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Estimated Density and Abundance of Humpback Whales (*Megaptera novaeangliae*) off West Maui, Hawai‘i

Results from 2018–2021 Vessel-Based Surveys

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National Ocean Service
Nicole LeBoeuf, Assistant Administrator

Office of National Marine Sanctuaries
John Armor, Director

Report Authors: Eden Zang[1], Marc Lammers[1]

[1]Hawaiian Islands Humpback Whale National Marine Sanctuary

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Cover Photo: A humpback whale surfacing in Hawaiian Islands Humpback Whale National Marine Sanctuary. Photo: Eden Zang/NOAA (NOAA permit #20043)

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Contact

Eden Zang, Research Specialist
Email: eden.zang@noaa.gov

Marc Lammers, Research Ecologist
Email: marc.lammers@noaa.gov

NOAA Hawaiian Islands Humpback Whale National Marine Sanctuary
726 S. Kihei Road
Kihei, Hawai‘i 96753
(808) 879-2818

Table of Contents

Abstract

Approximately half of the North Pacific humpback whale (*Megaptera novaeangliae*) population migrates from high-latitude feeding grounds to Hawai‘i each winter and spring to breed. Beginning in 2015, fluctuations in whale abundance were reported in Hawai‘i, and this trend has continued in subsequent years. These reports were consistent with passive acoustic monitoring data, which showed a decreasing whale presence off Maui during the same period using male humpback whale chorusing as a proxy for relative whale abundance.

To further quantify whale abundance in Maui and investigate fluctuations in the population, vessel-based surveys in a focal area off west Maui using distance sampling methods were initiated in 2018. In total, 26 survey days were completed over the 2018–2019, 2019–2020, and 2020–2021 breeding seasons; however, survey coverage in January and April differed among years. Estimates of pooled abundance, density (whales/km^2), and coefficients of variation (CV) during the peak of the three seasons (February–March) were:

1. 2018–2019: estimated abundance = 2,207, estimated density =1.20, CV= 0.08
2. 2019–2020: estimated abundance = 2,826, estimated density =1.59, CV= 0.08
3. 2020–2021: estimated abundance = 2,207, estimated density =1.24, CV= 0.10

Results indicate that after the reported period of decline in whale presence, the number of humpback whales using the west Maui area has generally increased, but has fluctuated, over the three seasons surveyed. Continued surveys and further studies are warranted to better understand the fluctuations occurring in the recently delisted Hawai‘i distinct population segment of humpback whales.

Chapter 1:
INTRODUCTION

Humpback whales (*Megaptera novaeangliae*) migrate from their high-latitude summer feeding areas to breeding grounds at lower latitudes in the winter months. The primary breeding grounds for the North Pacific population of humpback whales are the Hawaiian Islands, where approximately half of the population migrates to breed (Calambokidis et al., 2008). The Hawaiʻi distinct population segment (DPS) of the North Pacific humpback whale population has shown a steady recovery trend for the past several decades after being severely depleted by commercial whaling. In 2008, it was estimated that approximately 10,000 whales utilize the Hawaiian Islands each year and that the population was growing at an annual rate of about 6% (Calambokidis et al., 2008). Based on this assessment and a review of humpback whale populations worldwide, in 2016, the National Oceanic and Atmospheric Administration (NOAA) issued a ruling delisting the Hawaiʻi DPS of humpback whales from its endangered status (81 Fed. Reg. 62259[Oct 11, 2016]).

Nearly coincident with delisting of the DPS, in late 2015, ocean users and scientists in Hawaiʻi began to report reduced numbers of humpback whale sightings. These observations continued into 2018, which raised concerns about the status of the Hawaiʻi DPS (Cartwright et al., 2019). In 2018, Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) and NOAA's Pacific Islands Regional Office collaborated to organize a workshop for whale experts to discuss and assess the recent trends in humpback whale abundance, distribution, and health in both Hawaiʻi and Alaska. They considered potential explanations for the observed trends, identified knowledge gaps, and established research priorities for filling those gaps (National Oceanic and Atmospheric Administration [NOAA], 2019).

A knowledge gap identified was uncertainty regarding the abundance of whales using Hawaiʻi waters. Ongoing acoustic monitoring efforts have estimated trends in whale presence based on the singing activity of males (Lammers et al., 2020; Kügler et al., 2020), but it is not clear how well this captures patterns in the population overall, including non-singing males, females, and calves. To further quantify whale abundance, vessel-based surveys were conducted in the leeward waters off west Maui during the 2018–2019, 2019–2020, and 2020–2021 breeding seasons using distance sampling methods (Buckland et al., 2001), which facilitate the estimation of abundance and density of humpback whales in a given study area. Here, results are presented for the initial three years of this effort.

Chapter 2:
METHODS

Vessel surveys were conducted using the HIHWNMS R/V *Koholā*. Surveys were targeted between December and April to capture the beginning, peak, and tail end of humpback whale presence off west Maui. Due to a U.S. federal government shutdown, surveys were not conducted in January 2019 (three surveys were cancelled). In addition, all small boat operations ceased in late March 2020 because of concerns related to COVID-19, resulting in no surveys occurring in April 2020. In each of the first two seasons, eight surveys were completed. In the 2020–2021 season, ten surveys were completed.

Survey Area and Survey Design

The survey area was defined as the west Maui waters off Lahaina to Māʻalaea Bay. The survey area was chosen to overlap with parallel but separate efforts in the same area employing both a theodolite shore station and several bottom-moored acoustic recorders. Transect lines followed a saw-tooth pattern and included 10 transect legs labeled A through J (Figure 1). The starting point of each transect (leg A or J) alternated between surveys.

