Briefing for PWSRCAC Board of Directors – January 2022

ACTION ITEM

Sponsor: Danielle Verna and the Scientific Advisory Committee

Project number and name or topic: 9511 – Prince William Sound Forage Fish Surveys

1. **Description of agenda item:** This agenda item is seeking Board acceptance of a final report titled "2021 Prince William Sound Forage Fish Observations" by Dr. Scott Pegau of the Prince William Sound Science Center. Dr. Pegau conducted ariel surveys of forage fish throughout Prince William Sound in June 2021 to identify locations where forage fish congregate and may be impacted by a spill. The report describes the methods and results of the survey with comparison to prior survey years. This was the third of four expected years for this project; the Board has approved funding to conduct surveys for a final year in 2022. Dr. Pegau will provide a brief presentation about the report to the Board and will be available to answer questions, along with Council project manager Danielle Verna.

2. **Why is this item important to PWSRCAC:** This item is important to the PWSRCAC mission because it supports monitoring of forage fish and habitat in Prince William Sound that may be impacted by the operations of the terminal and tankers and may require additional protection in the event of an oil spill. Forage fish, including herring, sand lance, capelin, and euchalon, are a critical component of the marine food web. Prince William Sound provides valuable spawning grounds for these species. Forage fish are also important to subsistence, recreational, and commercial fisheries, both directly and indirectly. Results from the aerial surveys of juvenile forage fish contribute to an ongoing dataset of forage fish species and locations in Prince William Sound. Data from the survey will be archived in the Alaska Ocean Observing System portal and can help inform future monitoring or response to an oil spill. Data will also contribute to the Herring Research and Monitoring program's effort to predict recruitment potential (sponsored by the Exxon Valdez Oil Spill Trustee Council).

3. **Previous actions taken by the Board on this item:**

Meeting	Date	Action
XCOM	4/22/2019	Approved a sole source contract with the Prince William Sound Science Center in an amount not to exceed $42,500 to conduct the FY2019 aerial herring fish surveys along the Prince William Sound coastline.
Board	1/23/2020	Accepted the report titled "2019 Prince William Sound Forage Fish Observations" by Dr. Scott W. Pegau of the Prince William Sound Science Center dated November 4, 2019, as meeting the terms and conditions of contract number 9511.19.01, and for distribution to the public.
XCOM	4/30/2020	Approved a contract with the Prince William Sound Science Center, to conduct the Prince William Sound Forage Fish Surveys Project 9511, at an amount not to exceed $43,600.
Board	5/21/2020	Adopted the FY2021 budget as presented. This project was approved as a part of the FY2021 budget.

Board	1/28/2021	Accepted the report titled "2020 Prince William Sound Forage Fish Observations" by Dr. Scott Pegau of the Prince William Sound Science Center dated September 10, 2020, as meeting the terms and conditions of contract 9511.20.01 and for distribution to the public, and authorized a contract with the Prince William Sound Science Center for this project for FY2021.

4. **Summary of policy, issues, support, or opposition:** None.

5. **Committee Recommendation:**
The Scientific Advisory Committee recommends the Board of Directors accept this report.

6. **Relationship to LRP and Budget:** Project 9511 Herring/Forage Fish Survey is in the approved FY2022 budget and annual work plan.

9511--Herring/Forage Fish Survey	
As of December 10, 2021	
FY-2022 Budget	
Original	$46,300.00
Modifications	
Revised Budget	$46,300.00
Actual and Commitments	
Actual Year-to-Date	
Commitments (Professional Services)	$3,800.00
Actual + Commitments	$3,800.00
Amount Remaining	$42,500.00

7. **Action Requested of the Board of Directors:** Accept the report titled "2021 Prince William Sound Forage Fish Observations" by the Prince William Sound Science Center, dated September 21, 2021, as meeting the terms and conditions of Council contract 9511.21.01 for distribution to the public.

8. **Alternatives:** None recommended.

9. **Attachments:** Draft report titled 2021 Prince William Sound Forage Fish Observations by Dr. Scott Pegau from the Prince William Sound Science Center.

2021 Prince William Sound Forage Fish Observations

21 September 2021

W. Scott Pegau

Prince William Sound Science Center, Box 705, Cordova, AK

Contract 9511.21.01

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 third year of an expected 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. The data from this project also provides an index of age-1 Pacific herring (*Clupea pallasii*) that is used by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) sponsored Herring Research and Monitoring (HRM) program to predict recruitment to the spawning stock. The HRM program conducts aerial and acoustic surveys of the herring spawning stock within PWS and works to understand changes in the herring population. These aerial forage fish surveys complement the HRM effort by providing the only indication of recruitment potential.

Aerial surveys were conducted in June of 2021. 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 Prince William Sound and took 10 flight days to complete. Surveys are only flown when weather permits so the survey period extended throughout June.

Pacific herring was the dominant species observed, followed by Pacific sand lance (*Ammodytes hexapterus*). Based on historical surveys we expected to also observe capelin (*Mallotus villosus*) and eulachon (*Thaleichthys pacificus*). In recent years there have been very few observations of these latter two species and no eulachon or capelin were observed this year. The relative proportion of herring and sand lance varied along the coast. Sand lance were relatively rare for the second year in a row with only a few schools seen in normal areas such as Middle Ground Shoal and Naked Island (see map in Appendix for these locations), more were observed along Perry Island than in the past. Whale numbers were higher than the last two years but remain low.

Large numbers of juvenile herring were observed this year. They were concentrated in the northwest and eastern sections of the Sound. The number of schools observed was the greatest since 2017 and the weighted school index was similar in value to 2017. This may indicate that another large herring year class is in the system. The 2017 observations were of the 2016 year-class that was the largest seen in the Gulf of Alaska. We do not expect to see the fish observed in the aerial surveys this year to recruit to the spawning biomass until 2023. These large recruitment events are critical to the recovery of herring.

An unusual observation this year was of adult herring preparing to spawn in Simpson Bay in mid-June. This spawning event has been reported by a local oyster farmer many times in the past but this is the first year the fish were observed. The fish were sampled for age analysis by the Alaska Department of Fish and Game.

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).

