2022 Prince William Sound Forage Fish Observations

28 November 2022

W. Scott Pegau
Prince William Sound Science Center, Box 705, Cordova, AK

Contract 9511.22.01

Executive Summary

This project conducts aerial surveys of forage fish in Prince William Sound (PWS) to identify areas where forage fish congregate. It builds upon previous aerial forage fish surveys conducted in PWS. The aerial surveys allow for identifying forage fish schools that are in water too shallow for a survey vessel. This was the last year of a four-year project. The objective of the work is to provide aerial surveys of forage fish schools in PWS during June to map areas that they commonly use and therefore understand the potential impacts of a spill. Data from the past ten years of surveys are combined to examine areas of consistent occupancy by forage fish.

Aerial surveys were conducted in June of 2022. Fish species, school size, and the number of schools were recorded along with time and position electronically and on paper. Observations of whale numbers, species, date, and time are also logged. The surveys followed the coastline throughout PWS and took nine flight days to complete. Extremely good weather allowed the surveys to be completed by the middle of June.

Pacific herring was the dominant species observed, followed by Pacific sand lance. No eulachon or capelin were observed this year. A greater number of sand lance were found than in the past couple of years. Humpback whale numbers were also higher than the last few years. This was the second year in a row with a large number of juvenile herring schools observed. They were concentrated in the southwest and eastern sections of the Sound. The number of schools observed was the greatest since the surveys began in 2012 but the schools tended to be small. The weighted school index was still the third highest in the record. This may indicate that there are two large herring year class is in the system that have yet to recruit to the spawning stock. These large recruitment events are critical to the recovery of herring. However, the unusual long-clear spell in early June may have changed the observability of the fish leading to a larger number of schools being observed.

There was considerable variability in the distribution of the various forage fish over the past ten years. Examining the number of years that schools were observed with a 5 kilometer (km) by 5 km block, we found that age-1 herring were commonly observed in the eastern bays near where spawning had occurred, and along Naked and Knight Islands. This appears to be driven by the counter-clockwise surface circulation in central PWS and freshwater flow through Knight Island passage. Adult herring did not have distinct locations that they were found repeatedly. They were observed the most times south of Glacier and Knight Islands. Sand lance were most often seen around Middle Ground Shoal and Naked Island. Capelin and eulachon were not seen often enough to justify mapping in this manner.

Validation efforts suggest that herring are correctly identified from the air 95% of the time. The herring are separated by age correctly between 85-90% of the time. Sand lance are correctly identified 80-85% of the time. These results are consistent with similar work in the 1990s.

Introduction

Forage fish are small, schooling pelagic fish and are important to marine ecosystems. They may be commercially harvested or sustain a wide variety of large predatory fish which may, in turn, be commercially harvested (Pikitch et al., 2014). They also directly and indirectly support subsistence and recreational fisheries. Ecologically, they represent a vital trophic pathway between lower trophic level plankton and upper trophic level predators such as fish, seabirds, and marine mammals (Cury et al., 2000). Many of the forage fish can be found along the coasts in shallow water, which makes them susceptible to impacts from oil spills. Common forage fish in the Gulf of Alaska are Pacific herring (*Clupea pallasii*), capelin (*Mallotus villosus*), Pacific sand lance (*Ammodytes personatus*), juvenile walleye pollock (*Gadus chalcogrammus*), and eulachon (*Thaleichthys pacificus*).

Despite their importance to marine ecosystems, little is known about changes in forage fish distribution and abundance over time. They are difficult and expensive to monitor because they are patchy in their distribution, comprised of species with widely divergent life histories and habitats, and predisposed to experience large fluctuations in abundance. Much of what we know comes from surveys that target other species and were not designed for forage fish (Anderson and Piatt, 1999; Ormseth, 2014), or from studies of predator diets (Hatch and Sanger, 1992; Piatt and Anderson, 1996; Womble and Sigler, 2006; Yang et al., 2005). Fluctuations in the abundance of forage fish have been associated with highly variable recruitment of strong year classes over short periods (Hay et al., 2001) and climate-mediated regime shifts over longer periods (Anderson and Piatt, 1999; Arimitsu et al., 2021).

The coastal waters of PWS and other fjords and embayments in the Gulf of Alaska provide important nursery areas and spawning grounds for some forage fish species (Arimitsu et al., 2008; Brown, 2002; Robards, 1999). In these coastal areas, the distribution and abundance of forage fish are related to environmental gradients in temperature and freshwater inputs, as well as interactions with other organisms (e.g., zooplankton prey, gelatinous zooplankton competitors, and marine predators) (Abookire and Piatt, 2005; Arimitsu et al., 2016; Speckman et al., 2005).

Past survey methods for estimating the abundance and distribution of forage fish in PWS have included hydroacoustic surveys coupled with trawl sampling (Ostrand et al., 1998; Thedinga et al., 2000) and aerial surveys for surface-schooling fish (Brown and Moreland, 2000; Norcross et al., 1999). Hydroacoustic assessment of fish biomass in the water column works particularly well in deep, open waters (Carscadden et al., 1994; Demer et al., 2011), but has several disadvantages when working in shallow coastal areas: 1) the transducer near-field and surface noise exclude detections shallower than 4-5 meters (m); 2) the cone-shaped beam pattern covers a very narrow swath at shallow depths; 3) trawl-capable support vessels are unable to operate safely in shallow rocky coastal areas; and 4) shallow fish schools may actively avoid vessels underway.

Aerial surveys are useful for counting near-surface fish schools (i.e., schools that may be visible from just below the surface to depths of 10-20 m depending on water clarity) in nearshore areas where it is normally difficult to conduct hydroacoustic surveys. The high speeds of the plane allow a large area to be surveyed quickly. They also allow us to determine the broad-scale distribution of schools visible from an airplane (Photo 1).

Like all remote sensing techniques, aerial surveys benefit greatly from on-the-ground validation of species composition and age class. Indeed, noting a disparity between separate hydroacoustic and aerial survey efforts for forage fish in PWS, Brown and Moreland (2000) recommended the use of both survey methods. While both survey techniques are not funded by the Prince William Sound Regional Citizens' Advisory Council (PWSRCAC), we were able to work with the forage fish project in the Gulf Watch Alaska (GWA) program that provides information from acoustic surveys. The GWA forage fish project collected fish from schools identified from the air to provide validation of the aerial observations. The GWA forage fish group came to Cordova in mid-June to provide dedicated validation work and contracted with a vessel for additional validation work.

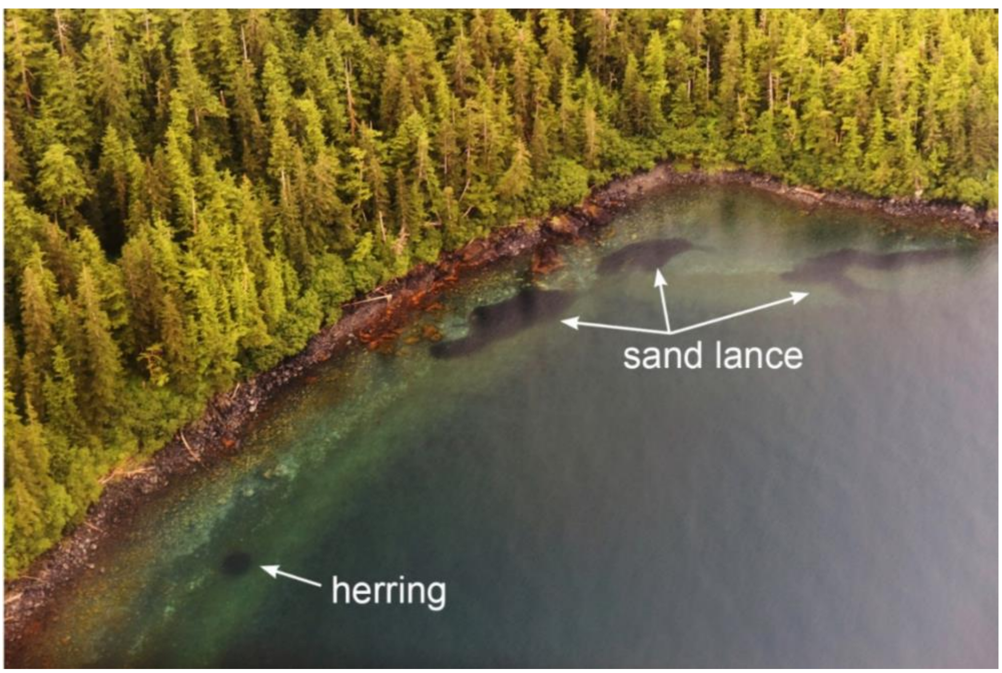


Photo 1. Aerial photograph of typical Pacific herring (n = 1) and Pacific sand lance schools (n = 3) along shorelines in Prince William Sound, Alaska. Herring schools are typically round or oval and sand lance schools are darker and irregularly shaped.

In this report, we describe the current distribution of coastal forage fish schools in PWS as observed during the June 2022 aerial surveys and provide some historic distributions for comparison. We examine forage fish distributions from 2013-2022 to identify areas where fish are consistently observed. We also examine the accuracy of the observations based on recent and historical validation efforts. Aerial shoreline census surveys of forage fish schools in PWS occurred in the late 1990s (Brown et al., 1999; Brown and Moreland, 2000; Norcross et al., 2001; Suryan et al., 2002) and more recently (2010-2018) surveys were again conducted under auspices of the Exxon Valdez Oil Spill Trustee Council. Beginning in 2019, the surveys were conducted with funding from PWSRCAC.

Methods

Aerial shoreline census survey methods followed those established during the Sound Ecosystem Assessment (SEA) and Alaska Predator Ecosystem Experiment (APEX) (Brown and Moreland, 2000; Norcross et al., 1999). Aerial surveys are conducted from a Cessna 185 floatplane traveling at speeds of 200-240 km per hour and a target altitude of 300 m. Surveys are flown parallel to shore, but we occasionally circled back to verify observations when school densities are high. The entire coastline of PWS is flown. It normally takes approximately 10-12 days, flying 4-5 hours in a day, to complete a survey of the entire Sound. The section of the Sound flown on any particular day depends on the weather and aircraft schedule. The completed sections are mapped on the aircraft's GPS and on a paper map to ensure there are no gaps in coverage. The survey was flown in June to reduce identification errors caused when age-0 herring and sand lance become visible, typically in July.

There were two observers in the aircraft on each flight. The primary observer counts and identifies the schools while the secondary observer records the observations and looks for schools on the other side of the plane. The primary observer is the one on the shoreline side of the plane where most schools are observed. The primary observer has at least two years of aerial survey experience. Observations during flights are collected on the location, altitude, number, and size of schools of forage fish. A GPS is used to provide position information to an electronic recording platform and paper logs are kept as a backup record. We changed the logging software this year, which resulted in a different file structure for the output but retained the logged variables. Norcross et al. (1999) contains a detailed description of the survey design and analysis of errors associated with observations.

The schools are identified by species (Pacific herring, Pacific sand lance, capelin, and eulachon, as well as unknown forage fish) and herring are classified by age (0, 1, or 2+). Age-1 herring are just over a year old in June and age-2+ herring are any herring older than one year old. Species identification was based on characteristics of the school including color, shape, location, and "flashing." Herring schools tend to be round (Photo 1) and the tendency of individuals within schools to roll creates a telltale flash of light. Younger (smaller) herring show a finer pattern of flashing compared to older fish. Adult herring (age-2+) tend to form larger schools in deeper water than age-1 herring. Sand lance schools tend to be darker in color, irregularly shaped, and in shallow areas with sand and gravel habitats (Photo 1; Norcross et al., 1999; Ostrand et al., 2005). Capelin tend to form large, crescent-shaped schools, whereas eulachon form very large shoals primarily associated with offshore waters and the Copper River Delta.