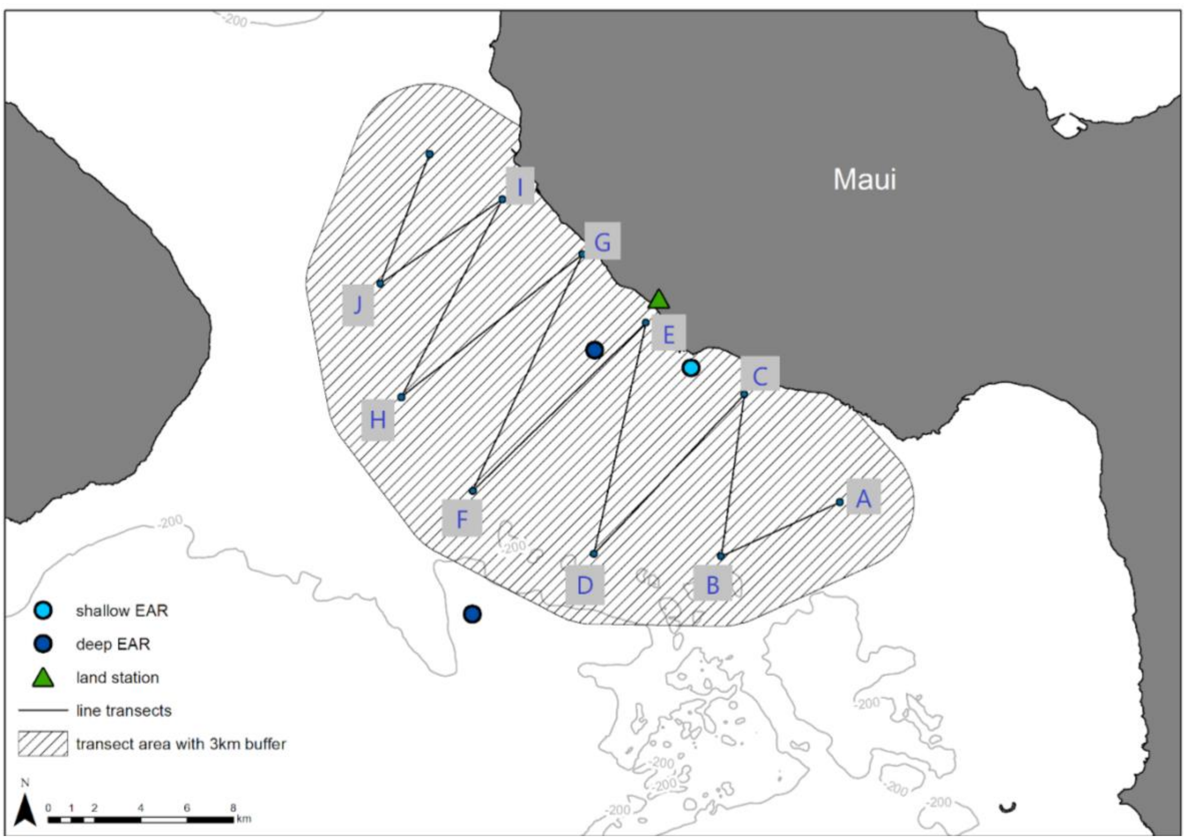

Figure 1. Map of study area showing survey transect lines, as well as the locations of a theodolite land station and ecological acoustic recorders (EARs) deployed in or near the study area.

Data Collection

Surveys along the trackline were conducted at a nominal speed of 10 kts (±2 kts). The R/V *Koholā* is 11.6 m in length and has an upper helm and observation deck 3.5 m from the surface of the water. The survey crew rotated through 3 positions: port observer, starboard observer, and data recorder, shifting positions every two transect legs. The port and starboard observer were stationed on either side of the vessel driver on the flying bridge, and the data recorder was directly in front of the helm station. The data recorder and captain were instructed not to call out sightings. Observers actively searched for humpback whales between 90° from the bow (i.e., abeam) on their side of the vessel and 10° on the opposite side (i.e., 100° viewing arc), with unaided eyes. This approach resulted in a 10°overlap in observers' detection range on each side of the bow to maximize the detection of animals on and near the trackline (Kinzey et al., 2000). Observers used a Celestron® TrekGuide™ Lite digital compass to measure the angle between the sighting and the trackline, and distance to sightings was estimated with unaided eyes. On-water distance estimation training, using a large moored buoy of known distance from the vessel, was provided for each observer prior to participating in a survey. In addition, a blind calibration of all observers was completed before most survey days (see Appendix A). While on survey, observers used binoculars to count or verify the number of whales in distant pods and establish the presence of calves. Survey effort was conducted in sea conditions that ranged between Beaufort sea state 0 and 4. If the sea state was greater than 4, observer effort was halted and the vessel continued to transit along the transect line until the sea state improved, or the remainder of the survey was cancelled if no improvement in conditions was anticipated.

Data Entry

Survey data were entered into a digital datasheet on an Apple® iPad® Mini using a custom form created in the Poimapper™ program (Pajat Solutions Ltd.). The data recorder entered the survey number, transect leg, observer positions, and environmental data (sea state, swell size, cloud cover, and glare) at the start of each transect leg or if conditions changed. When a humpback whale was sighted, a sighting log was entered. The observer who made the sighting reported the initial compass bearing from the trackline, obtained from the handheld digital compass, then estimated distance to the whale(s) and the group size (minimum, maximum, and best estimate), which were recorded for each sighting. For sightings less than 2000 m away, the observer provided an explicit distance estimate in meters (e.g., 1100m). For sightings greater than 2000m, the distance was estimated in the following bins: 2000–2500m, 2500–3000m, and >3000m.

Data Analysis

Analyses were performed using the software package Distance (Miller, 2019) in R (R Core Team, 2018). Because true bearings were collected, the relative angle between the sighting and the trackline was calculated by using the difference between the trackline heading and the bearing to the group. Using this value, radians were calculated using the formula $r = degrees \times \frac{\pi}{180}$, where r is radians. Perpendicular distances (x) were then computed as $x = r \times sin(\theta)$, where r is radians and θ is the angle between the pod and the trackline. In order to account for vessel deviations in course and/or potential measurement errors made by observers, only sightings made at bearings greater than 260° or less than 100° relative to the ship's course were considered. Eighteen sightings (27 whales) in 2018–2019, 37 sightings (66 whales) in 2019–2020, and 28 sightings (54 whales) in 2020–2021 were not included in the final analysis because the sighting bearing was between 101° and 259° degrees.

Preliminary analyses were conducted by inspecting histograms of perpendicular distances and by fitting preliminary detection probability models to decide appropriate truncation distances and the best fitting models (Buckland et al., 2001). Conventional distance sampling and multiple covariate distance sampling (MCDS) were used to investigate best fitting models. Exploratory analysis started with simple models, progressing to models with one adjustment term. MCDS models were tested starting with a single covariate, then all possible combinations of non-correlated covariates. There were 16 different observers used over the three seasons. The maximum number of observers used in any one season was eight. MCDS models considered the covariates listed in Table 1.

Table 1. Covariates tested in detection function models.

Covariate	Factor/Numeric	Levels
Sea state (SEA)	Factor	Beaufort sea state 1–4
Hours after sunrise (HAS)	Numeric	1–8
Observer (OBS)	Factor	Individual observers (n=16)
Group size (size)	Numeric	1–11

Data for each season were pooled and detection functions, density, abundance, coefficients of variation (CV), and 95% confidence intervals (CI) were estimated using the Distance package in R. Covariate selection within models was guided by the Akaike information criterion (AIC) (Burnham & Anderson, 2002). However, if multiple models were supported (i.e., models' AIC were less than 2 units apart), the model with the least amount of parameters was chosen.

Chapter 3:
RESULTS

Surveys covered a cumulative area of 3629 km² in 2018–2019, 3777 km² in 2019–2020, and 4705 km² in 2020–2021. A truncation distance of 2 km was determined for all seasons, so sightings beyond this distance were not considered. Surveyed area was 2419 km² in 2018–2019, 2519 km² in 2019–2020, and 3099 km² in 2020–2021 after truncation (Tables 2a, 2b, and 2c). In total, the number of humpback whale groups sighted was 594 in 2018–2019, 907 in 2019–2020, and 748 in 2020–2021.

Table 2a. Summary of survey dates and effort for 2018–2019.

2018–2019 dates (MM/DD/YY)	Transects completed	Effort (km)
12/21/18	6	50.8
2/13/19	10	83.4
2/21/19	10	82.6
2/28/19	8	56.4
3/12/19	10	83.0
3/27/19	10	82.9
4/16/19	10	82.6
4/24/19	10	83.2
Total	**74**	**604.9**

Table 2b. Summary of survey dates and effort for 2019–2020.