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. This approach allowed for the collection of more samples than in the past.

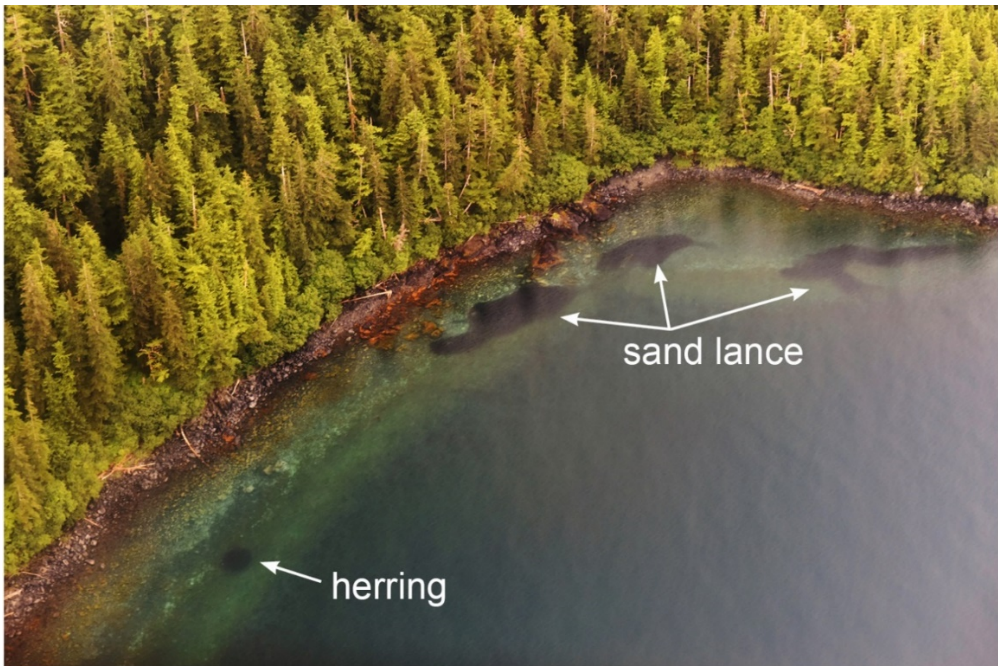

Photo 1. Aerial photograph of typical Pacific herring (n = 1) and Pacific sand lance schools (n = 3) along shorelines in Prince William Sound, Alaska. Herring schools are typically round or oval and sand lance schools are darker and irregularly shaped.

In this report, we describe the current distribution of coastal forage fish schools in PWS as observed during the June 2020 aerial surveys and provide some historic distributions for comparison. 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 EVOSTC. 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 kilometers 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 12 days, flying four to five 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. A video camera is placed in a rear window to provide an additional record of the flight. Normally the video only covers a section of the flight because the video camera batteries do not last the entire flight time. 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 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.

Findings & Discussion

This year, 10 days were spent surveying. Most of the flights were conducted between June 9 and 18, but weather and other scheduling caused the last three flights to occur at the end of June. All of PWS is flown, including the outsides of Montague and Hinchinbrook islands as well as the islands in southwest PWS (Figure 1).

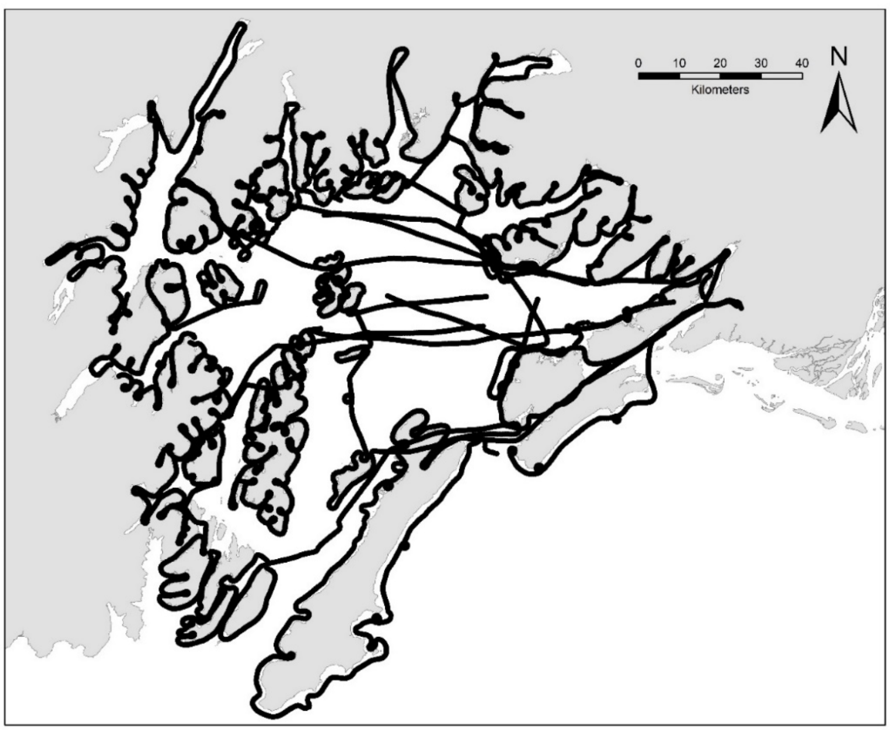

Figure 1. The 2019 survey flight tracks, which were essentially the same as the 2021 tracks. The apparent gaps in the survey flight tracks from 2019 are due to issues with the GPS recording device, but they were flown and recorded on the backup paper logs.

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 2021, there were relatively few sand lance and a very large number of age-1 herring. As often occurs, sand lance were concentrated on Middle Ground Shoal with some schools observed in other areas, particularly Perry Island this year.

This year we observed the most age-1 herring since 2017 (Figure 3). We counted 1028 small, 785 medium, and 112 large schools of age-1 herring. The distribution of age-1 herring was not uniform around PWS and was different in many respects to that seen in 2017 (Figure 4). There were large concentrations of schools in the eastern section and northwest near the top of Knight Island passage up to College Fjord. The medium and large schools were mostly found in areas with a large number of schools, such as northwester PWS. Very few fish were observed in northern PWS. The large number of schools observed 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).