The size of schools are estimated using a sighting tube constructed of PVC pipe with a grid drawn on mylar on the far end (see Norcross et al. 1999 for details). The focal length (F) of the tube is 210 millimeters and a full tick mark on the grid is 1 centimeter. School size is reported as small (diameter < 0.5 ticks), medium (> 0.5 ticks and < 1.0 ticks), and large (> 1.0 tick marks). From an observation height of 300 m, this provides an equivalent surface area of < 75 m^2 for small schools, 75 – 300 m^2 for a medium school, and > 300 m^2 for a large school. We assume that the typical small school size is 0.25 ticks, medium school size is 0.75 ticks, and large school size is 1.25 ticks to develop the weighting criteria used in the development of the index. Since the area of the school is the square of the radius we get a medium school is nine times in area larger than a small school and a large school is 25 times larger. The Small School Equivalent (SSE) index is then the sum of small schools, plus 9 times the sum of medium schools, plus 25 times the sum of large schools.

Whales are identified to species and the number observed is logged into the same software used for the forage fish observations. The species of whale is identified by a four-letter code. The code starts with the first two letters of the common name of the whale and ends with "wh." For instance, a humpback whale is logged as "huwh."

Validation of aerial observations is conducted by having the aircraft guide a vessel to a forage fish school. The aerial observers radio their species/age identification to the vessel. The vessel then attempts to sample the school using jigs, seine nets, cast nets, underwater cameras, and other gear that allows sampling from the school. The vessel records what the aerial observers indicated and what was determined from vessel sampling. At the end of the season, the validation observations are provided to the aerial survey project.

The species, number, and size information are mapped to show the locations of forage fish. The number of schools of age-1 herring is weighted by the school size to provide an index that can be used to provide an estimate of future recruitment.

<u>Findings & Discussion</u>

2022 Surveys

This year, 9 days were spent surveying. The flights were conducted between June 1-15, making this the earliest year that we were able to complete the survey. All of PWS is flown, including the outsides of Montague and Hinchinbrook islands as well as the islands in southwest PWS (Figure 1).

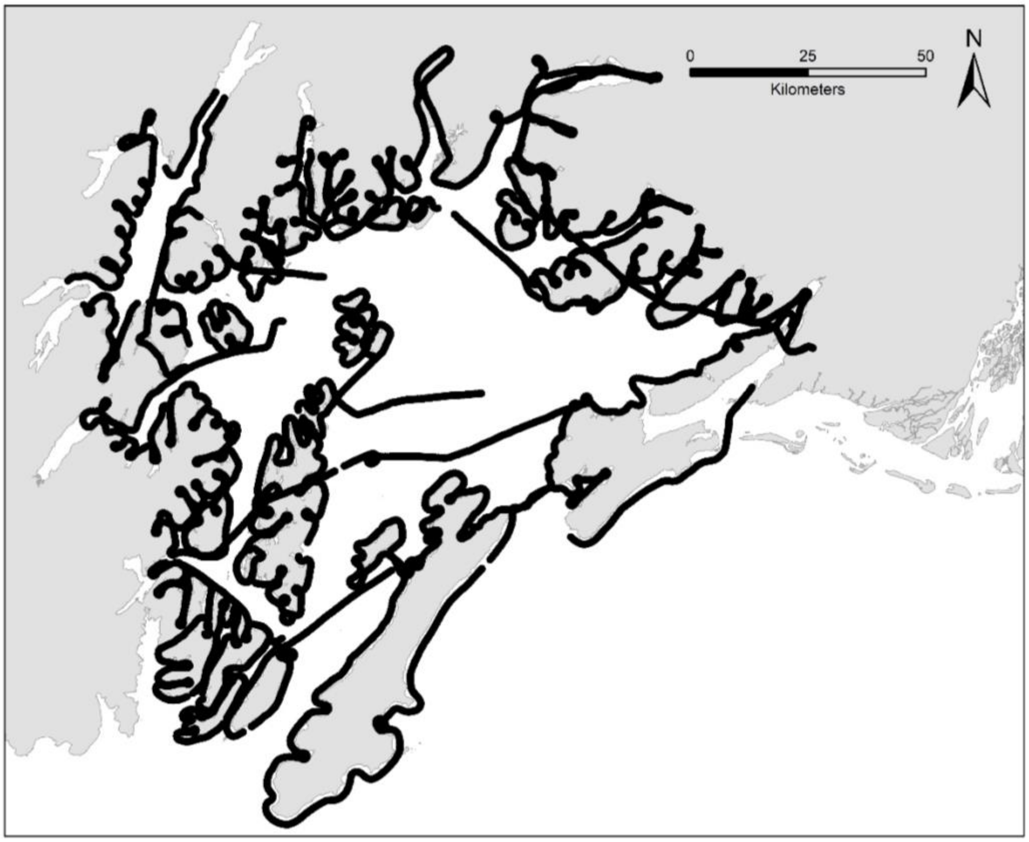


Figure 1. The 2022 survey flight tracks.

Forage fish school observations are mapped in Figure 2. Larger versions of the maps provided in Figure 2 and a map with the locations identified are provided as an appendix. Age-1 herring make up the majority of the observed forage fish schools. They are followed by age-2+ herring and sand lance. In 2022, there were a moderate number of sand lance and a very large number of age-1 herring. The distribution of sand lance schools was relatively broad.

This year we observed the most age-1 herring since 2012. We counted 3037 small, 616 medium, and 45 large schools of age-1 herring. The percentage of small schools was greater than normal which resulted in the area weighted number of schools being the third largest in our observations (Figure 3). The distribution of age-1 herring was not uniform around PWS and was different in many respects to that seen in 2021 (Figure 4). The distribution was more similar to that seen in 2017. There were large concentrations of schools in the eastern section and southwest along Knight Island and the tops of the islands associated with the southwest passages with few fish seen in the northern and northwestern regions of PWS.

There is some concern that the large number of schools observed may have been associated with the unusually long stretch of nice weather at the end of May and early June. While transiting across Port Gravina on later surveys, we did not observe nearly as many schools as we saw on the first day of surveys in the area. Having two large year classes in a row is highly unusual. The large number of schools observed in 2021 is consistent with the herring recruitment peaking every four years. Large herring recruit classes around the Gulf of Alaska include the 2012 and 2016 year classes, although the 2012 year class was not large in PWS. This four-year cycle in recruitment was also seen in the 1970s and 1980s (Williams and Quinn, 2000). The only instance with two strong years of recruitment are the 1976 and 1977 year classes that also came from a relatively small overall herring population.

Adult herring tend to migrate out of PWS by June and therefore we expect that we only see a small portion of the total adult population. There are always some age-2+ herring that remain in PWS. These may be fish that are not mature yet or ones that choose to feed within PWS instead of migrating into the Gulf of Alaska. This year we observed a relatively large number of age-2+ schools. Most were in the southwest portion of PWS in areas where older herring have been observed in the past.

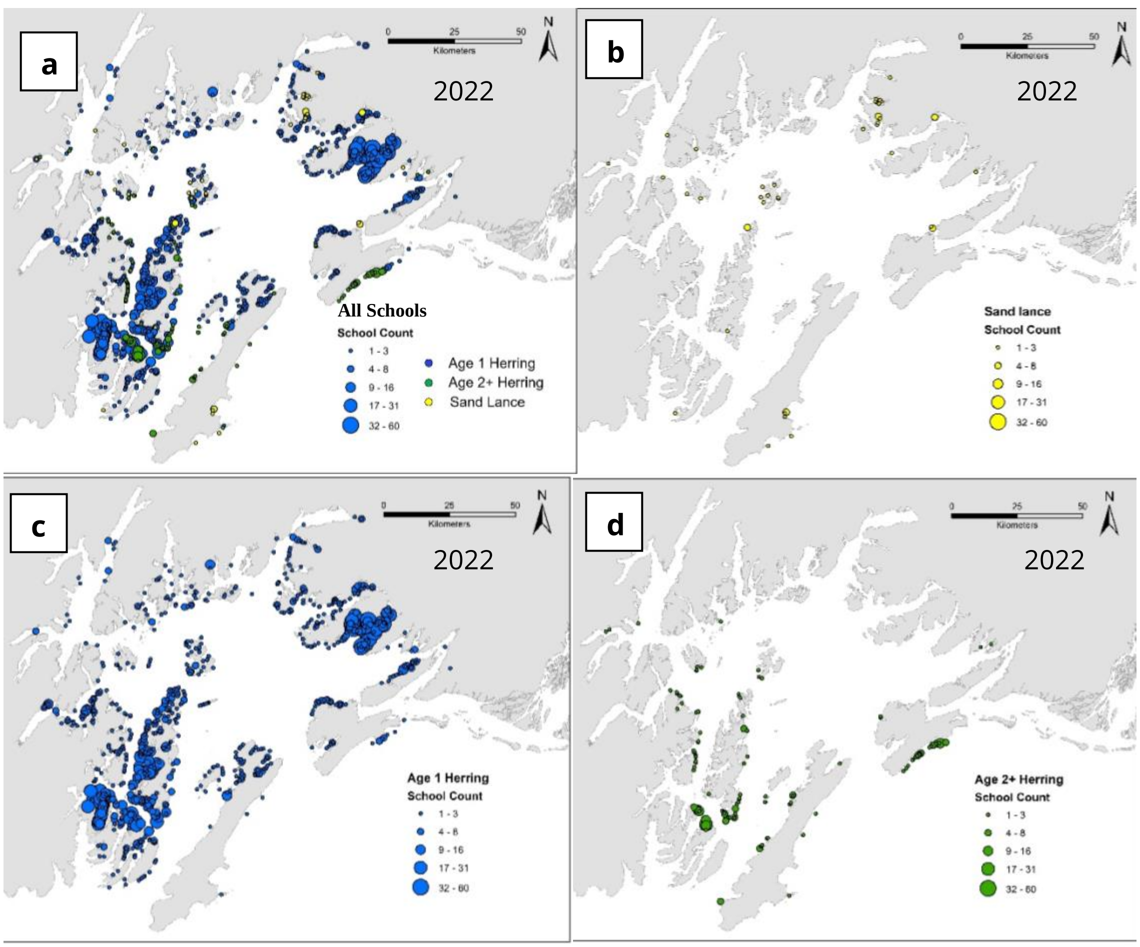


Figure 2. Observations of the number of schools for all forage fish (a), sand lance (b), age-1 herring (c), and age-2+ herring (d) in 2020. No capelin were seen this year.

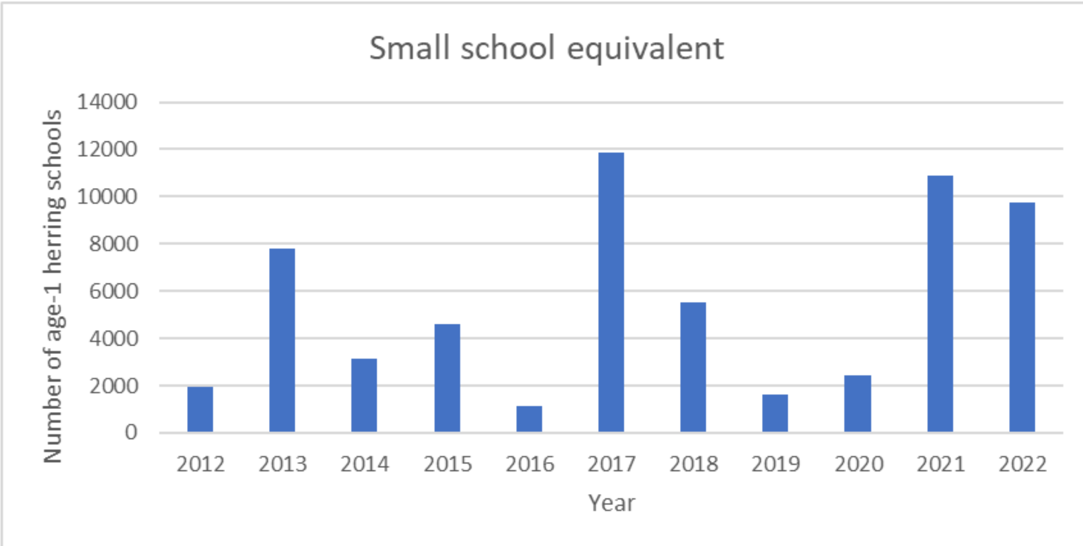


Figure 3. Number weighted by school size of age-1 herring schools by year.