2019–2020 dates (MM/DD/YY)	Transects completed	Effort (km)
12/11/19	10	82.8
1/15/20	10	84.4
1/29/20	10	82.9
2/5/20	10	83.7
2/26/20	6	50.7
3/3/20	10	80.8
3/11/20	10	81.7
3/19/20	10	82.9
Total	**76**	**629.9**

Table 2c. Summary of survey dates and effort for 2020–2021.

2020–2021 dates (MM/DD/YY)	Transects completed	Effort (km)
12/15/20	10	81.6
1/6/21	10	80.0
1/20/21	10	82.6

2020–2021 dates (MM/DD/YY)	Transects completed	Effort (km)
2/2/21	10	83.4
2/17/21	10	81.5
2/25/21	6	59.6
3/9/21	8	72.3
3/24/21	10	83.9
3/31/21	10	81.6
4/13/21	9	68.0
Total	**93**	**774.7**

As a result of modeling, the following were chosen as the most adequate models: half-normal key function with observer as a covariate for the 2018–2019 season, half-normal key function with observer and hours after sunrise as covariates for the 2019–2020 season, and half-normal key function with observer and sea state as covariates for the 2020–2021 season. The most supported detection functions for each season are presented in Table 3. In Table 4, the chosen detection functions for the peak of all seasons (February–March) are presented. The selected models' detection functions are shown in Appendix B.

Table 3. Summary of most supported models. Chosen models are highlighted in grey. Par = number of parameters; P_a= probability of detection; SE = standard error; GOF-CvM = goodness-of-fit Cramer von-Mises test.

Date	Key Function	Covariate/Adjustment	Delta AIC	Par	P_a(SE)	GOF-CvM
2018–2019	Half-normal	OBS	0	10	0.55 (0.02)	0.91
2018–2019	Half-normal	OBS + size	0.43	11	0.55 (0.02)	0.91
2018–2019	Half-normal	OBS + HAS	1.98	11	0.55 (0.02)	0.91
2019–2020	Half-normal	OBS + HAS+ size	0	11	0.61 (0.02)	0.19
2019–2020	Half-normal	OBS + HAS	1.14	10	0.61 (0.02)	0.15
2020–2021	Hazard rate	OBS + SEA	0	10	0.55 (0.03)	0.79
2020–2021	Half-normal	OBS + SEA	0.51	9	0.52 (0.03)	0.90
2020–2021	Hazard rate	OBS + HAS + SEA	1.83	11	0.55 (0.03)	0.78

Table 4. Chosen models for peak season.

Date	Key Function	Covariate/Adjustment	Delta AIC	Par	P_a(SE)	GOF-CvM
2018–2019	Hazard rate	None	0	2	0.56 (0.03)	0.97
2019–2020	Half-normal	OBS + HAS + size	0	9	0.55 (0.02)	0.34
2020–2021	Half-normal	OBS + SEA	0	8	0.50 (0.04)	0.83

Table 5 shows pooled estimates of density, abundance, CV, and 95% CI by season. The estimates for the pooled abundance and density for all surveys in 2018–2019 were 2,676 whales and 0.74 whales per km², respectively. In 2019–2020, estimates were 3,818 whales and 1.01 whales per km², respectively. In 2020–2021, estimates were 3,859 whales and 0.82 whales per km², respectively. Estimates of density for each season and 95% CIs show that there were more whales in the west Maui area in the 2019–2020 season than in the 2018–2019 and 2020–2021 seasons. However, there is overlap in CIs between the 2019–2020 and 2020–2021 seasons (Figure 2). It should be noted that on 12/21/18, 2/28/19, 2/26/20, 2/25/21, 3/9/21, and 4/13/21, survey effort was less than other survey days due to sea conditions or logistical constraints. Also, survey coverage in January and April differed among years. During the months of February and March (which is considered peak season), when survey effort was equivalent during the three seasons, estimates of pooled abundance and density were 2,207 whales and 1.20 whales per km² in 2018–2019, 2,826 whales and 1.59 whales per km² in 2019–2020, and 2,207 whales and 1.24 whales per km² in 2020–2021 (Figure 3).

Table 5. Humpback whale pooled density and abundance estimates.D=pooled density, N=pooled abundance, %CV= coefficient of variation, CI = 95% confidence interval.

Date	Survey	D	D Lower CI	D Upper CI	N	N Lower CI	N Upper CI	%CV
2018–2019	1–8	0.74	0.63	0.86	2,676	2,301	3,111	7.6
2019–2020	9–16	1.01	0.90	1.13	3,818	3,416	4,268	5.6
2020–2021	17–26	0.82	0.71	0.95	3,839	3,330	4,471	7.6

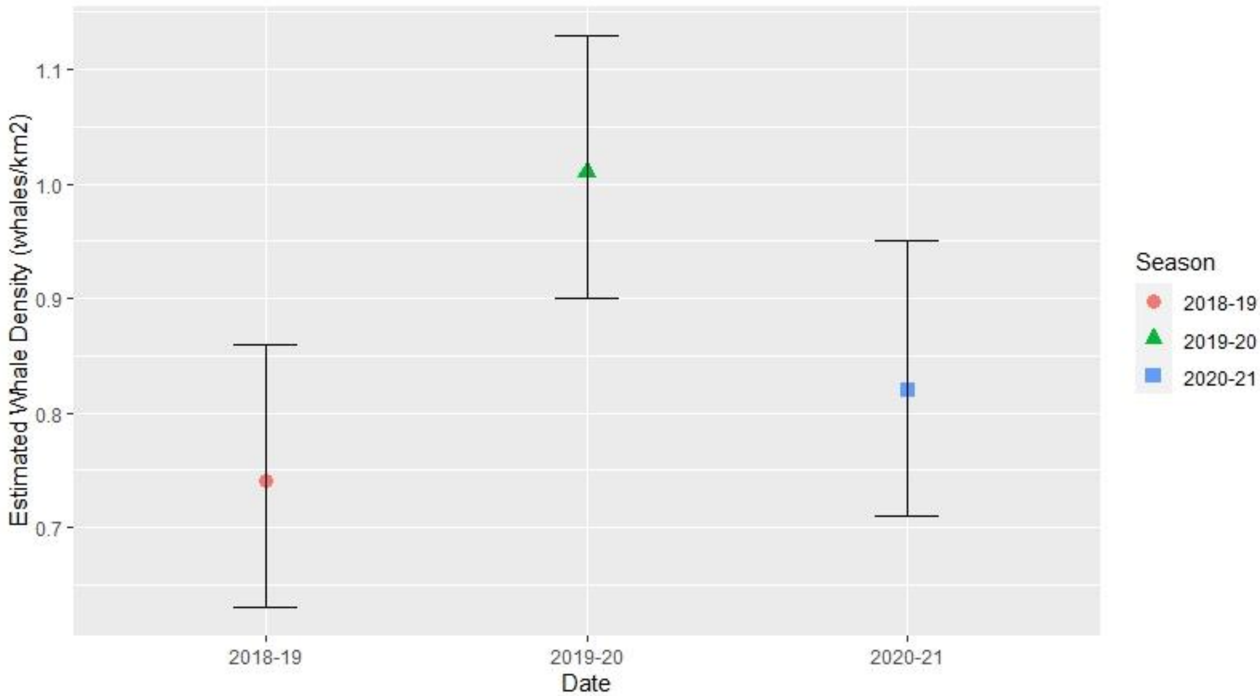

Figure 2. Estimated pooled density of whales and CIs for all surveys per season.