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. An unusual observation this year was of a small population of spawning herring in Simpson Bay. They were misidentified from the air but were sampled by the validation vessel and identified as adult herring. ADF&G was able to collect fish from this population and the age structure was predominately age-3 and -4, which is very different than the main spawning population (mostly age-5). Spawning herring in Simpson Bay has been reported by a local oyster fisherman for many years but this is the first year we have been able to collect a sample. We don't know if the spawning herring are ones that were not fully ripe during the early spawn event or represent a different population than observed earlier.

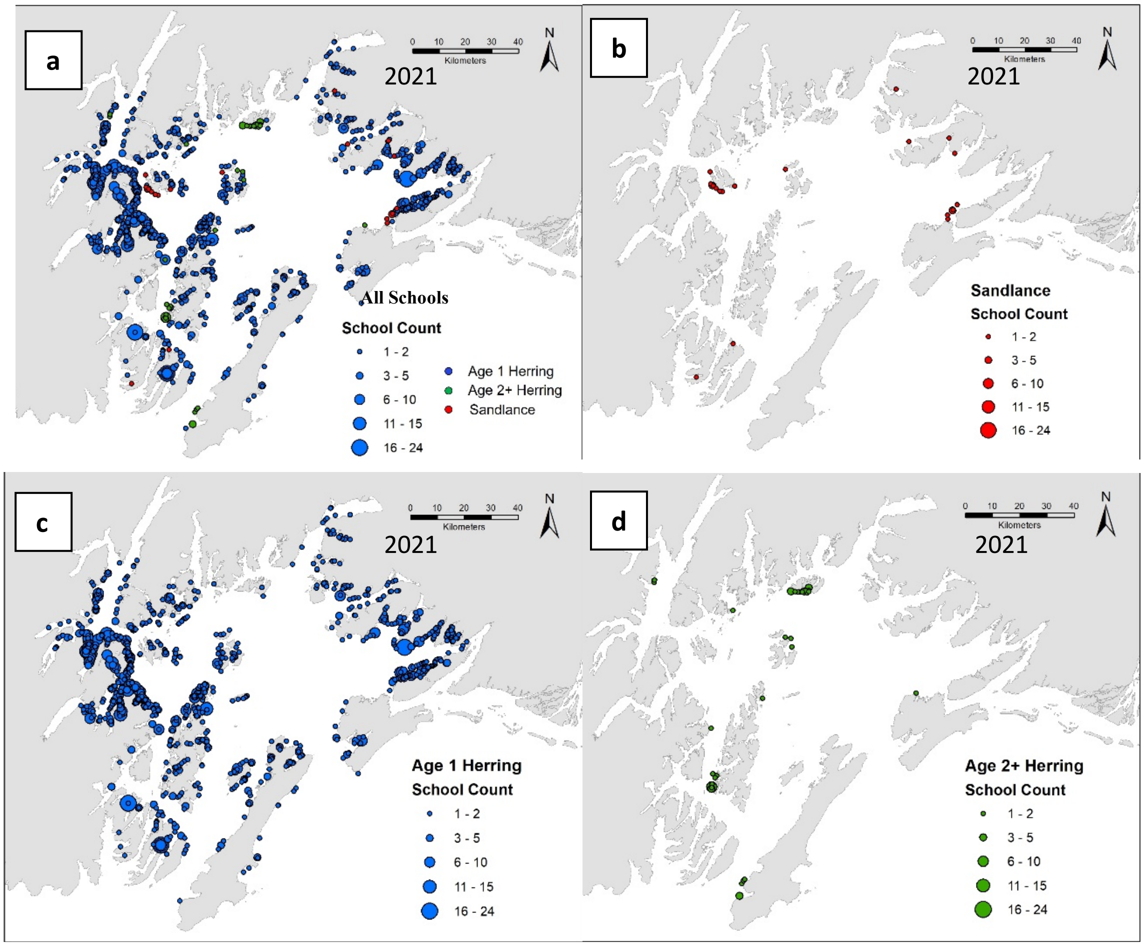

Figure 2. Observations of the number of schools for all forage fish (a), sand lance (b), age-1 herring (c), and age-2+ herring (d) in 2020. No capelin were seen this year.

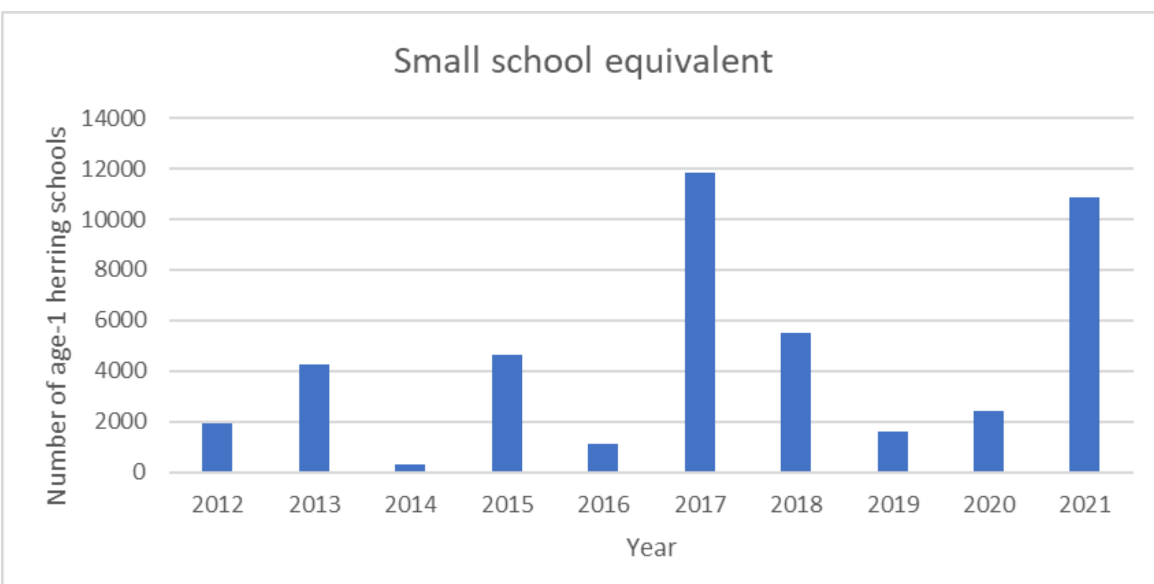

Figure 3. Number weighted by school size of age-1 herring schools by year.