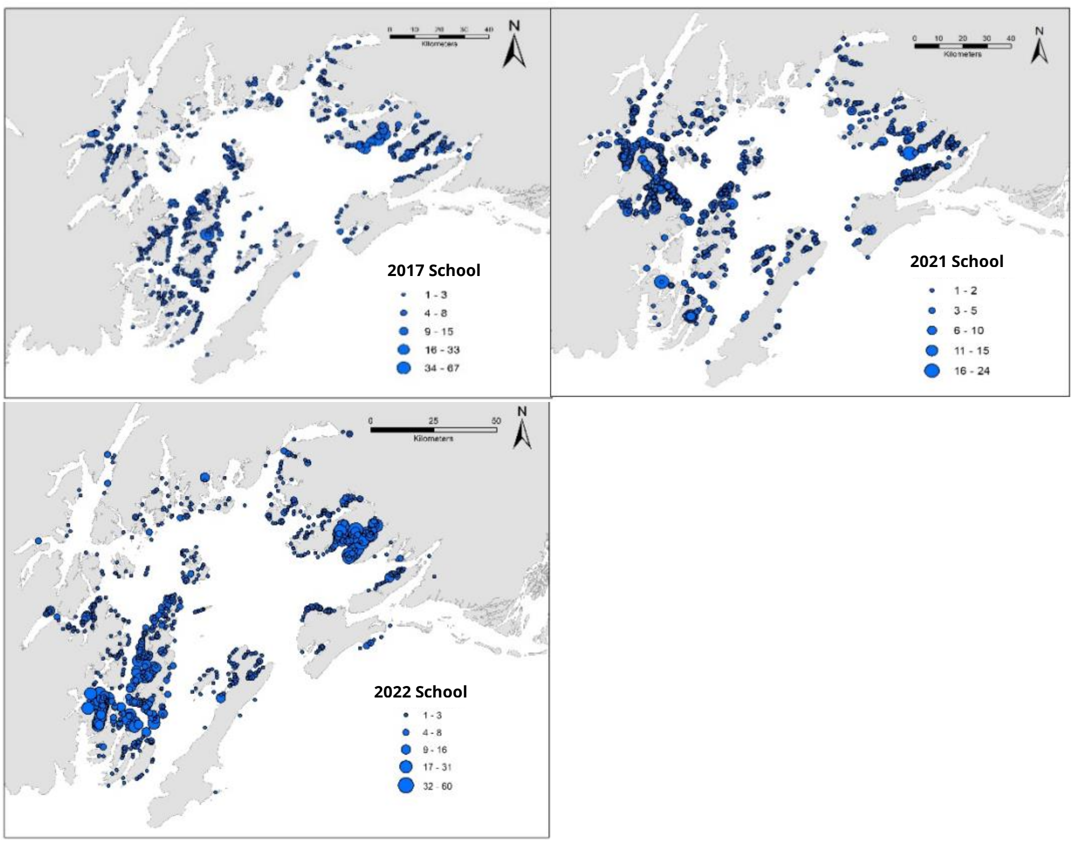


Figure 4. Distribution of age-1 herring schools in 2017, 2021, and 2022. These are the three years with the greatest number of age-1 herring schools observed.

Observations of whales also are collected during the surveys. A map of their 2022 distribution is provided in Figure 5. More humpback whales were observed than in the last two years. This is the third year in a row that fin whales were seen.

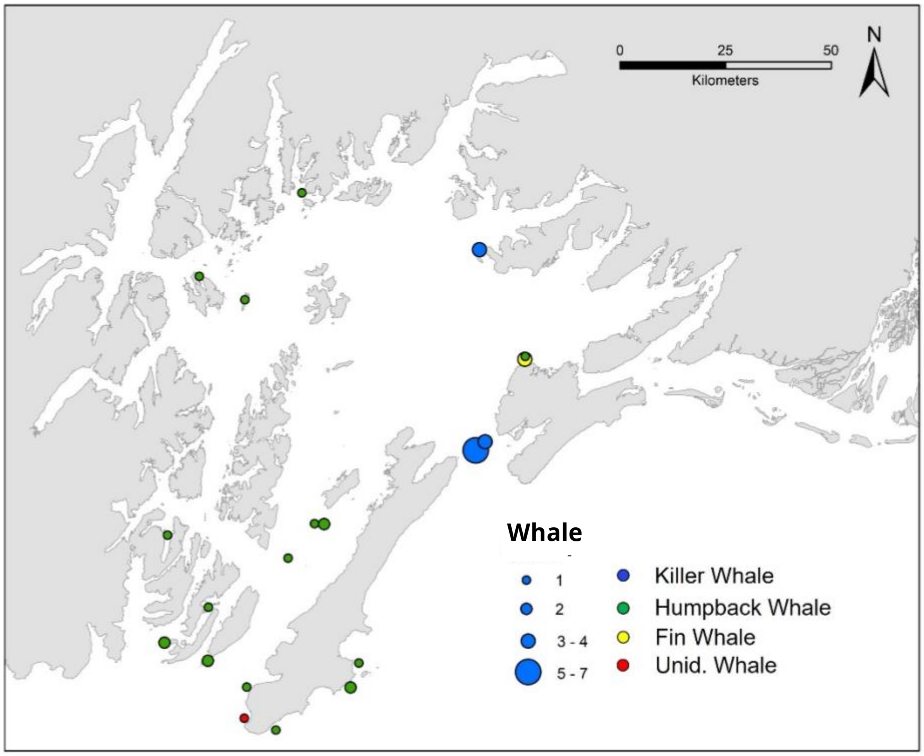


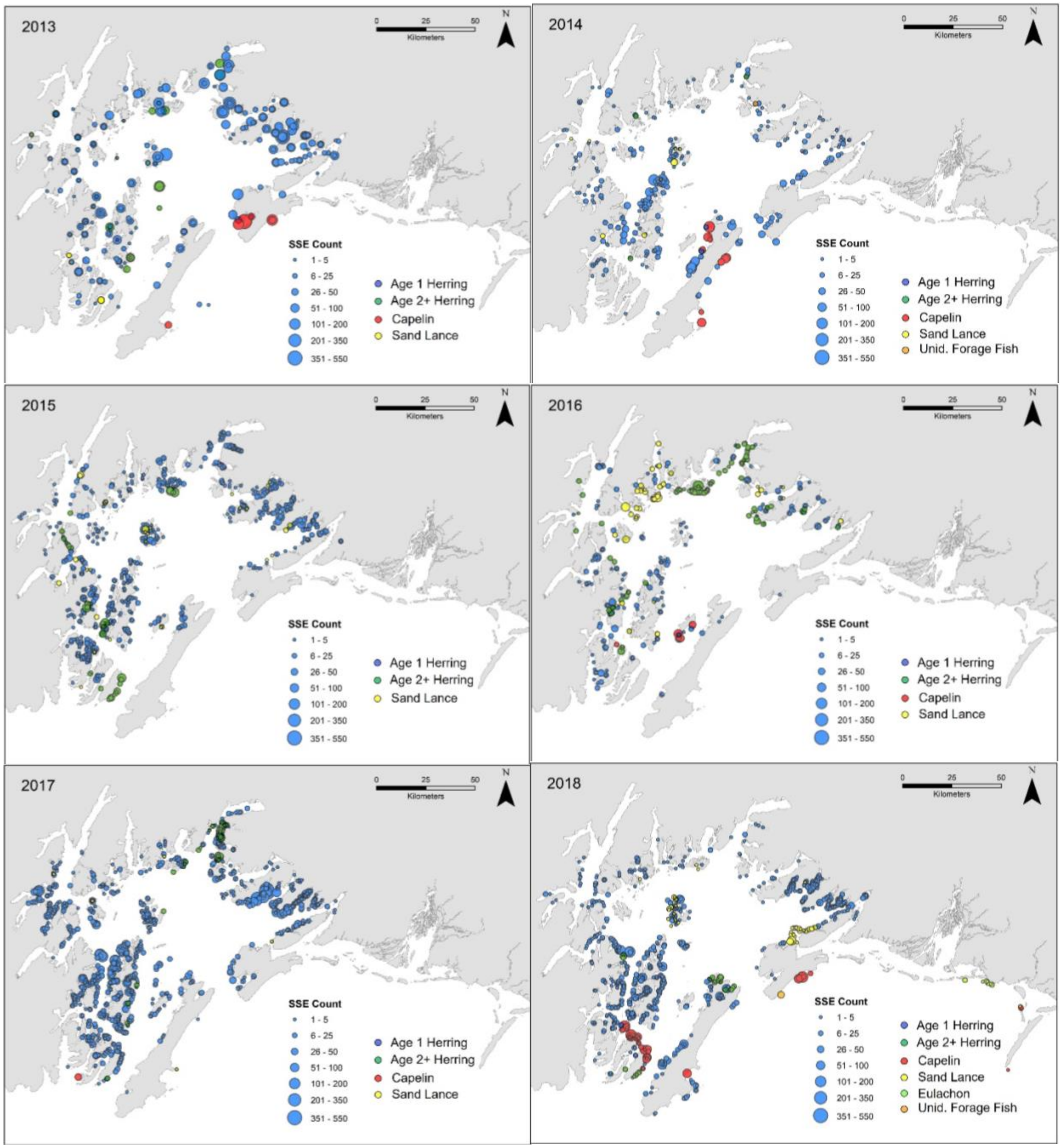
Figure 5. Type and number of individual whales observed during the forage fish surveys in 2022. The size of the circle depicts the number of individual whales observed, while the color of the circle indicates whale type.

The 2022 aerial survey data has been made available through the Alaska Ocean Observing System (AOOS) data portal at https://portal.aoos.org/gulf-of-alaska#metadata/2f2367fa-6f4c-44e6-9c7a-150dc156154c/project.

This year the Forage Fish group led by Dr. Mayumi Arimitsu of the United States Geological Service, who we work with to provide validation of aerial observations, were able to bring a small boat to Cordova to allow more opportunities for validation work in 2022. Over two days we were able to validate seven aerial observations. Of those seven observations, the aerial observers identified five as age-1 herring and two as age-2+ herring. All seven identifications were confirmed by sampling from the schools. The age-2+ herring were once again adult herring that later spawned in Simpson Bay.

2013-2022 Observations

The survey data from 2013 through 2022 has been combined to look for areas with persistent occupation by forage fish. Since eulachon and capelin were not commonly observed we only consider age-1 herring, age-2+ herring, and sand lance. Maps of the distributions of forage fish in each year is provided in Figure 6. Plotting all the years together shows that the three most commonly observed fish are distributed throughout the Sound (Figure 7). Age-1 herring are observed nearly everywhere along the coastline except near the heads of fjords where the water clarity is too poor to make observations. To examine the issue of persistent occupation of an area, we chose to create a grid using 5 km by 5 km cells and looked at how often the fish were observed in each grid cell (Figure 8). Age-1 herring were primarily found in the eastern bays, along Naked Island group, Knight Island, and in Port Nellie Juan. Age-2+ herring did not consistently occupy any areas but the southern sides of Knight and Glacier Islands were the areas they were most often observed. Sand lance were commonly found on Middle Ground Shoal and in the Naked Island group.