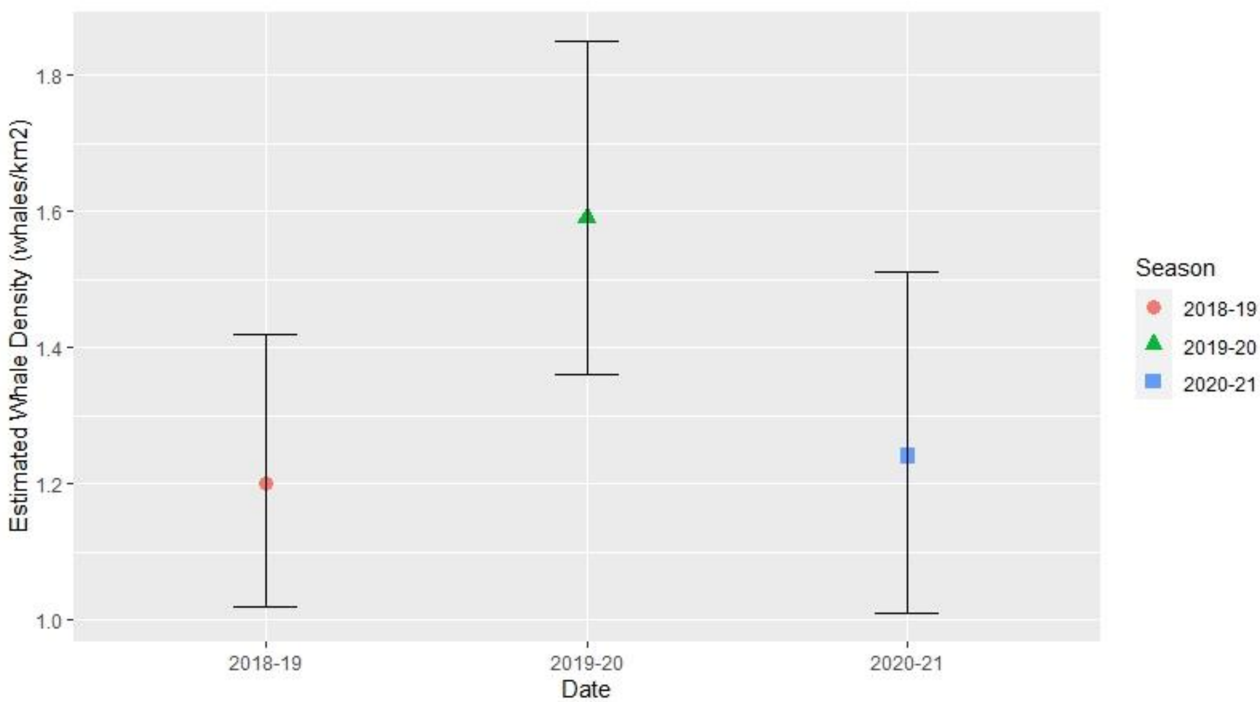

Figure 3. Estimated pooled density of whales and CIs for four surveys in February and March for each season.

Density and abundance estimates, CVs, and 95% CIs for individual survey days within each season are shown in Table 5. In 2018–2019, the highest estimates of abundance and density were 916 whales and 1.85 whales per km^2 on 2/21/19. In 2019–2020, the highest estimates of abundance and density were 788 whales and 1.57 whales per km^2 on 2/5/20. In 2020–2021, the highest estimates of abundance and density were 794 whales and 1.27 whales per km^2 on

2/17/21. In Figure 4, estimates of whale abundance and 95% CI for individual survey days are presented, revealing trends within and among seasons. The data indicate that in all three seasons, peak abundance of whales occurred in February, but whale presence during the month of March was greater in 2019–2020 than in 2018–2019 and 2020–2021, suggesting that the timing of the migration and/or the number of whales wintering in Maui differed among the three seasons.

Table 6. Humpback whale density and abundance estimates by survey.D = density, N = abundance, %CV = coefficient of variation, CI = 95% confidence intervals.

Date	Survey	D	D Lower CI	D Upper CI	N	N Lower CI	N Upper CI	%CV
12/21/18	1	0.35	0.18	0.69	106	54	210	28.20
2/13/19	2	1.35	1.02	1.80	678	510	900	13.07
2/21/19	3	1.85	1.43	2.39	916	709	1182	11.74
2/28/19	4	0.87	0.48	1.57	294	164	530	25.67
3/12/19	5	0.67	0.46	0.98	333	227	487	17.37
3/27/19	6	0.40	0.19	0.84	197	93	416	37.28
4/16/19	7	0.12	0.06	0.23	58	30	112	30.01
4/24/19	8	0.19	0.08	0.45	94	39	227	44.56
12/11/19	9	0.15	0.08	0.27	72	40	132	27.49
1/15/20	10	0.53	0.31	0.92	271	157	466	24.61
1/29/20	11	1.09	0.79	1.50	540	391	746	14.76
2/5/20	12	1.57	1.24	1.99	788	621	999	10.94
2/26/20	13	1.04	0.66	1.64	317	202	499	18.29
3/3/20	14	1.31	1.09	1.56	633	530	756	8.41
3/11/20	15	1.44	1.16	1.79	702	565	873	10.13
3/19/20	16	0.99	0.65	1.51	494	326	750	18.94
12/15/20	17	0.20	0.10	0.38	96.8	50	188	30.83
1/6/21	18	0.58	0.37	0.91	278.9	178	438	20.74
1/20/21	19	1.45	1.18	1.77	718.4	587	879	9.80
2/2/21	20	1.40	1.05	1.87	700.9	526	934	13.51
2/17/21	21	1.62	1.27	2.07	793.6	623	1011	11.57
2/25/21	22	1.06	0.69	1.61	377.4	248	575	17.79
3/9/21	23	0.66	0.44	1.00	287.7	190	435	18.36
3/24/21	24	0.56	0.37	0.84	279.8	184	425	19.85
3/31/21	25	0.52	0.33	0.83	255.5	160	409	21.61
4/13/21	26	0.15	0.08	0.28	69.4	38	128	27.52