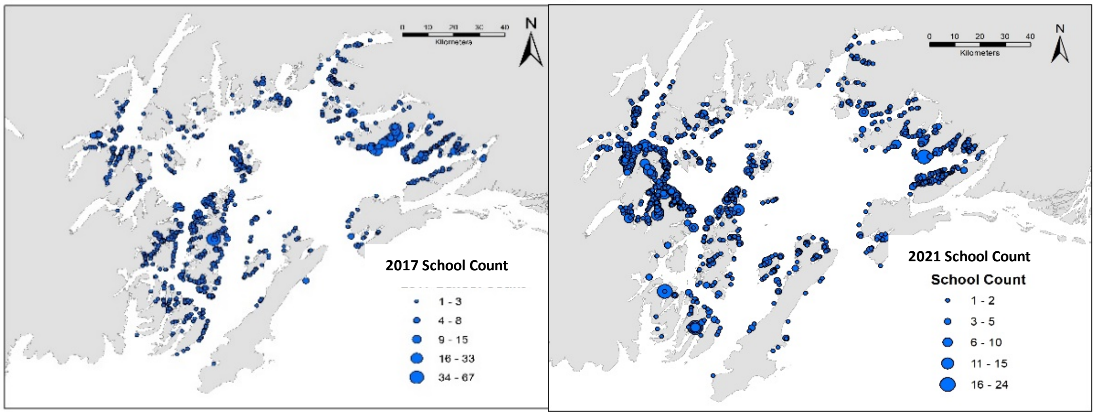

Figure 4. Distribution of age-1 herring schools in 2017 and 2021. These are the two years with the greatest number of age-1 herring schools observed.

Observations of whales also are collected during the surveys. A map of their 2021 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.

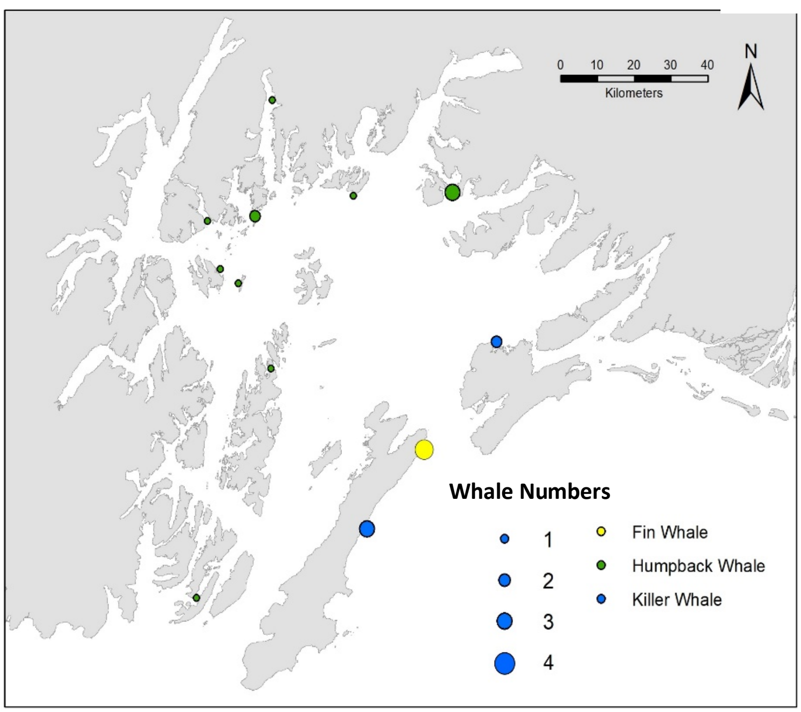

Figure 5. Type and number of individual whales observed during the forage fish surveys in 2021. The size of the circle depicts the number of individual whales observed, while the color of the circle indicates whale type.

The 2021 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. Video was collected during many portions of the aerial survey and is available from Scott Pegau.

This year the Forage Fish group led by Dr. Mayumi Arimitsu of the United States Geological Service that 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 2021. Over two days we were able to validate 23 aerial observations. Of those 23 observations, the aerial observers identified 21 as age-1 herring and 2 as sand lance. Neither sand lance observation was correct. Of the 23 schools identified as age-1 from the air, 19 were validated as age-1 herring, two were the adult herring preparing to spawn, one was a mix of age-1 and age-2, and one was age-2 herring. Additional validation was provided by Dr. Rob Campbell of Prince William Sound Science Center. He was able to sample two schools in Eaglek Bay. Those were identified by the aerial observers as age-1 herring and the vessel captured age-1 herring in both schools.

The historic 2014-2021 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. From the combination of all validation efforts, the July aerial survey identification error of herring is between 5-10% and the error in identifying sand lance is approximately 20%. Ignoring the errors associated with age-0 fish to simulate what we can expect to see in June, the error in identification of herring is about 5% and sand lance about 15%. The identification of the age of herring has a larger error than the identification of species. Ignoring the cases involving age-0 fish, herring identified as age-2+ by the aerial observers has been correct nine out of nine times, and 27 of 32 schools identified as age-1 were correct. Several schools of herring were confirmed to be herring, but it wasn't possible to estimate their age. We are currently working with the Forage Fish group to increase the number of schools sampled in June to provide better statistics on the observation errors when there are no age-0 fish expected.

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 results are consistent with the larger set of samples collected by Norcross et al.

Conclusions and Recommendations

While the PWS herring populations remain low, they still represent the largest number of schools of forage fish observed. In 2021, the number of age-1 herring schools was large and may indicate that a second large year class in four years is in the system. The herring were concentrated in larger schools in the east near the spawning grounds and the northwest portion of PWS.