2013
2014
2015
2016
2017
2018
0 25 50
Kilometers
N
SSE Count
1 - 5
6 - 25
26 - 50
51 - 100
101 - 200
201 - 350
351 - 550
Age 1 Herring
Age 2+ Herring
Capelin
Sand Lance
Eulachon
Unid. Forage Fish

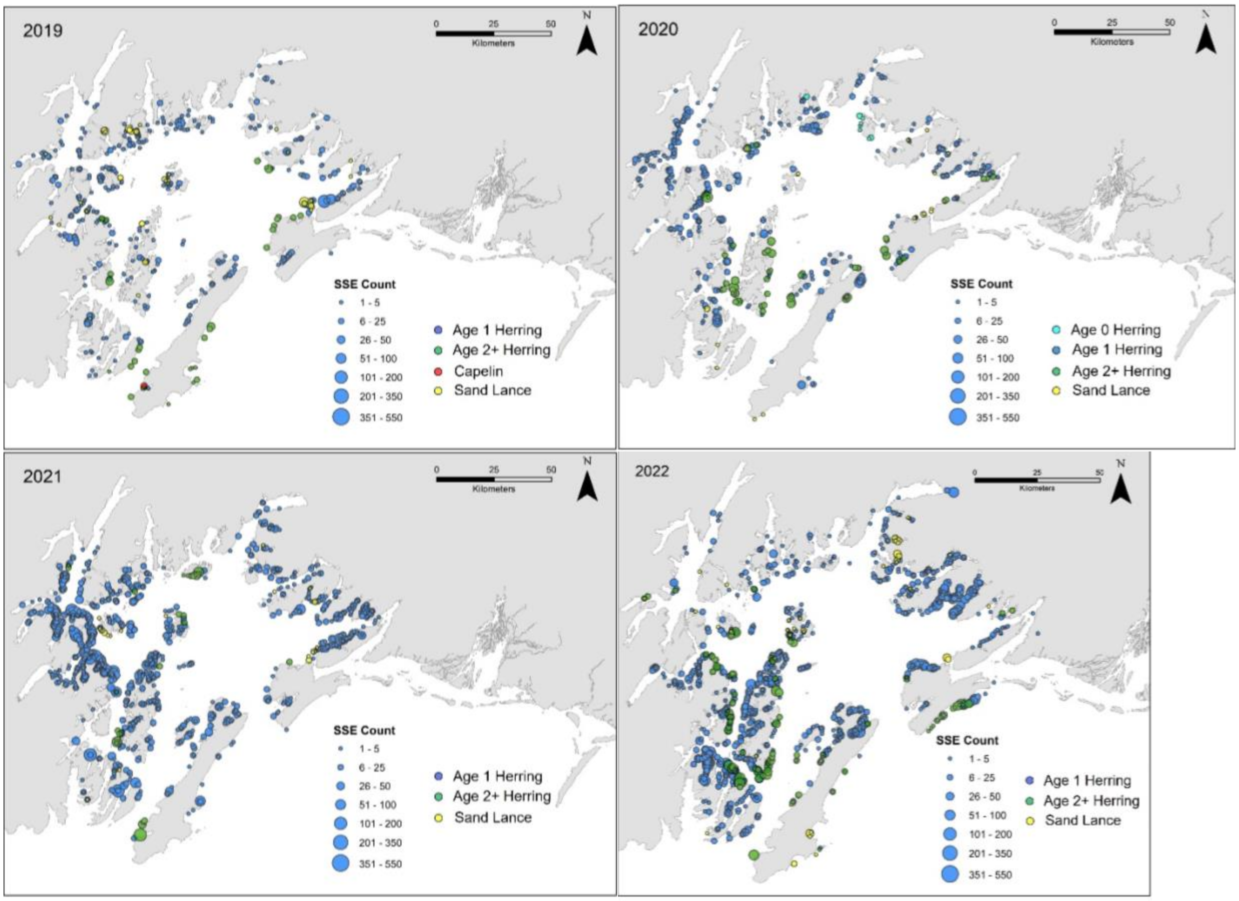


Figure 6. The SSE index of forage fish observations from 2013 to 2020.

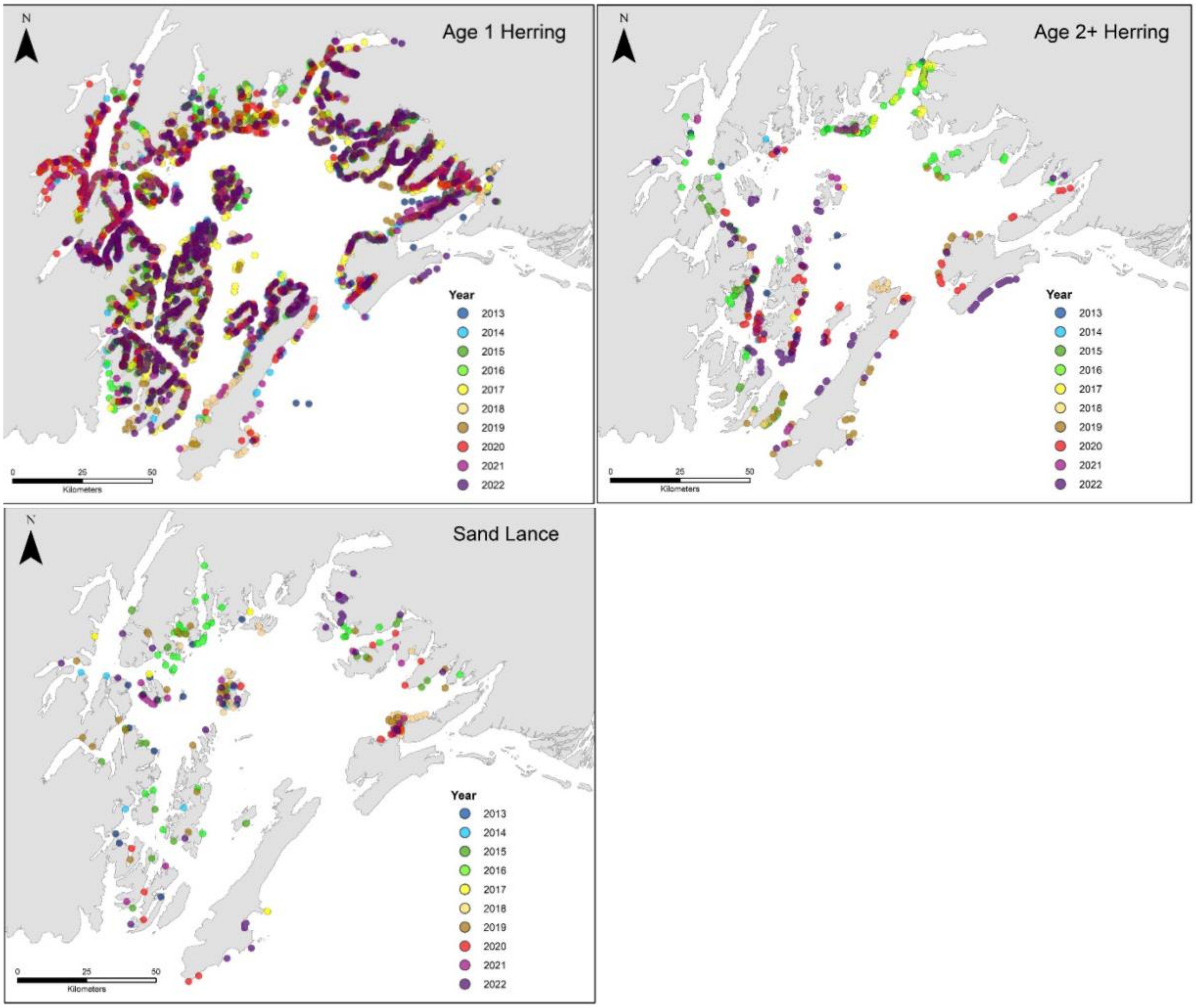


Figure 7. Locations where age-1 herring, age-2+ herring, and sand lance were observed between 2013 and 2022.

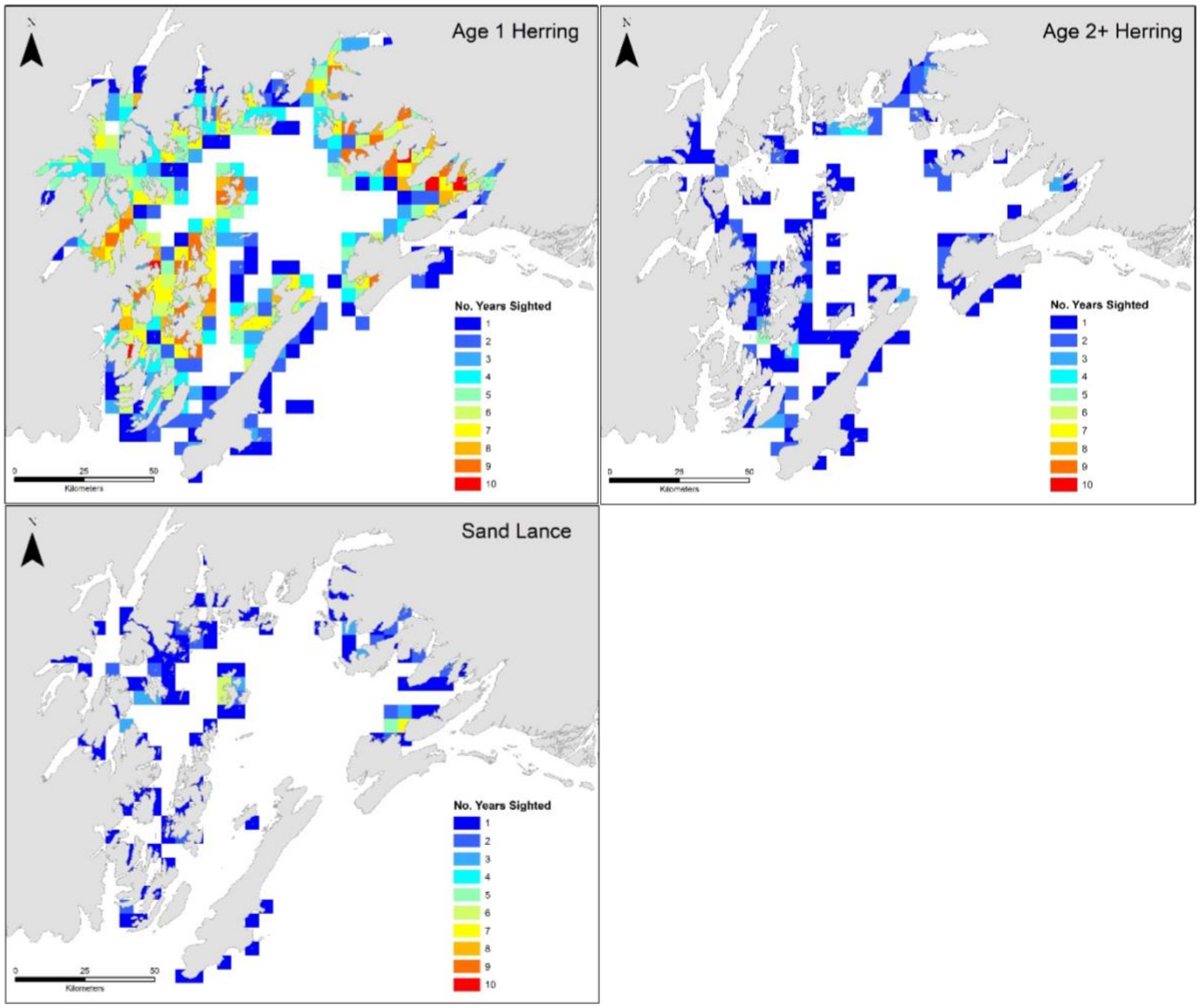


Figure 8. The number of years at each location that age-1 herring, age-2+ herring, and sand lance were observed between 2013 and 2022.