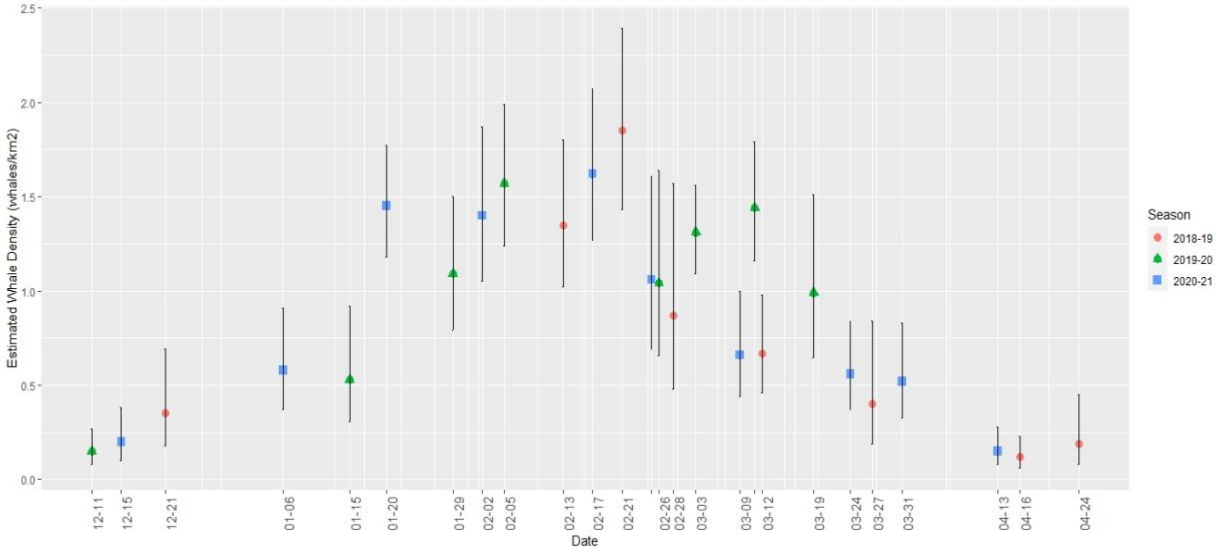

Figure 4. Estimated density of whales and 95% CIs in the west Maui area calculated during 26 vessel-transect surveys during the 2018–2019, 2019–2020, and 2020–2021 whale seasons.

Chapter 4:
DISCUSSION

The cause of the reduction in whale presence in Hawai‘i between 2015 and 2018 remains a topic of investigation. There is a general consensus that a combination of climatological factors played an important role by altering the availability of the whales’ prey at feeding grounds (NOAA, 2019). There is still uncertainty, however, about how this translated to the reduced presence of whales observed in Hawai‘i. It is unclear whether the lower whale numbers observed reflected a decrease in the population (i.e., a die-off), a shift in the distribution of whales (e.g., going to other breeding habitats), a change in migration patterns (i.e., skipped or shorter migration), or some combination of these.

The survey results provide estimates of whale abundance and densities, showing evidence of a general increase in whale presence in west Maui waters over the three seasons, with the highest densities observed in the 2019–2020 season. Lower densities during 2018–2019 and 2020–2021 primarily reflect reduced whale numbers during the month of March compared to 2019–2020, suggesting an earlier departure of whales from the study area during those seasons. These results complement acoustic data obtained for the same region (see Appendix C), which show fluctuating levels of male chorusing between 2014 and 2021 and suggest that, following a period of decline in whale presence in Hawai‘i, whale numbers have begun to increase. The results presented provide additional evidence that the Hawai‘i humpback whale DPS continues to exhibit fluctuations that are not yet fully understood. Continued surveys to enumerate whales in the west Maui region will help track trends in the population. Combined with other efforts, these surveys help provide additional insights on humpback whales’ responses and ability to adapt to increasing changes in their habitat.

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APPENDIX A: Observer Calibration

Calibration of observers was performed at the start or end of most survey days. Observers were positioned on the flying bridge and directly in front of the helm station so they would be in the same position as they were during surveys. Observers were instructed to report distance estimates, using unaided eyes, to a large, stationary buoy located outside of Lahaina Harbor at 20.866933, -156.68915. The captain maneuvered the vessel to six haphazard distances between 0–2000m (although three out of 97 distances were >2000m) and instructed observers to write their estimate in a personal notebook without sharing their estimates with others. Simultaneously, the captain recorded the true distance using a Garmin™ GPSMAP® 1242xsv chartplotter in a separate notebook. Quadratic regression models were used to analyze distances estimated by each observer in relation to true locations. To use the most accurate data in the distance analysis, model estimates from the approach above were used to correct distances estimated by observers during surveys (see Methods).

After applying the regression, if some values were negative, they were converted back to original estimates. This only applied to two sightings in 2018–2019.

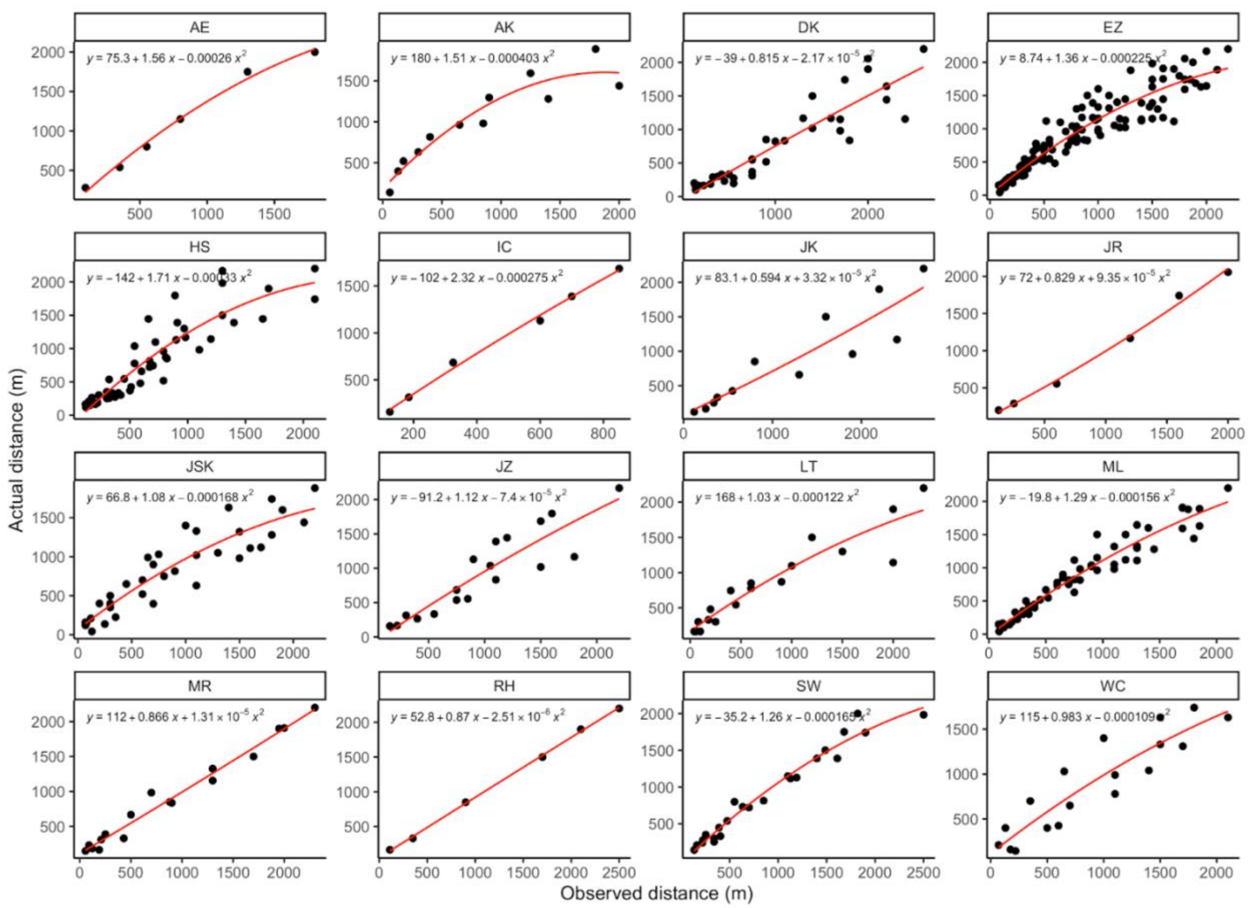

Figure A.1. Regression chart of actual versus observed distances.

