	1.987
hn	~Sea.State	-739.785	2.602
hn	~Glare.Conditions	-739.662	2.725
hn	~Visibility.Conditions	-739.283	3.104
hr	~Sea.State+Visibility.Conditions	-739.270	3.117
hr	~Sea.State+Glare.Conditions	-739.267	3.120
hn	~size	-739.200	3.187
hn	~Cloud.Cover	-739.174	3.213
hr	~Visibility.Conditions+Glare.Conditions	-738.980	3.407
hr	~size+Glare.Conditions	-738.946	3.441
hr	~Sea.State+size	-738.943	3.444
hr	~Sea.State+Cloud.Cover	-738.854	3.533
hr	~Glare.Conditions+Cloud.Cover	-738.840	3.547
hr	~size+Visibility.Conditions	-738.662	3.725
hr	~Visibility.Conditions+Cloud.Cover	-738.654	3.733
hn	~Sea.State+Glare.Conditions	-738.449	3.938
hr	~size+Cloud.Cover	-738.434	3.953
hn	~Sea.State+Visibility.Conditions	-738.123	4.264
hn	~size+Glare.Conditions	-738.086	4.301
hn	~Sea.State+size	-737.939	4.448
hn	~Sea.State+Cloud.Cover	-737.800	4.587
hn	~Visibility.Conditions+Glare.Conditions	-737.742	4.645
hn	~Glare.Conditions+Cloud.Cover	-737.668	4.719
hn	~Sea.State+size+Glare.Conditions	-737.544	4.843
hr	~Sea.State+Visibility.Conditions+Glare.Conditions	-737.544	4.843
hr	~Sea.State+size+Glare.Conditions	-737.492	4.895
hr	~Sea.State+size+Visibility.Conditions	-737.352	5.036
hn	~size+Visibility.Conditions	-737.299	5.088
hn	~Visibility.Conditions+Cloud.Cover	-737.285	5.103

hr	~Sea.State+Visibility.Conditions+Cloud.Cover	-737.275	5.112
hr	~Sea.State+Glare.Conditions+Cloud.Cover	-737.268	5.119
hn	~size+Cloud.Cover	-737.201	5.187
hr	~size+Visibility.Conditions+Glare.Conditions	-737.069	5.318
hr	~Visibility.Conditions+Glare.Conditions+Cloud.Cover	-736.987	5.400
hr	~size+Glare.Conditions+Cloud.Cover	-736.949	5.438
hr	~Sea.State+size+Cloud.Cover	-736.947	5.440
hn	~Sea.State+Visibility.Conditions+Glare.Conditions	-736.730	5.658
hr	~size+Visibility.Conditions+Cloud.Cover	-736.676	5.711
hn	~Sea.State+Glare.Conditions+Cloud.Cover	-736.509	5.878
hn	~Sea.State+size+Visibility.Conditions	-736.273	6.115
hn	~Sea.State+Visibility.Conditions+Cloud.Cover	-736.140	6.248
hn	~size+Visibility.Conditions+Glare.Conditions	-736.107	6.281
hn	~size+Glare.Conditions+Cloud.Cover	-736.093	6.295
hn	~Sea.State+size+Cloud.Cover	-735.952	6.435
hn	~Visibility.Conditions+Glare.Conditions+Cloud.Cover	-735.744	6.643
hr	~Sea.State+size+Visibility.Conditions+Glare.Conditions	-735.741	6.646
hn	~Sea.State+size+Visibility.Conditions+Glare.Conditions	-735.723	6.665
hr	~Sea.State+Visibility.Conditions+Glare.Conditions+Cloud.Cover	-735.546	6.841
hr	~Sea.State+size+Visibility.Conditions+Cloud.Cover	-735.356	7.031
hn	~size+Visibility.Conditions+Cloud.Cover	-735.301	7.087
hr	~size+Visibility.Conditions+Glare.Conditions+Cloud.Cover	-735.075	7.313
hn	~Sea.State+Visibility.Conditions+Glare.Conditions+Cloud.Cover	-734.785	7.602
hn	~Sea.State+size+Visibility.Conditions+Cloud.Cover	-734.288	8.099
hn	~size+Visibility.Conditions+Glare.Conditions+Cloud.Cover	-734.111	8.276
hn	~Sea.State+size+Visibility.Conditions+Glare.Conditions+Cloud.Cover	-733.811	8.576
hr	~Sea.State+size+Visibility.Conditions+Glare.Conditions+Cloud.Cover	-733.742	8.645

Appendix 4. Seasonal and stratum specific estimates of harbor porpoise density, abundance, and other quantities of interest in Hood Canal 2022/2023.