Assuming that the age-1 herring have not moved much since settling in nursery habitats the previous winter, the distribution of these herring is consistent with the oceanography likely to carry larvae to the nursery grounds. The primary spawning grounds have been in eastern PWS, particularly within Port Gravina. Local retention of larvae explains why the eastern bays consistently have age-1 herring in them. Springtime deployment of surface drifters (Pegau unpublished data) from Port Gravina had drifters that traveled eastward and more that went to the west to be caught in the circulation of PWS. Easterly winds are common in the spring and will transport surface water and larvae to the west where they are incorporated in the central Sound circulation. In central PWS there is a cyclonic circulation (Halverson et al., 2013) that would carry larvae from eastern PWS to the north where it meets the freshwater flow that passes to the southwest (Musgrave et al., 2013). This also matches the flow of oil from the Exxon Valdez oil spill.

Validation

Confidence in the survey results depends on how accurate the observations are and determining accuracy depends on validation. The historic validation efforts found that identification errors often involved age-0 herring or age-0 sand lance, probably because these fish occur in overlapping regions and do not have as well-defined schooling characteristics (Norcross et al., 1999). In part, this is why our surveys have focused on June which is before the age-0 herring become visible. Still, when the validation effort began in 2014, much of that effort occurred in July because of vessel schedules.

During the past four years (2019-2022) we have been able to focus the validation efforts to the June period when the surveys were occurring. This resulted in 50 validation observations. Combining those with July validations (2014-2018), and ignoring any validation with age-0 fish, we have a total of 74 validation observations. In 41 cases the aerial observer called the school age-1 herring. The validation showed 39 of those schools were herring but three of them were older than age-1. The validation effort also showed that some of the schools were a mixture of age-1 and age-2 fish. All 13 schools identified as age-2+ herring were found to be correctly identified. Of the 20 schools identified as sand lance, 17 were found to be sand lance with the other three being herring. The aerial observers identified the herring correctly 96% of the time and sand lance 85% of the time. The correct identification of the age of age-1 herring was over 90% although if the mixed-age schools are counted as older fish that drops to 84%.

Earlier school identification validation efforts were conducted in the late 1990s. Norcross et al. (1999) provided an analysis of 419 validation observations in PWS. In their work, only herring (N= 310) and sand lance (N=109) schools were validated. They found that herring identifications from the aircraft were correct 96.1% of the time and incorrect identifications from the air were generally associated with age-0 sand lance. In the validation dataset from the 1990s, sand lance were correctly identified 80.4% of the time and the errors involved sand lance incorrectly identified as age-0 herring. Our recent validation results are consistent with the larger set of samples collected by Norcross et al.

The schools containing a mixture of age-1 and age-2 herring are worth further consideration. It is not possible to determine if there is a vertical structure in the school that would cause the aerial observer to see age-1 herring with the validation effort catching age-2 herring deeper in the water column. We could change the classification to juvenile (age-1 and -2) and adult (age-3+). The disadvantage being that a juvenile index would be a mixture of the two year classes and more difficult to use as a predictor of recruitment. The mixed schools seem to be infrequent enough that staying with a separation of age-1 and age-2+ is reasonable.

Conclusions and Recommendations

While the PWS herring populations remain low, they still represent the largest number of schools of forage fish observed. In 2022, the number of age-1 herring schools was large for the second year in a row and may indicate that two large year class will be recruiting to the spawning stock in the next two years. If this is true, we can expect that the herring population will have robust growth in the near future.

Sand lance were dispersed throughout PWS but Middle Ground Shoal and Naked Island were the areas with the greatest concentrations of sand lance. Capelin and eulachon were not observed this year.

We are working with Dr. Arimitsu to analyze the validation and distribution data. The goal is to be able to identify the forage fish hot spots and hopefully understand the factors that influence changes in the distribution of the fish observed. If we can identify the conditions that lead to a particular distribution, we would have a better idea of where these forage fish might be if a spill were to occur. The frequency of schools provided in Figure 8 provides a good indication of where fish are commonly found. The age-1 herring are commonly found in the eastern bays, Naked Island, and along Knight Island, although they can be found most anywhere in PWS. There are years, like 2021, where the distribution is different. The mechanisms driving the differences in distributions is what we hope to get from the analysis with Dr. Arimitsu. Sand lance are commonly found near Middle Ground Shoal and Naked Island.

Data from this project is also being used by the modeling project within the Herring Research and Monitoring (HRM) program to predict recruitment to the spawning stock. By working with the HRM and GWA programs we are building a better understanding of the conditions that lead to the success and distribution of forage fish. That information is then used to predict changes in the herring populations and impacts to marine birds and mammals.

The number of validations in June remain small for statistical analysis. They are consistent with previous efforts that indicate that we can identify herring correctly about 95% of the time and sand lance over 80% of the time. We were able to correctly separate age-1 herring from older herring between 85 and 90% of the time.

We believe that the project has been able to identify areas important to herring and sand lance through the persistence in their presence. These forage fish also are important for attracting marine mammals, birds, and fish which makes these areas important during spill response.

Acknowledgments

This material is based on work supported by PWSRCAC under contract No. 9511.22.01. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of PWSRCAC. Pegau received additional support from the Exxon Valdez Oil Spill Trustee Council funded Herring project for salary while conducting the aerial surveys and the validation collection effort was supported by the Exxon Valdez Oil Spill Trustee Council funded Forage Fish project.

Literature Cited

Anderson, P.J., Piatt, J.F., 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Mar. Ecol. Prog. Ser. 189, 117–123.

Abookire, A.A., Piatt, J.F., 2005. Oceanographic conditions structure forage fishes into lipid-rich and lipid-poor communities in lower Cook Inlet, Alaska, USA. Mar. Ecol. Prog. Ser. 287, 229–240. doi:10.3354/meps287229

Arimitsu, M.L., Piatt, J.F., 2008. Forage fish and their habitats in the Gulf of Alaska and Aleutian Islands: Pilot study to evaluate the opportunistic use of the U.S. Fish and Wildlife refuge support vessel for long-term studies.

Arimitsu, M.L., Piatt, J.F., Mueter, F.J., 2016. Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords. Mar. Ecol. Prog. Ser. 560, 19–40.

Arimitsu, M., J. Piatt, S. Hatch, R. M. Suryan, S. Batten, M. A. Bishop, R. W. Campbell, H. Coletti, D. Cushing, K. Gorman, S. Haught, R. R. Hopcroft, K. J. Kuletz, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, W. S. Pegau, A. Schaefer, S. Schoen, J. Straley, and V. R. von Biela. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. *Global Change Biology.* 27, 1859-1878 https://doi.org/10.1111/gcb.15556

Brown, E.D., 2002. Life history, distribution, and size structure of Pacific capelin in Prince William Sound and the northern Gulf of Alaska. ICES J. Mar. Sci. 59, 983–996. doi:10.1006/jmsc.2002.1281

Brown, E.D., Moreland, S.M., 2000. Ecological factors affecting the distribution and abundance of forage fish in Prince William Sound, Alaska: An APEX synthesis product. Restoration Project 00163T. Final Report. Fairbanks, AK 79 pp.

Brown, E.D., Wang, J., Vaughan, S.L., Norcross, B., 1999. Identifying seasonal spatial scale for the Ecological Analysis of Herring and Other Forage Fish in Prince William Sound , Alaska, in: Ecosystem Approaches for Fisheries Management. Alaska Sea Grant College Program, AK-SG-99-01, pp. 499–510.

Cury, P., Bakun, A., Crawford, R., Jarre, A., Quiñones, R., Shannon, L., Verheye, H., 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in “wasp-waist” ecosystems. ICES J. Mar. Sci. 57, 603–618. doi:10.1006/jmsc.2000.0712

Hatch, S.A., Sanger, G.A., 1992. Puffins as samplers of juvenile pollock and other forage fish in the Gulf of Alaska. Mar. Ecol. Prog. Ser. 80, 1–14.

Hay, D.E., Thompson, M.J., Mccarter, P.B., 2001. Anatomy of a Strong Year Class: Analysis of the 1977 Year Class of Pacific Herring in British Columbia and Alaska, in: Herring: Expectations for a New Millennium. pp. 171–198.

Halverson, M.J., J.C. Ohlmann, M.A. Johnson, W.S. Pegau, 2013. Disruption of a cyclonic eddy circulation by wind stress in Prince William Sound, Alaska, *Cont. Shelf Res.*, 63, S13-S25.

Musgrave, D.L., M.J. Halverson, and W.S. Pegau, 2013. Seasonal Surface Circulation, Temperature, and Salinity in Prince William Sound, Alaska, *Cont. Shelf Res.*, 53, 20-29. doi:10.1016/j.csr.2012.12.001.

Norcross, B., Brown, E.D., Foy, R.J., Frandsen, M., Seitz, J., Stokesbury, K., 1999. *Exxon Valdez* Oil Spill Restoration Project Final Report- Juvenile Herring Growth and Habitats-Restoration Project 99320T-ch10 juvenile herring growth.

Norcross, B.L., Brown, E.D., Foy, R.J., Frandsen, M., Gay, S.M., Kline, T.C., Mason, D.M., Patrick, E.V., Paul, A.J., and Stokesbury, K.D., 2001. A synthesis of the life history and ecology of juvenile Pacific herring in Prince William Sound, Alaska, Fish. Oceanogr. (Suppl. 1), pp. 42-57.

Ormseth, O.A., 2014. Appendix 2 . Forage species report for the Gulf of Alaska.

Ostrand, W.D., Coyle, K.O., Drew, G.S., Maniscalco, J.M., Irons, D.B., 1998. Selection of forage fish schools by murrelets and tufted puffins in Prince William Sound, Alaska. Condor 100, 286–297.

Pegau, W.S., 2018. Aerial Survey Support. Exxon Valdez Long-Term Herring Research and Monitoring Final Report (Restoration Project 15120111-R), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

Piatt, J.F., Anderson, P.J., 1996. Response of common murres to the *Exxon Valdez* oil spill and long-term changes in the Gulf of Alaska marine ecosystem. Am. Fish. Soc. Symp. 18, 720–737.

Pikitch, E.K., Rountos, K.J., Essington, T.E., Santora, C., Pauly, D., Watson, R., Sumaila, U.R., Boersma, P.D., Boyd, I.L., Conover, D.O., Cury, P.M., Heppell, S.S., Houde, E.D., Mangel, M., Plagányi, É., Sainsbury, K., Steneck, R.S., Geers, T.M., Gownaris, N., Munch, S.B., 2014. The global contribution of forage fish to marine fisheries and ecosystems. Fish Fish. 15, 43–64. doi:10.1111/faf.12004

Robards, M.D., 1999. Maturation, fecundity, and intertidal spawning of Pacific sand lance in the northern Gulf of Alaska. J. Fish Biol. 54, 1050–1068. doi:10.1006/jfbi.1999.0941

Speckman, S.G., Piatt, J.F., Mintevera, C., Parrish, J., 2005. Parallel structure among environmental gradients and three trophic levels in a subarctic estuary. Prog. Oceanogr. 66, 25–65. doi:10.1016/j.pocean.2005.04.001

Suryan, R.M., Irons, D.B., Kaufman, M., Benson, J., Jodice, P.G.R., Roby, D.D., Brown, E.D., 2002. Short-term fluctuations in forage fish availability and the effect on prey selection and brood-rearing in the black-legged kittiwake *Rissa tridactyla*. Mar. Ecol. Prog. Ser. 236, 273–287. doi:10.3354/meps236273

Thedinga, J.F., Hulbert, L.B., Coyle, K.O., 2000. Abundance and distribution of forage fishes in Prince William Sound. Restoration Project 00163A Final Report. Juneau, AK. 58 pp.

Williams, E.K., and Quinn, T.J., 2000. Pacific herring, *Clupea pallasi*, recruitment in the Bering Sea and north-east Pacific Ocean, I: relationships among different populations. Fish. Oceanogr. 9:4, 285-299.