For the second year in a row, there were few observations of sand lance. Middle Ground Shoal and Perry Island were the areas with the greatest concentrations of sand lance. Capelin were not seen or captured by other surveys this year, although the summer forage fish survey was cut short by mechanical difficulties.

We have begun 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.

Data from this project is also being used by the modeling project within the HRM program to predict recruitment to the spawning stock. By working with the HRM and GWA programs we can build 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.

We have a proposal to the EVOSTC to support the surveys after next year as an input to the modeling effort. We recommend the PWSRCAC support the surveys for one additional year to ensure the continuation of the time series and build a time series that is better suited for determining the likely locations of forage fish and the potential connections to environmental variables. When the 2020 year class begins recruiting to the spawning stock in 2023, we will better understand the utility of these surveys in predicting incoming year-class strength. Before then, the maps of forage fish distributions that we will be able to generate will help identify sensitive nearshore areas in PWS.

Acknowledgments

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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.

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.

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

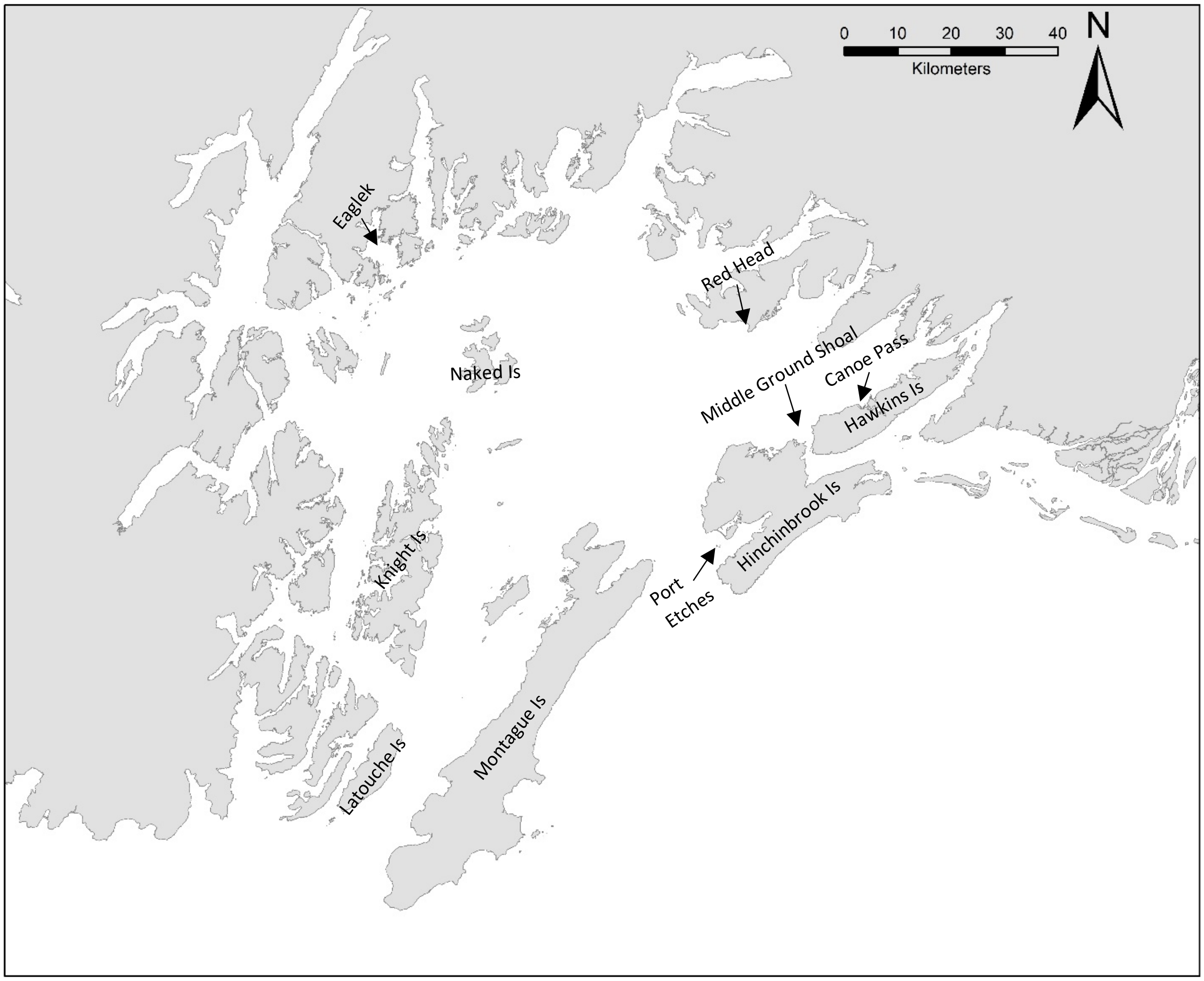

Figure 6. Map of locations in Prince William Sound.