APPENDIX B:
Detection Function Curves

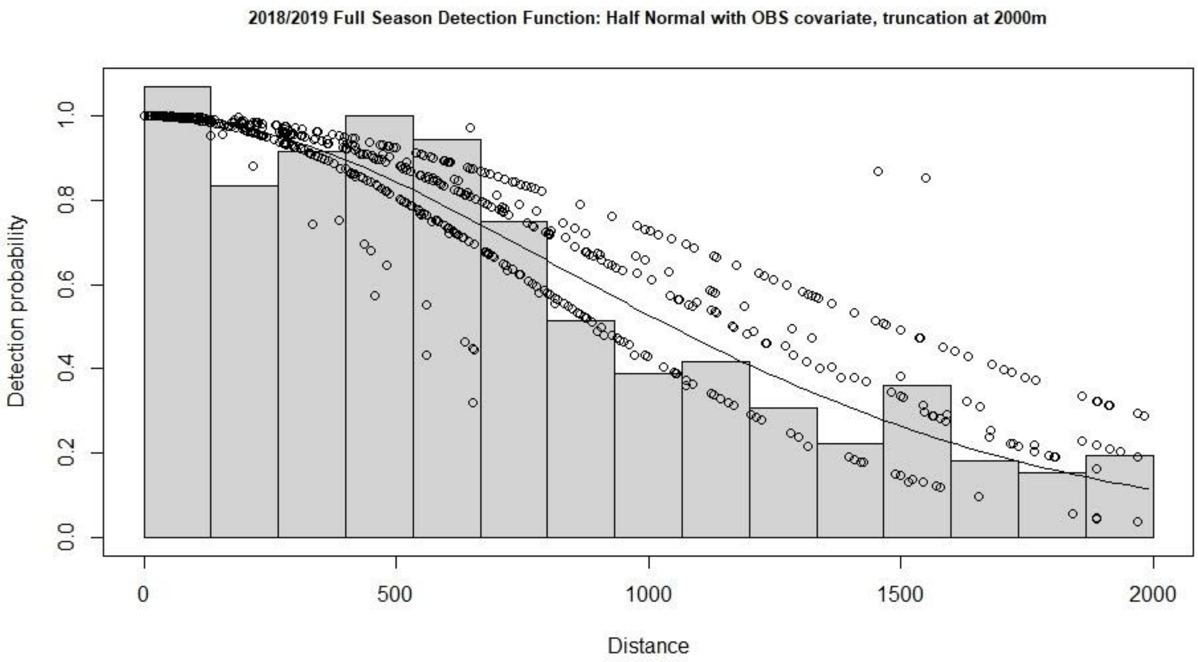

Figure B.1. Detection function curves for humpback whales in the full 2018–2019 season.

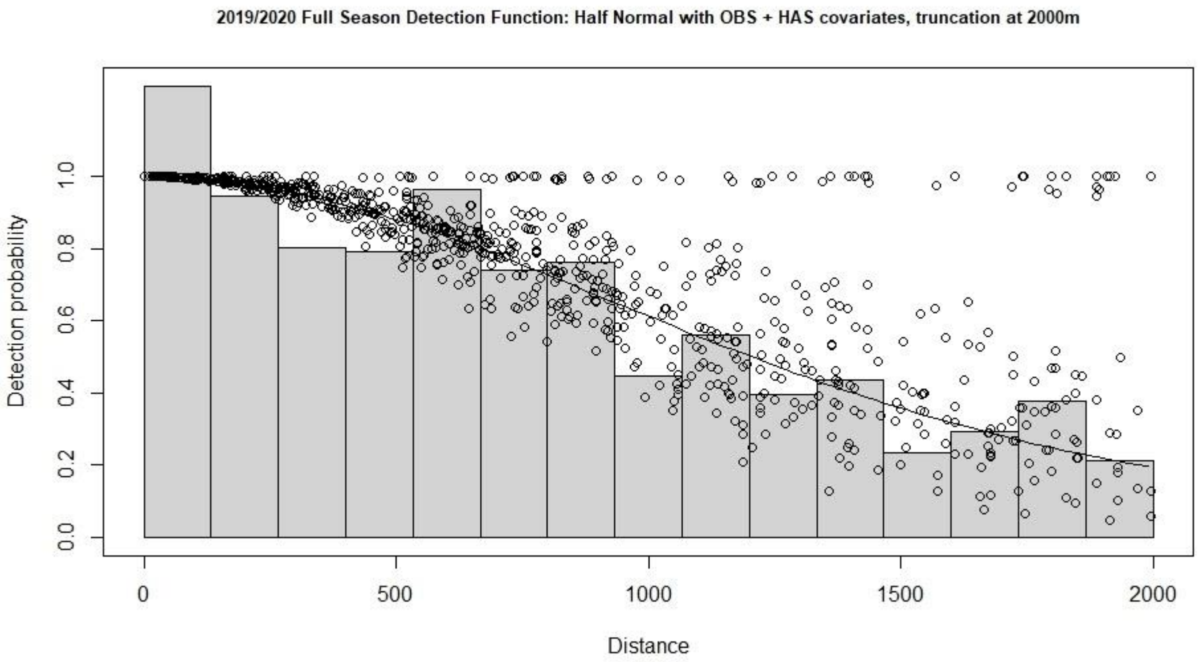

Figure B.2. Detection function curves for humpback whales in the full 2019–2020 season.