Womble, J.N., Sigler, M.F., 2006. Seasonal availability of abundant, energy-rich prey influences the abundance and diet of a marine predator, the Steller sea lion *Eumetopias jubatus*. Mar. Ecol. Prog. Ser. 325, 281–293. doi:10.3354/meps325281

Yang, M., Aydin, K.Y., Greig, A., Lang, G., Livingston, P., 2005. Historical Review of Capelin (*Mallotus villosus*) Consumption in the Gulf of Alaska and Eastern Bering Sea. NOAA Technical Memorandum NMFS-AFSC-155.

Appendix

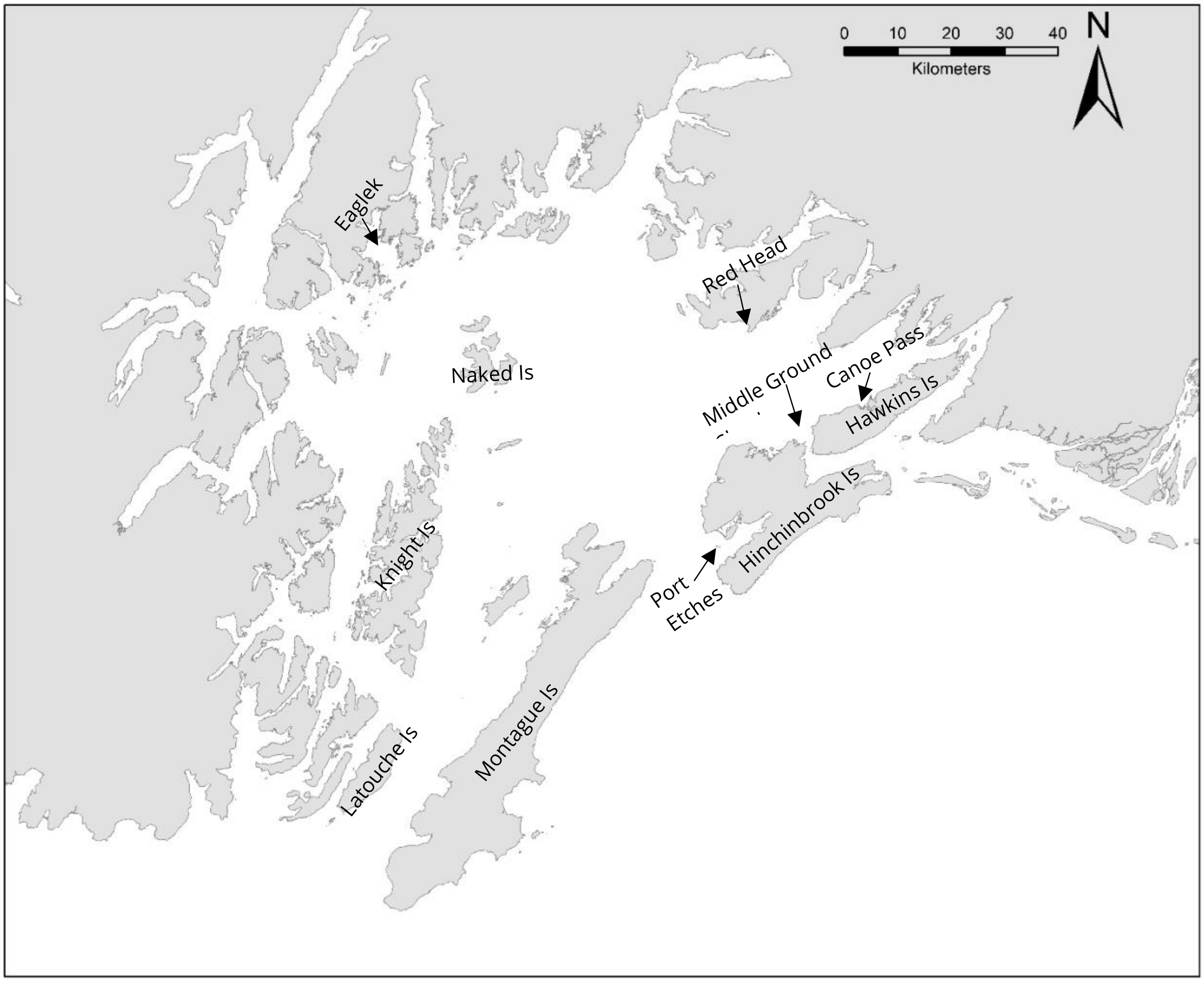


Figure A-1. Map of locations in Prince William Sound.

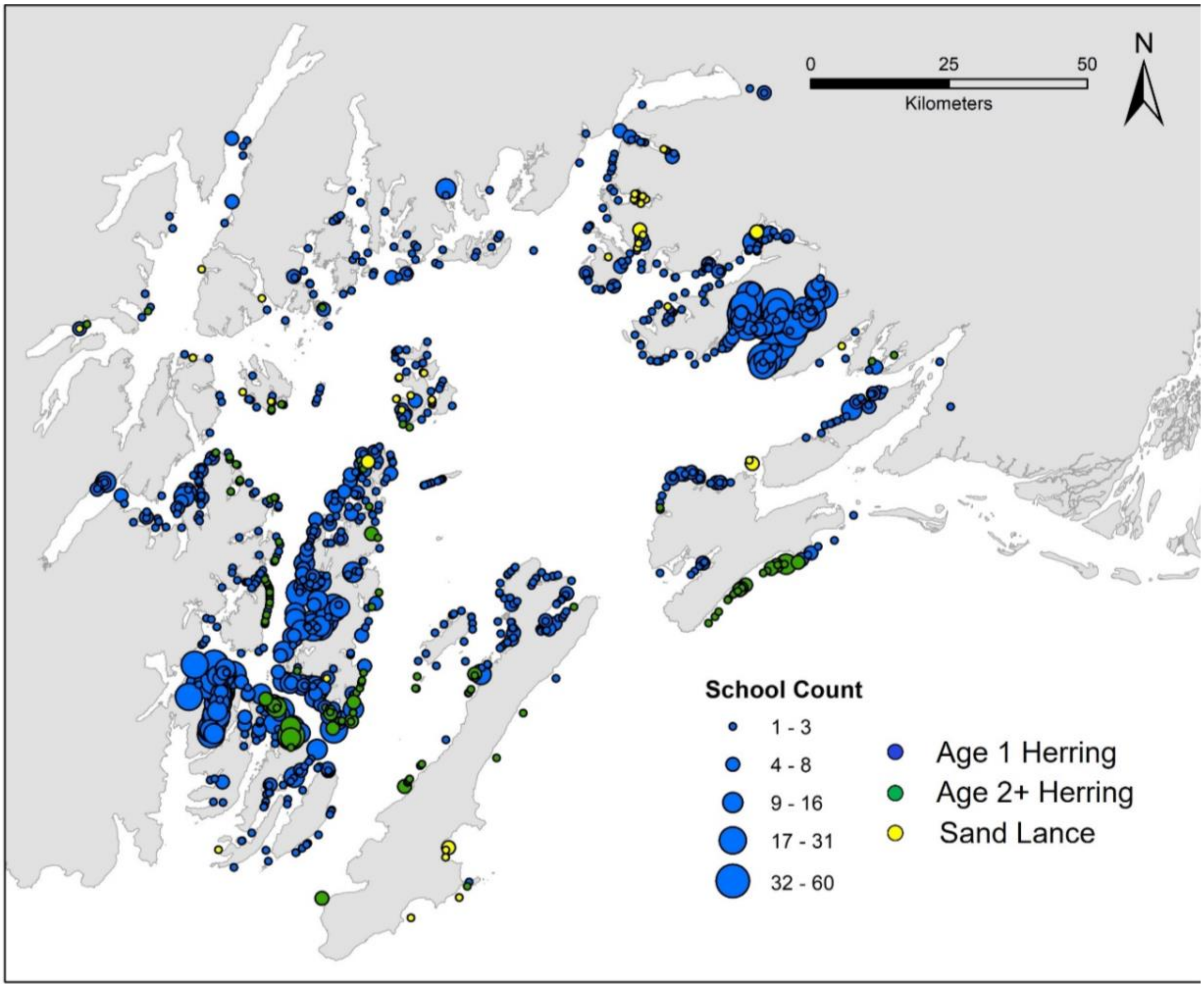


Figure A-2. June 2022 forage fish distribution. This is an enlarged version of Figure 2a.

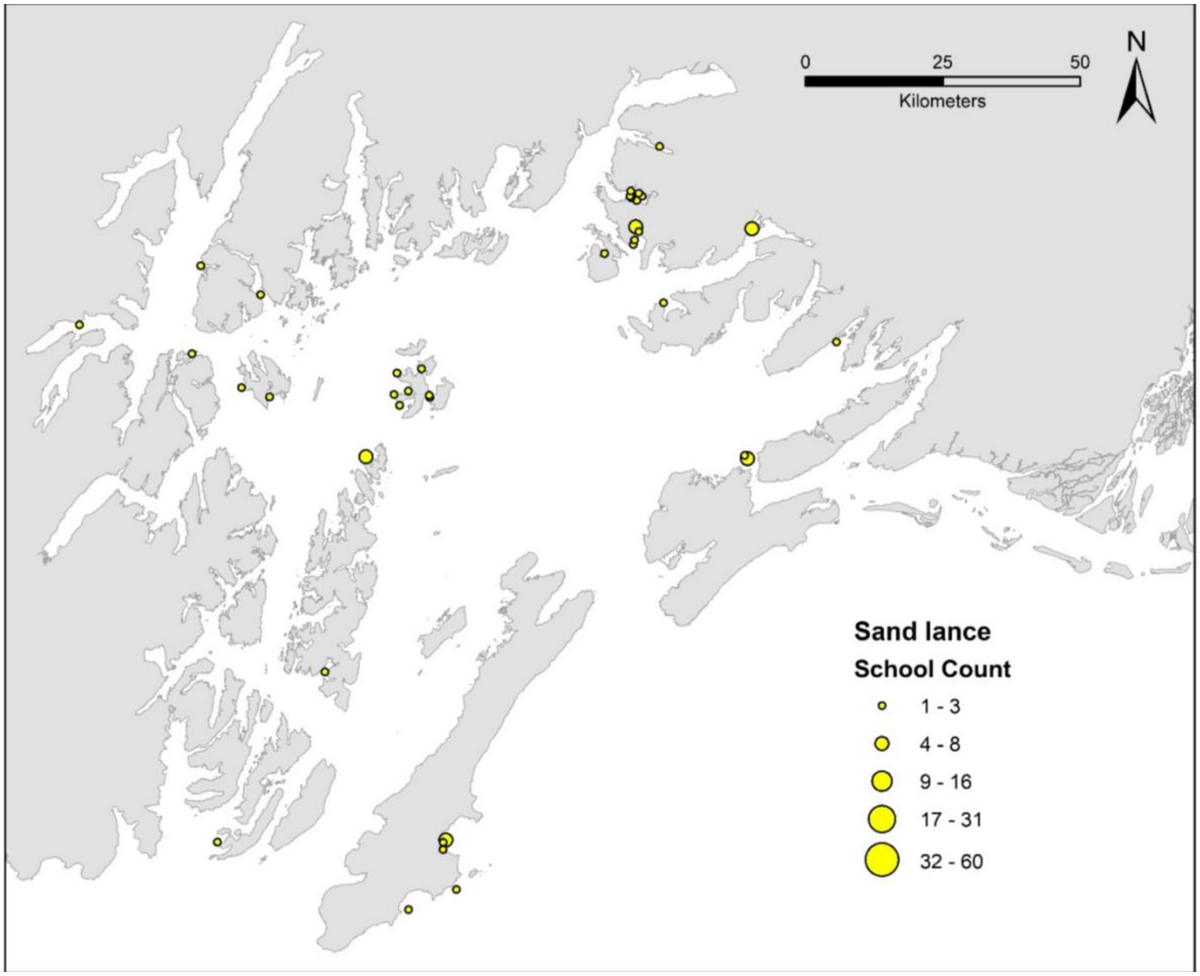


Figure A-3. June 2022 sand lance distribution. This is an enlarged version of Figure 2b.