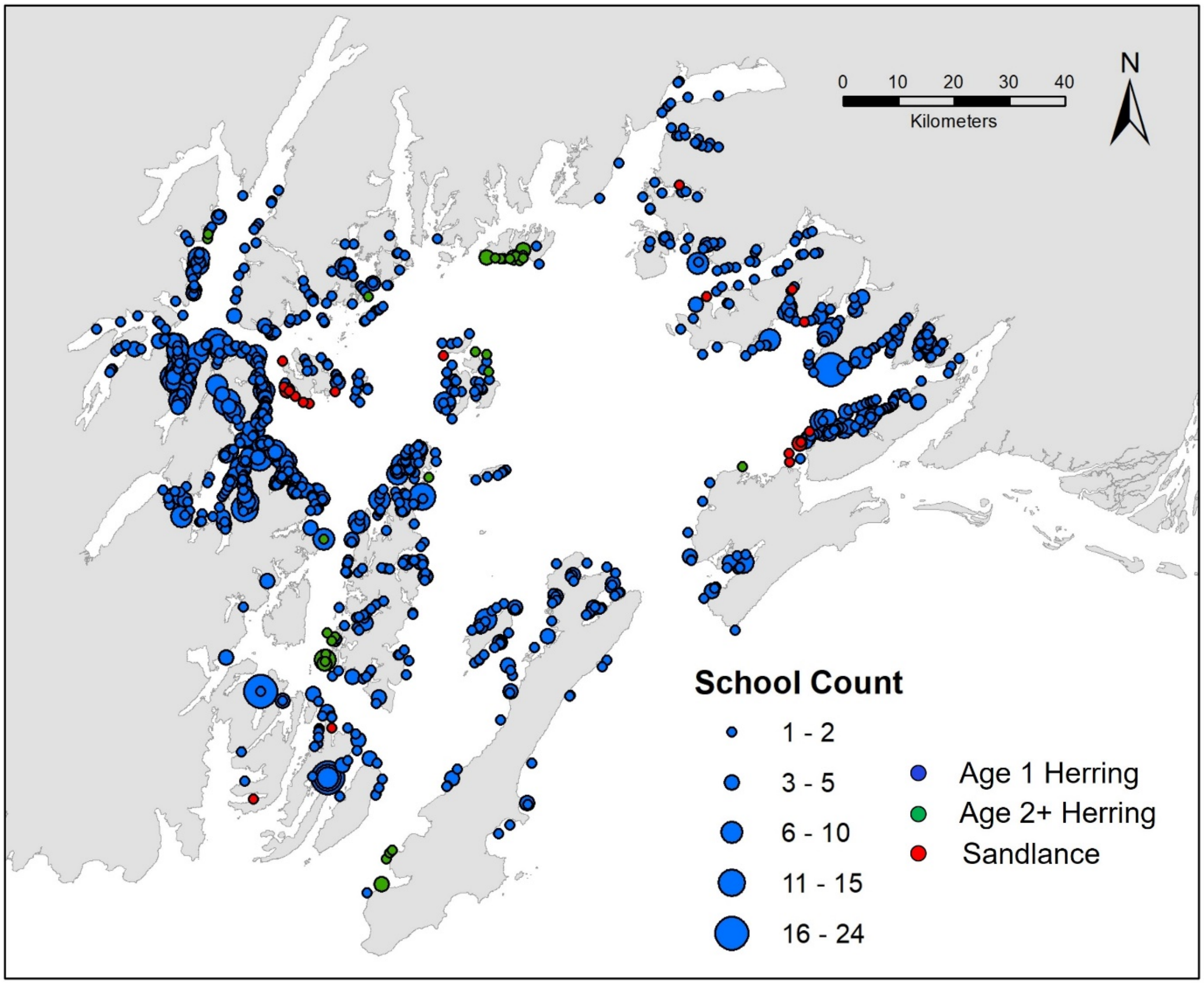

Figure 7. June 2021 forage fish distribution.

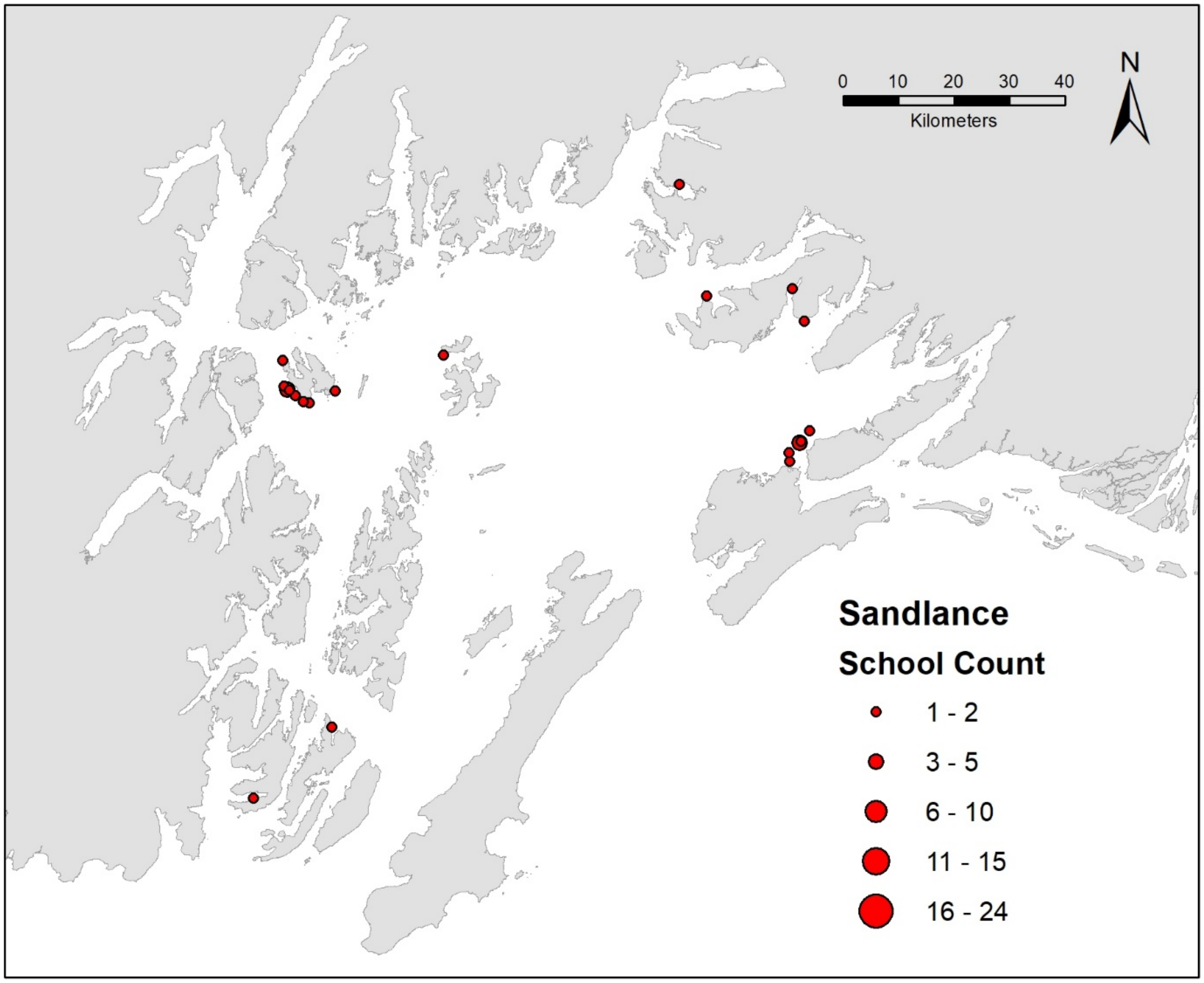

Figure 8. June 2021 sand lance distribution.