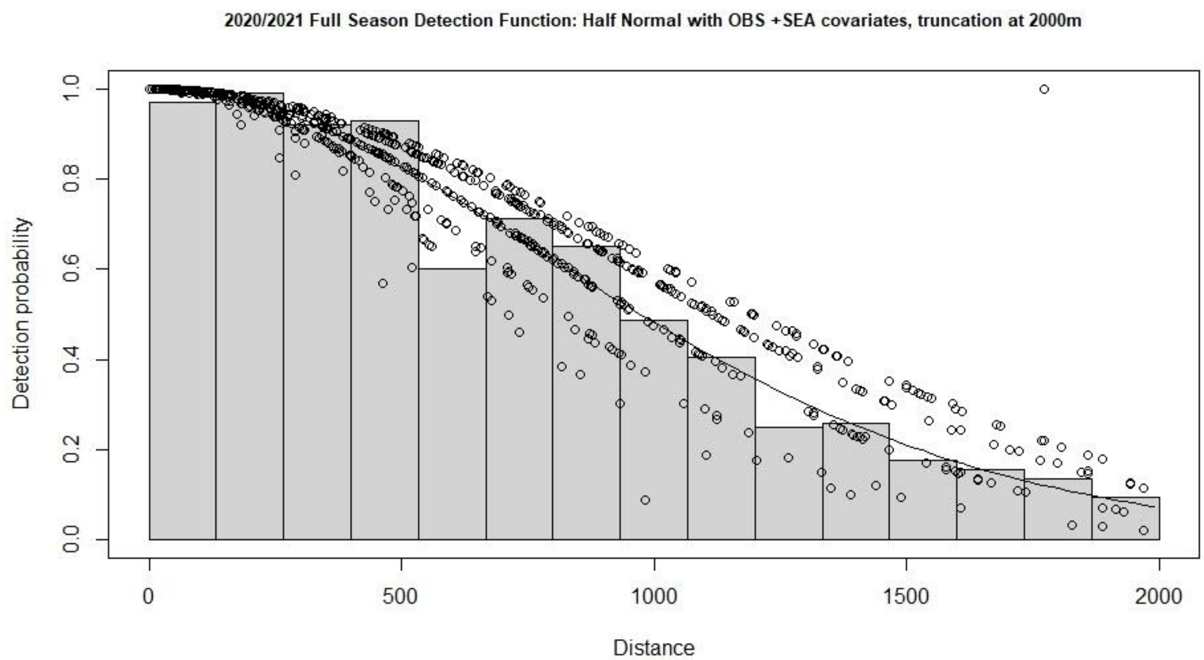

Figure B.3. Detection function curves for humpback whales in the full 2020–2021 season.

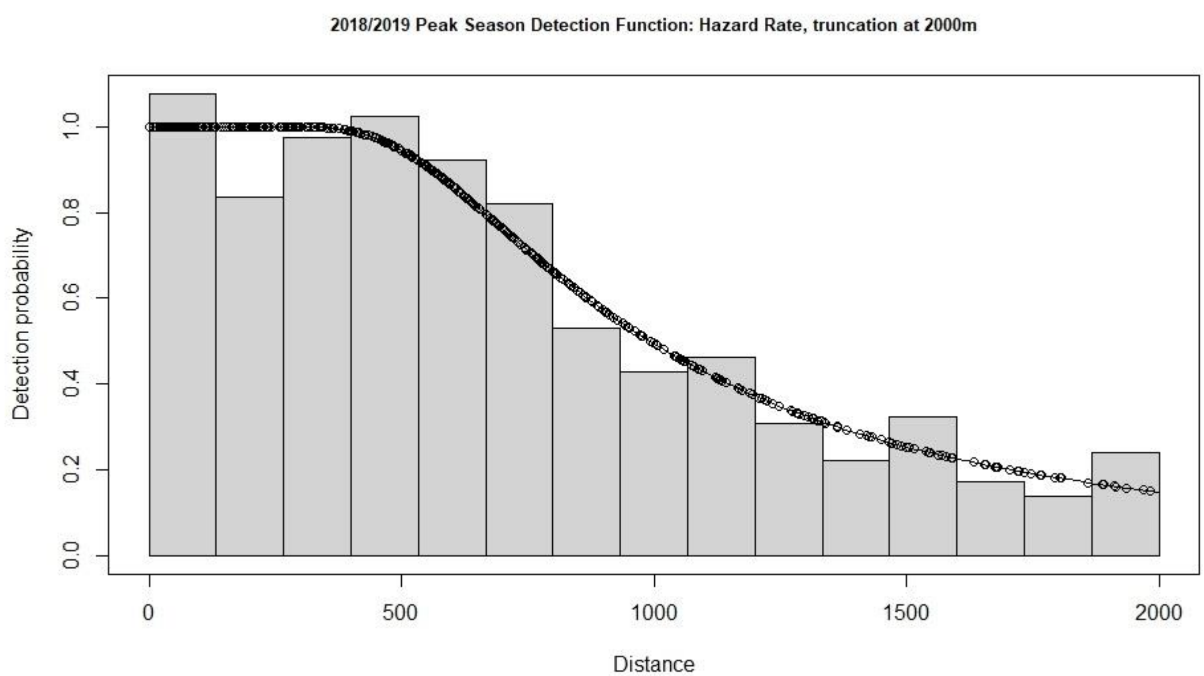

Figure B.4. Detection function curve for humpback whales in 2018–2019 during the months of February and March.

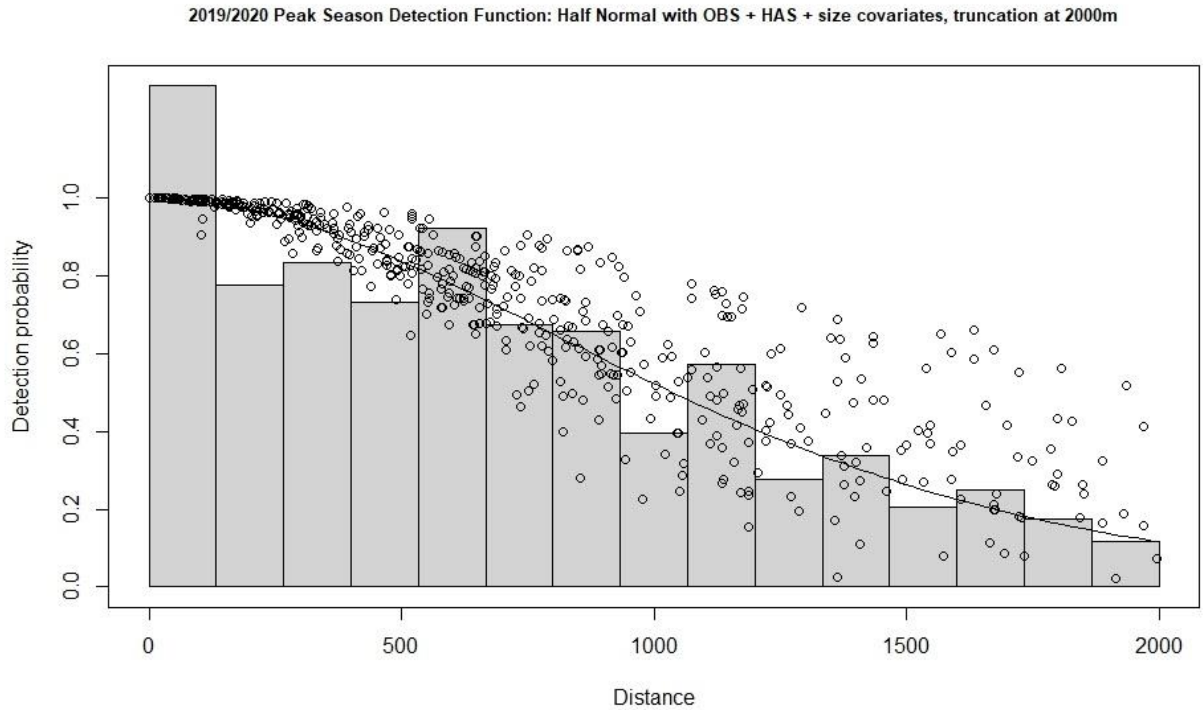

Figure B.5. Detection function curves for humpback whales in 2019–2020 during the months of February and March.