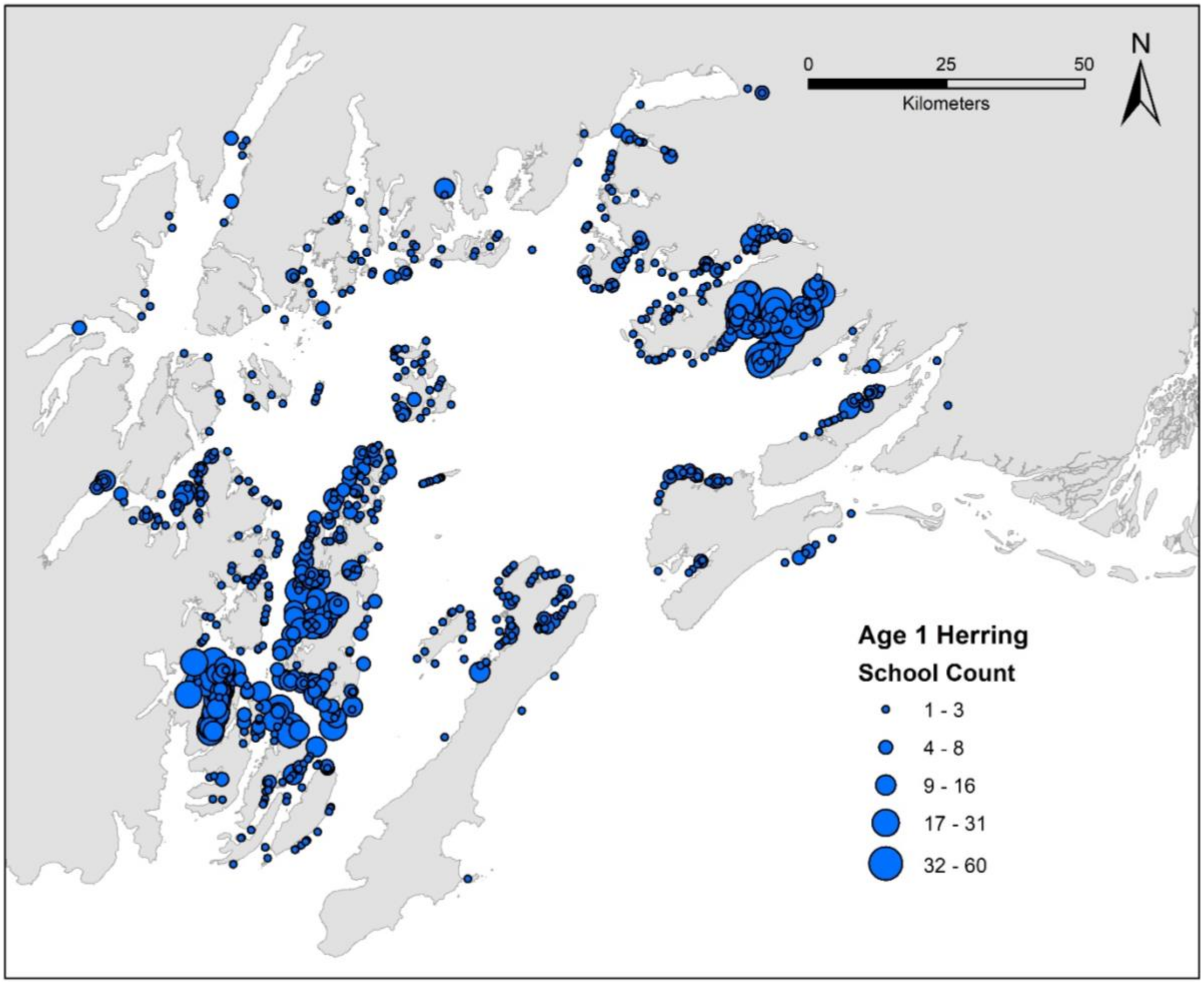


Figure A-4. June 2022 age-1 herring distribution. This is an enlarged version of Figure 2c.

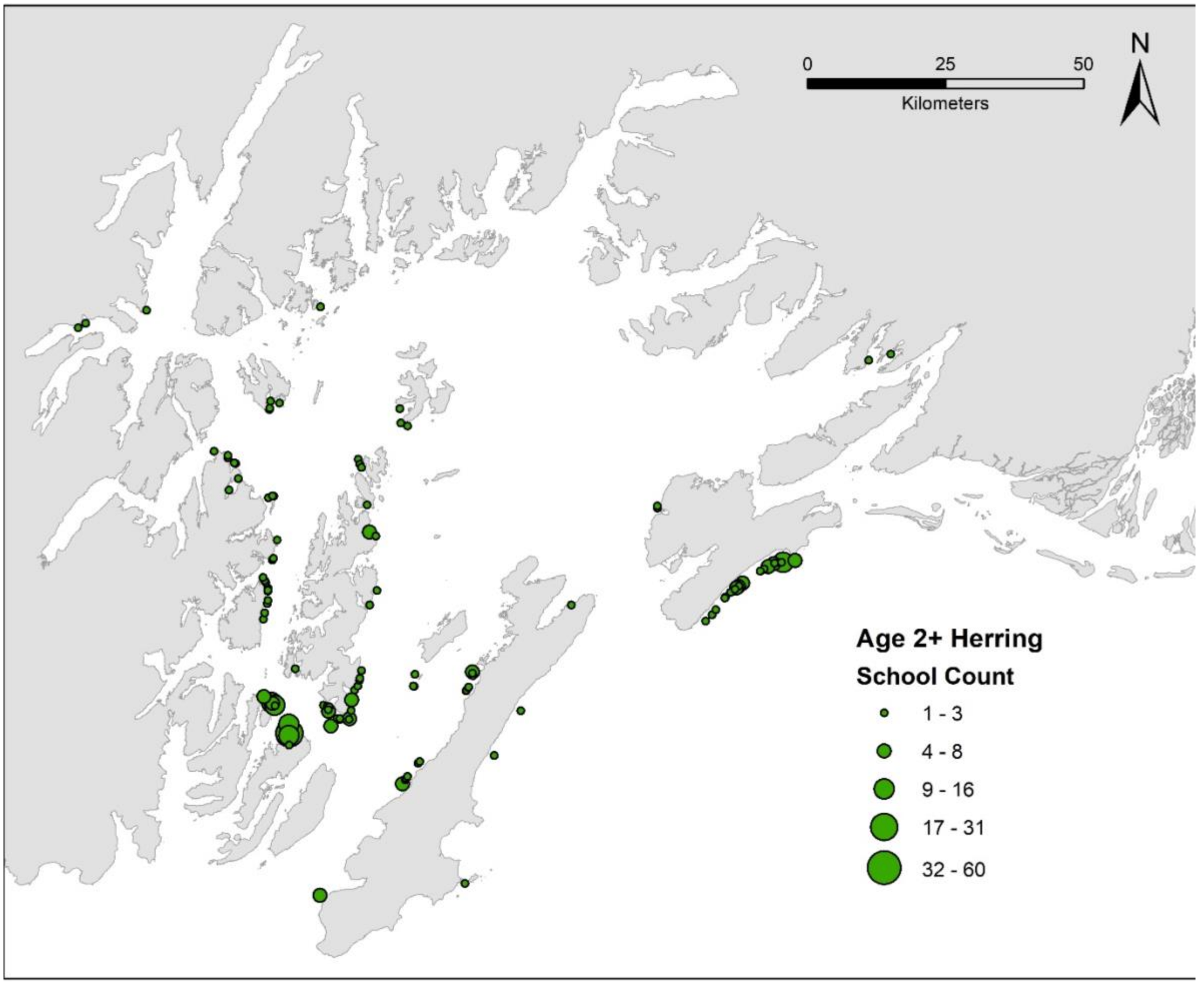


Figure A-5. June 2022 age-2+ herring distribution. This is an enlarged version of Figure 2d.

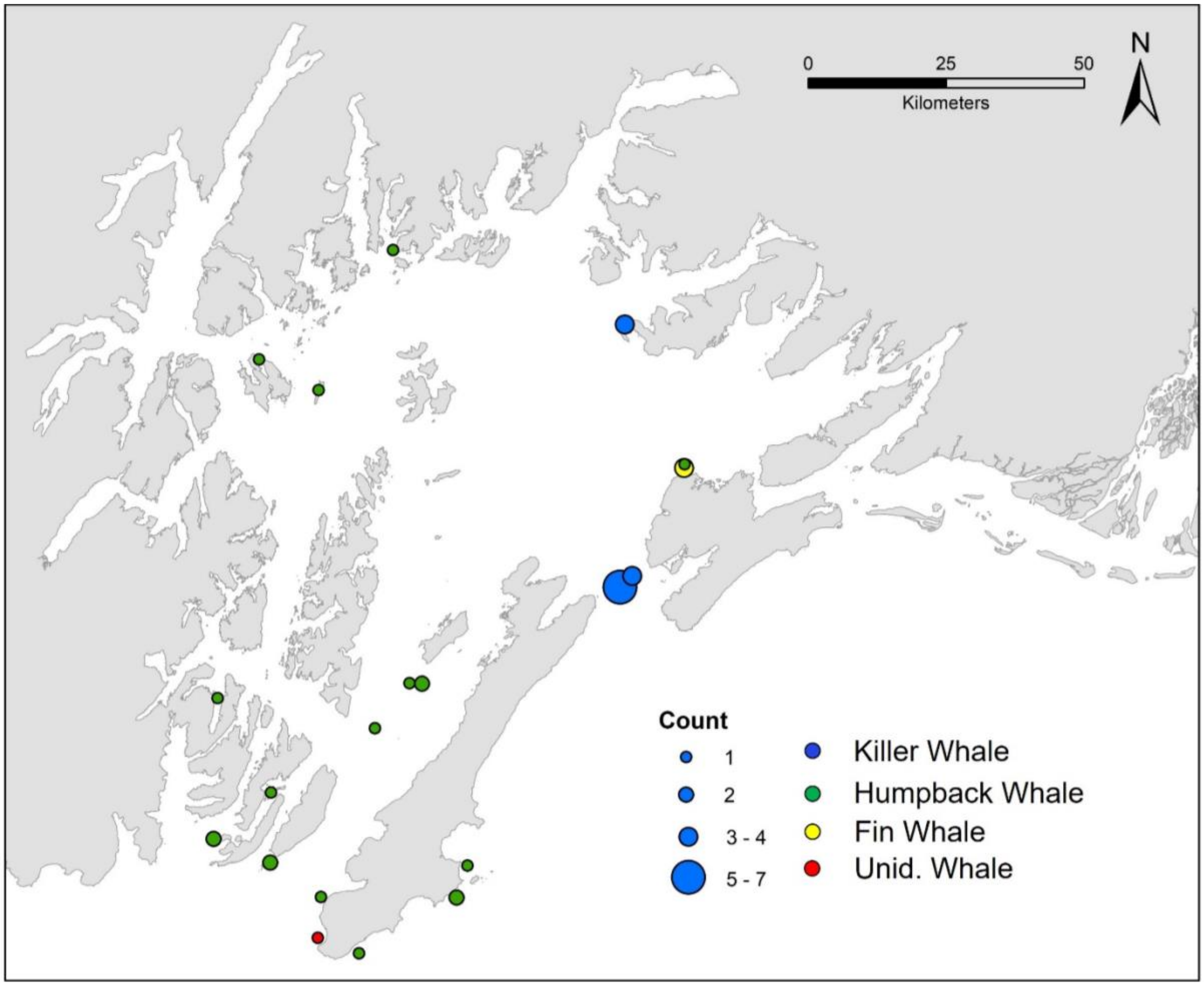


Figure A-6. June 2022 number and type of whales observed. The size of the circle depicts the number of individual whales observed, while the color of the circle indicates whale type. This is an enlarged version of Figure 5.