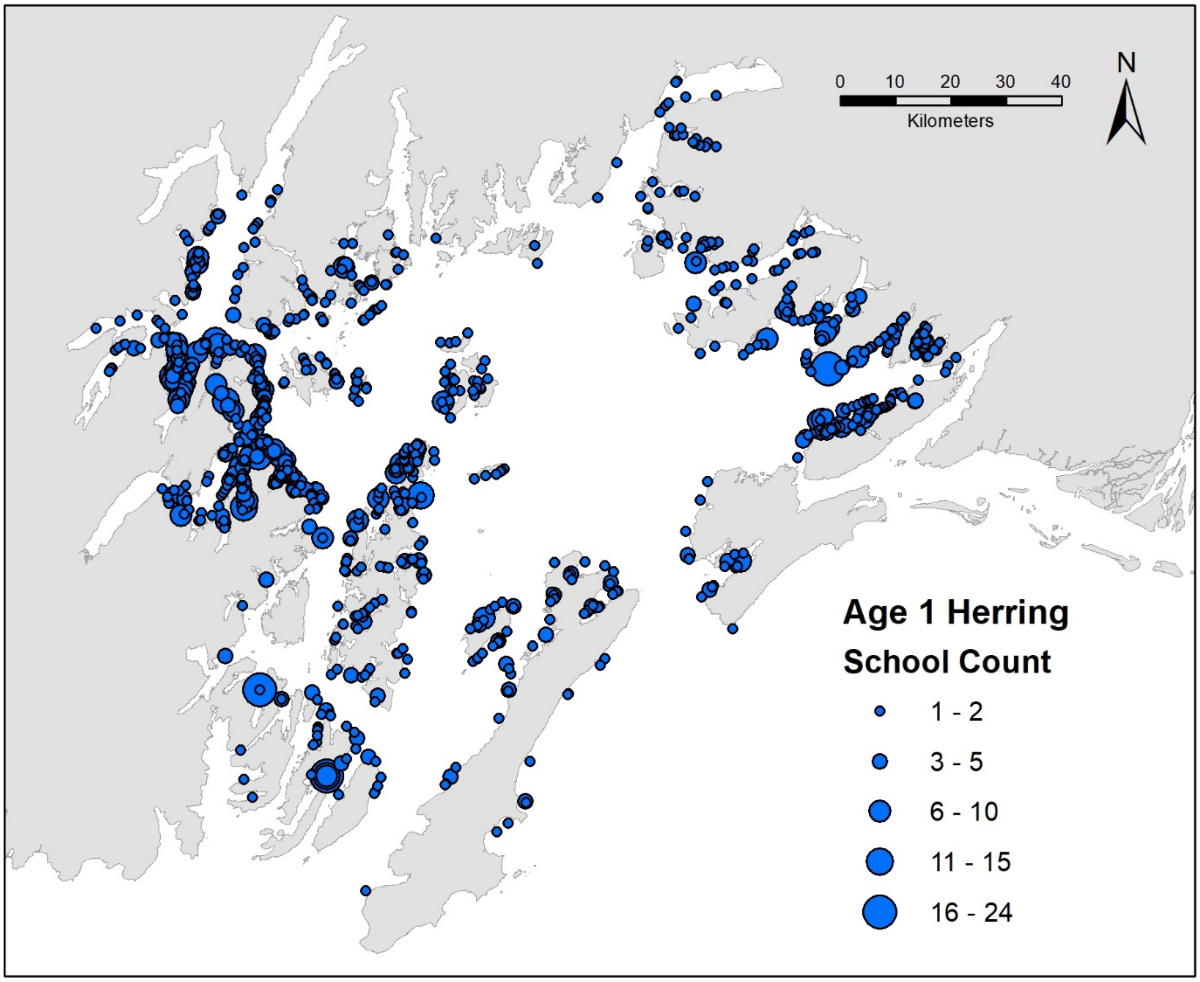

Figure 9. June 2021 age-1 herring distribution.