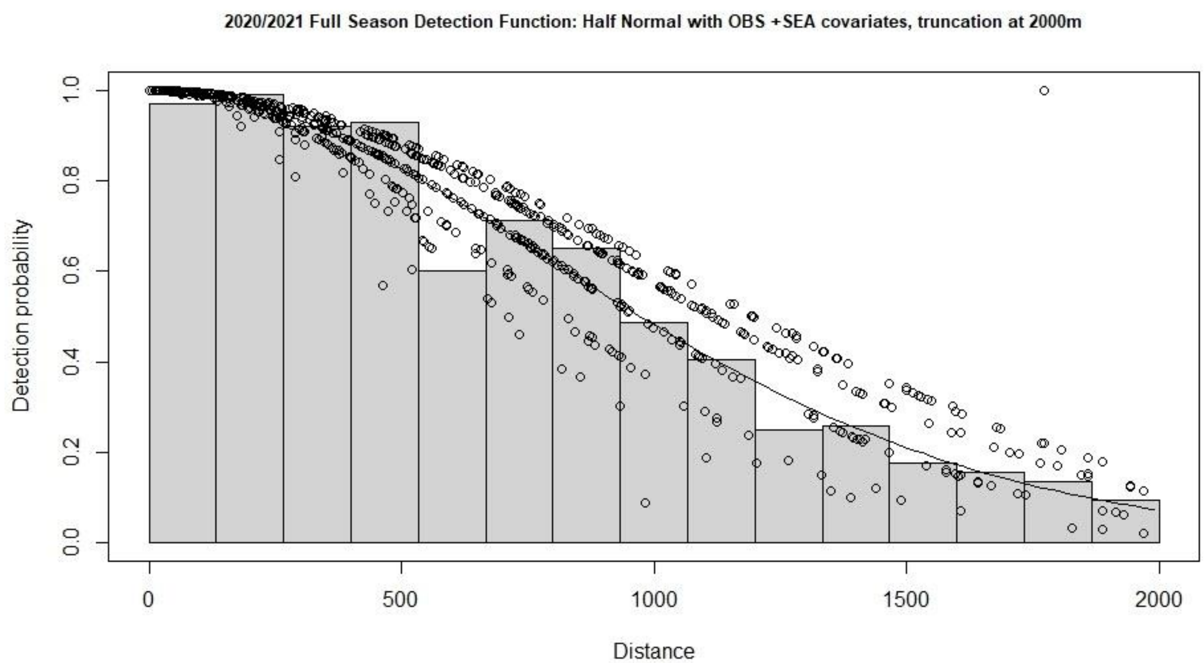

Figure B.6. Detection function curves for humpback whales in 2020–2021 during the months of February and March.

APPENDIX C:
Humpback Whale Chorusing Levels, 2014–2021

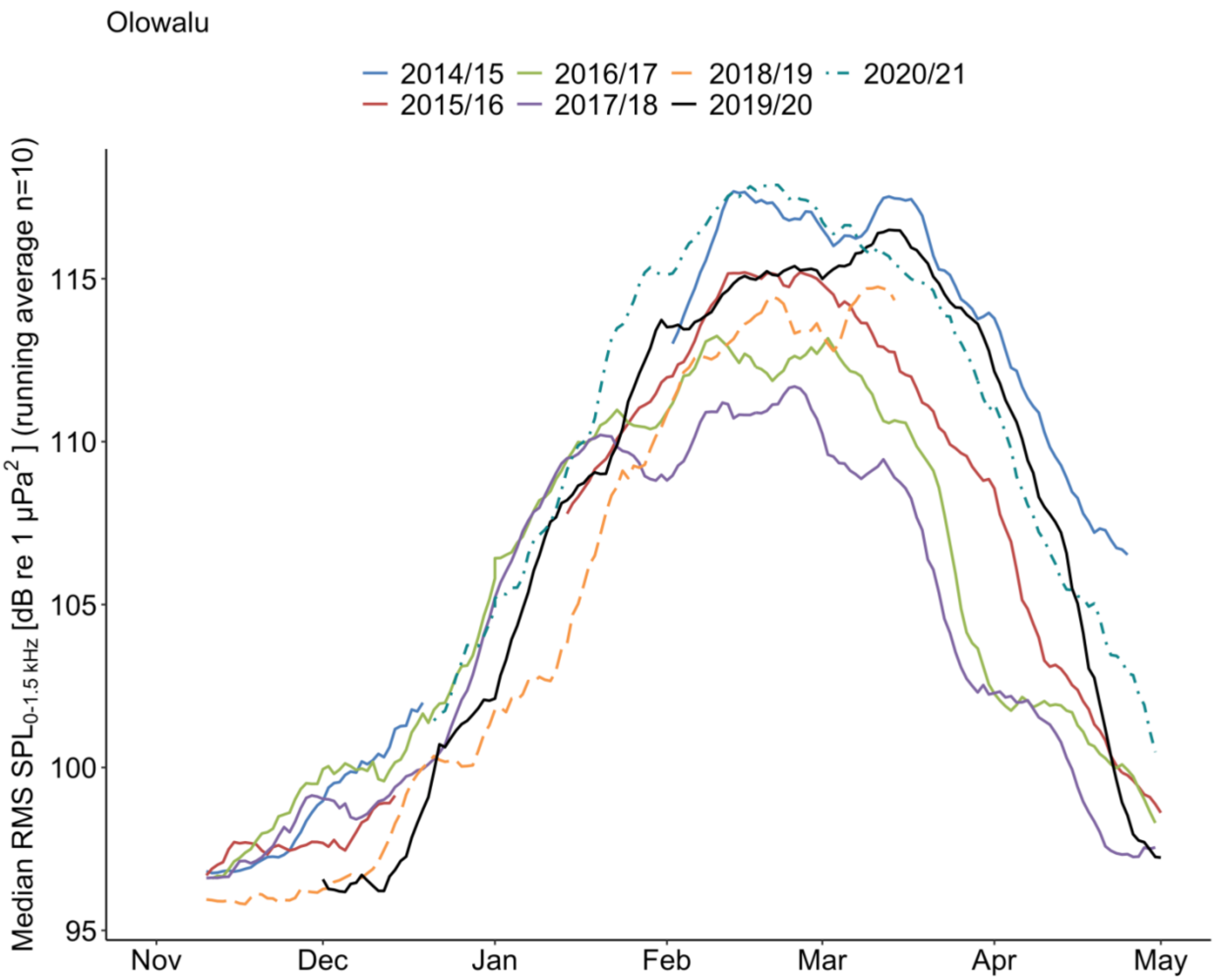

Figure C.1. Humpback whale chorusing levels (in decibels) off Olowalu, Maui between 2014 and 2021. Data gaps represent periods when the EAR did not record. RMS SPL = root-mean-square sound pressure level.

This section presents data on humpback whale chorusing levels in decibels, measured by an Ecological Acoustic Recorder (EAR) deployed off Olowalu over the past seven years. Data gaps represent periods when the EAR did not record. See Lammers et al. (2020) and Kügler et al. (2020) for additional details on the methods used to obtain these data.

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