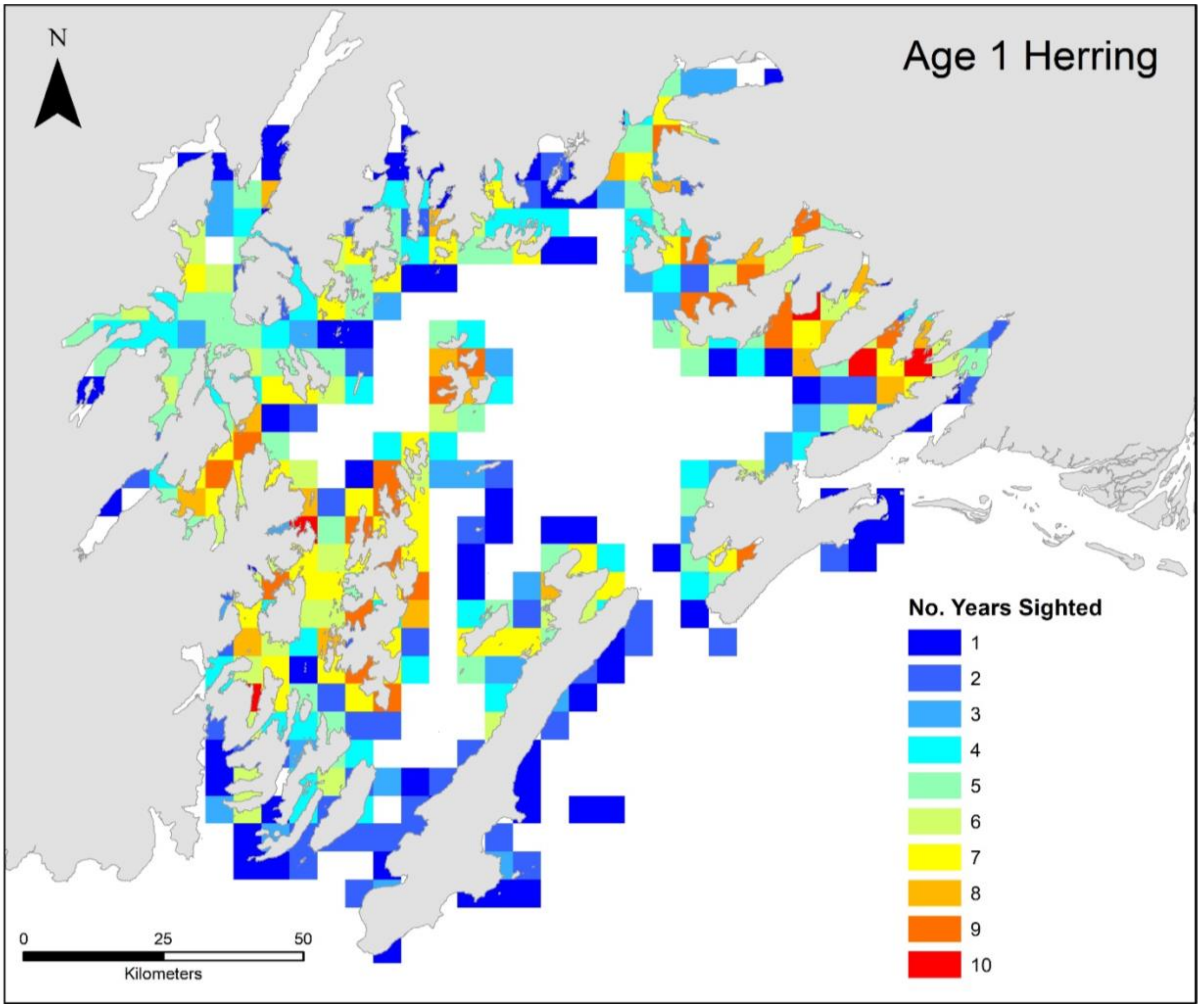


Figure A-7. The number of years that schools of age-1 herring were seen within a 5 km by 5 km block between 2013 and 2022. This is an enlarged version of Figure 8a.

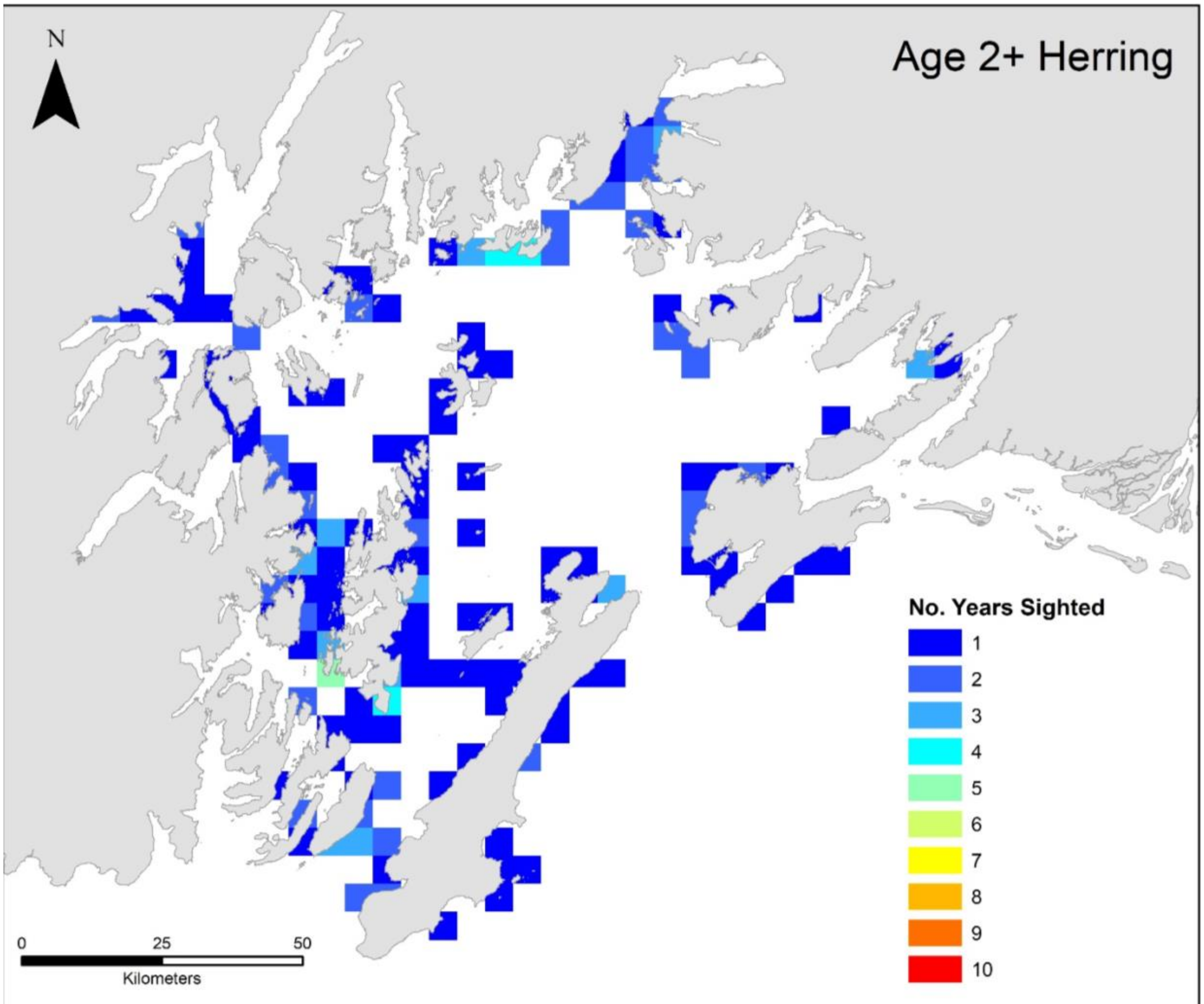


Figure A-8. The number of years that schools of age-2+ herring were seen within a 5 km by 5 km block between 2013 and 2022. This is an enlarged version of Figure 8b.

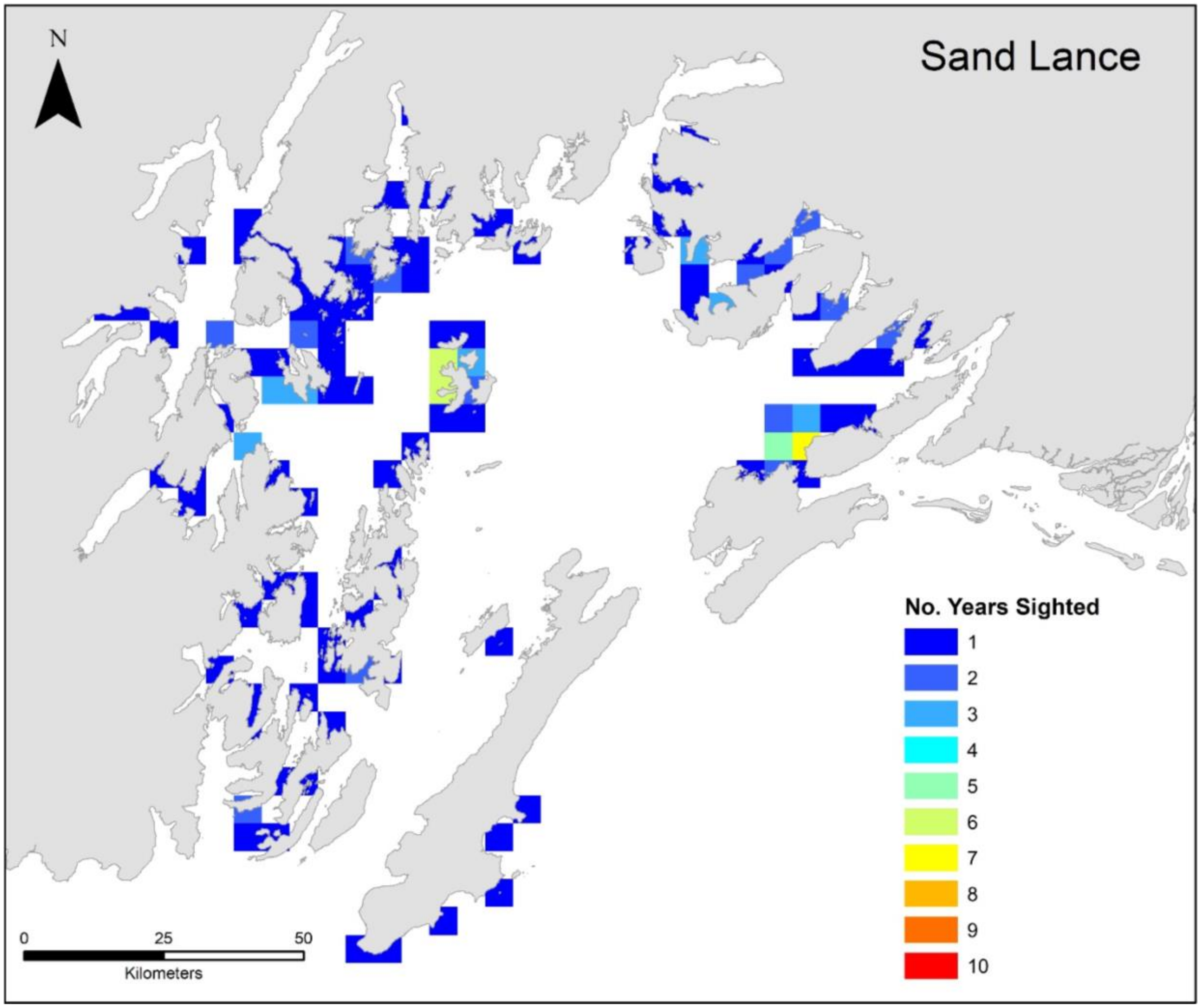


Figure A-9. The number of years that schools of sand lance were seen within a 5 km by 5 km block between 2013 and 2022. This is an enlarged version of Figure 8c.