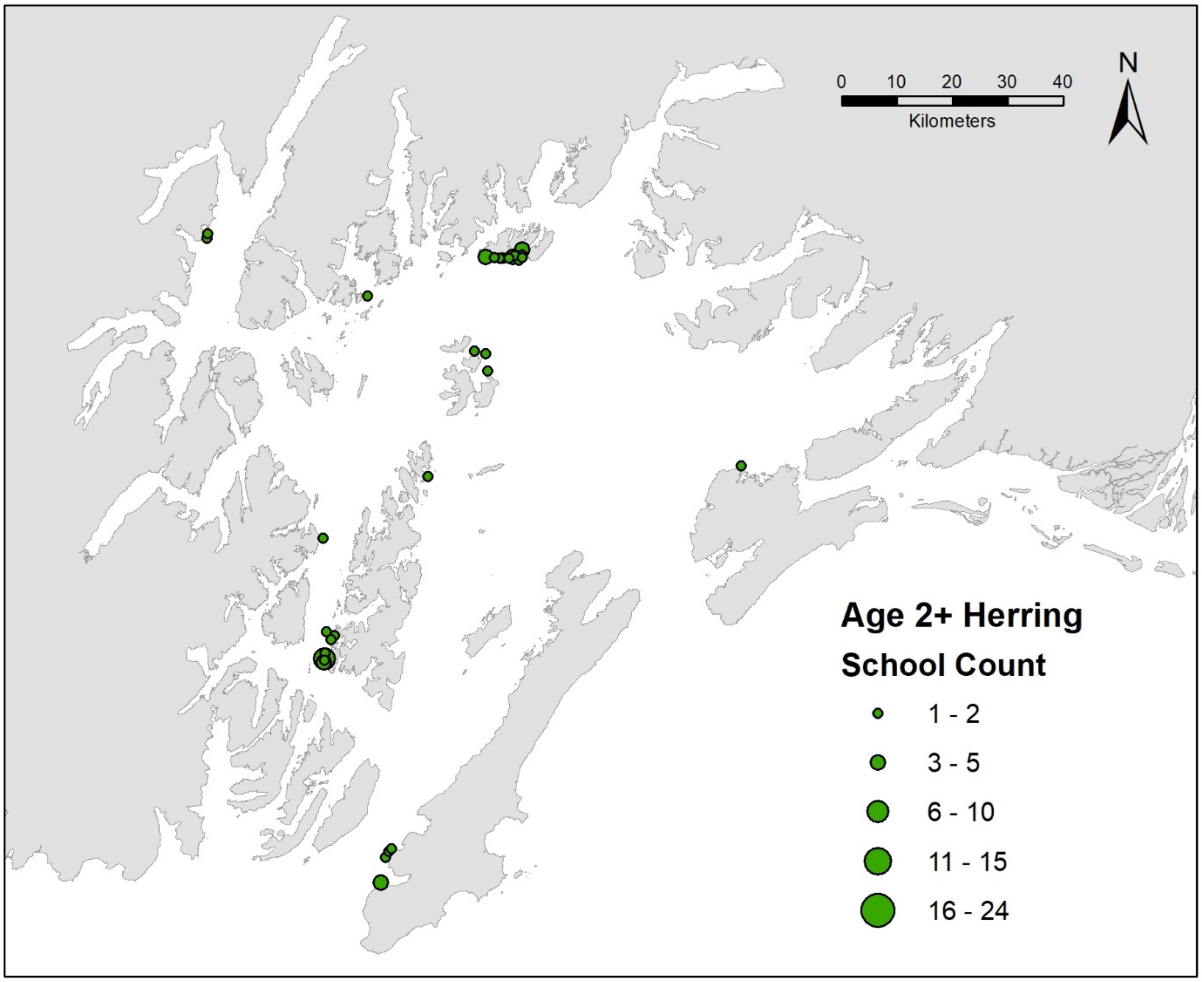

Figure 10. June 2021 age-2+ herring distribution.

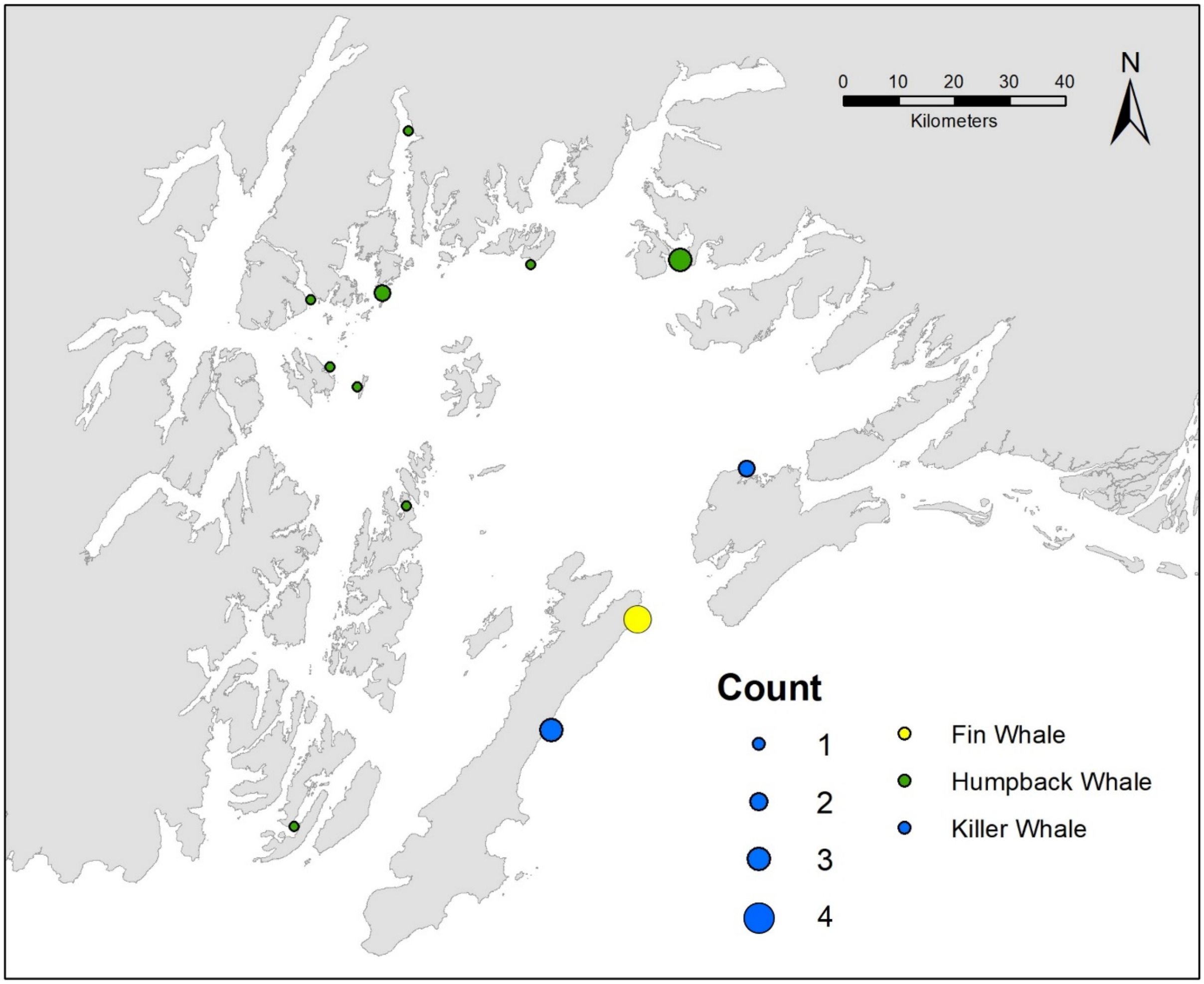

Figure 11. June 2021 number and type of whales observed. The size of the circle depicts the number of individual whales observed, while the color of the circle indicates whale type.

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