(ER = encounter rate, E_S = expected group size, D_ind = density of individuals, N_ind = number of individuals, CV = coefficient of variation, LCL = 95% lower confidence interval for the abundance estimate, UCL = 95% upper confidence interval for the abundance estimate).

Season	Stratum	Effort_km	n_groups	n_lines	ER	CV_ER	E_S	CV_E_S	D_ind	CV_D_ind	N_ind	CV_N_ind	N_LCL	N_UCL
Spring	1	81.03	10	29	0.123	0.43	1.88	0.29	0.946	0.45	43	0.45	18	104
Spring	2	129.72	69	41	0.532	0.24	1.53	0.08	3.426	0.25	250	0.25	154	407
Spring	3	135.33	5	34	0.037	0.56	1.53	0.34	0.238	0.55	18	0.55	6	51
Spring	4	98.14	68	29	0.693	0.31	1.61	0.13	4.703	0.31	235	0.31	126	438
Spring	5	88.08	0	31	0	0	0	0	0	0	0	0	0	0
Spring	6	25.44	0	12	0	0	0	0	0	0	0	0	0	0
Total Spring		*557.74*	*152*	*176*										
Summer	1	71.14	25	25	0.351	0.31	1.58	0.12	2.128	0.35	98	0.35	49	195
Summer	2	129.58	116	40	0.895	0.16	1.31	0.06	4.604	0.18	336	0.18	236	478
Summer	3	128.04	24	33	0.187	0.44	1.5	0.11	1.083	0.48	81	0.48	32	205
Summer	4	89.98	68	28	0.756	0.24	1.68	0.09	4.802	0.26	240	0.26	143	404
Summer	5	86.27	11	31	0.128	0.33	1.08	0.08	0.553	0.33	53	0.33	27	103
Summer	6	24.06	1	12	0.042	0.92	1	0	0.168	0.92	7	0.92	1	37
Total Summer		*529.07*	*245*	*169*										
Fall	1	77.52	4	26	0.052	0.46	1.43	0.25	0.615	0.52	28	0.52	10	76
Fall	2	131.4	41	41	0.312	0.22	1.72	0.16	4.112	0.29	300	0.29	170	532
Fall	3	136.16	67	34	0.492	0.21	1.63	0.11	6.301	0.28	473	0.28	272	822
Fall	4	92.1	21	30	0.228	0.37	1.52	0.19	2.822	0.44	141	0.44	61	328
Fall	5	92.27	24	32	0.26	0.46	1.63	0.1	3.327	0.5	319	0.5	123	827
Fall	6	25.12	4	11	0.159	1.02	1.43	0.02	1.897	1.04	74	1.04	11	490
Total Fall		*554.57*	*161*	*174*										
Winter	1	74.7	12	26	0.161	0.35	1.79	0.17	1.261	0.39	58	0.39	27	124
Winter	2	122.09	14	42	0.115	0.3	1.52	0.21	0.805	0.34	59	0.34	30	114
Winter	3	127.22	3	33	0.024	0.56	2.16	0.69	0.215	0.61	16	0.61	5	51
Winter	4	99.11	32	29	0.323	0.42	1.93	0.16	2.723	0.44	136	0.44	58	322
Winter	5	87.17	5	32	0.057	0.48	1.56	0.18	0.407	0.49	39	0.49	15	101
Winter	6	24.12	0	10	0	0	0	0	0	0	0	0	0	0
Total Winter		*534.41*	*66*	*172*										