***Exxon Valdez* Oil Spill Trustee Council**

Long-Term Research and Monitoring, Mariculture, Education and Outreach

Annual Project Reporting Form

Project Number: 22120114-C

Project Title: Monitoring long-term changes in forage fish distribution, relative abundance, and body condition in Prince William Sound and the Northern Gulf of Alaska

Principal Investigator(s): Mayumi Arimitsu and John Piatt USGS-Alaska Science Center

Reporting Period: February 1, 2022 – January 31, 2023

Submission Date (Due March 1 immediately following the reporting period): March 8, 2023

Project Website: https://gulfwatchalaska.org/

Please check all the boxes that apply to the current reporting period.

☒ **Project progress is on schedule.**

☐ **Project progress is delayed.**

☐ **Budget reallocation request.**

☐ **Personnel changes.**

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1. Summary of Work Performed:

The Gulf Watch Alaska-Long Term Research and Monitoring (GWA-LTRM) program Forage Fish project has three main components including: 1) continuation of the longest time series on forage fish availability to seabirds in the Gulf of Alaska, i.e., a study that tracks the diets of adult and nestling seabirds at Middleton Island and is conducted in collaboration with Scott Hatch (Institute for Seabird Research and Conservation [ISRC]), 2) ship-based surveys including the Integrated Predator Prey (IPP) survey in Prince William Sound (PWS) conducted in collaboration with the humpback whale study (project 22120114-O, John Moran, National Oceanographic and Atmospheric Administration [NOAA], Lauren Wild, University of Alaska Southeast [UAS]) project, and 3) summer forage fish sampling - including aerial survey validation, forage fish sampling for condition in PWS, and juvenile salmon otolith analysis (Fig. 1). In this report we describe work conducted in 2022.

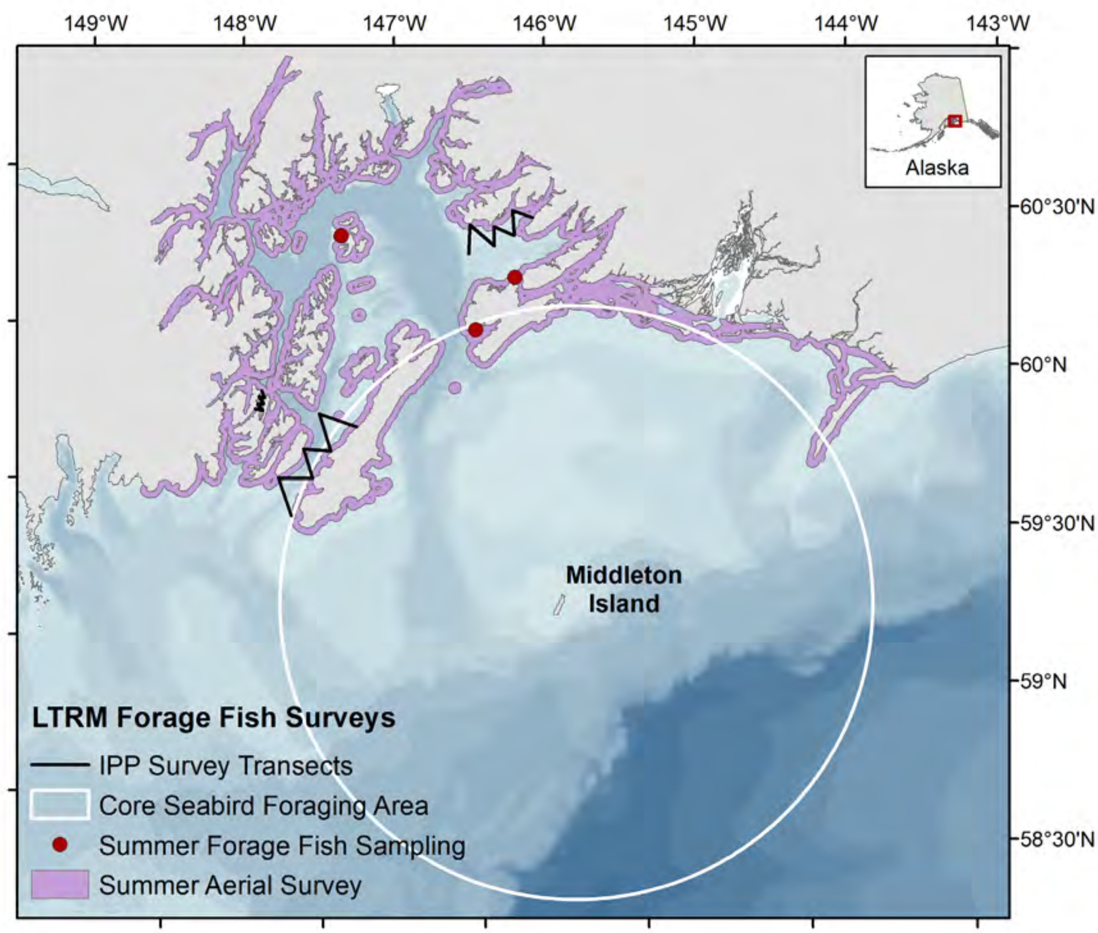

Figure 1. Distribution of Gulf Watch Alaska Long-Term Research and Monitoring (LTRM) seasonal forage fish survey effort in Prince William Sound and Middleton Island. Bathymetry is shown in blue with darker shades indicating deeper seafloor depth; IPP is the integrated predator prey survey.

Seabird Diets

Middleton Island seabird diet sampling was conducted by the ISRC scientific team according to schedule. We provide a brief summary of 2022 seabird diet results below, which were also reported in a contribution to NOAA's 2022 Gulf of Alaska Ecosystem Status Report.

Additionally, a more detailed report on findings from Middleton Island by Shannon Whelan and Scott Hatch is provided in Appendix A.

Seabird diet information from Middleton Island integrates forage fish species composition and availability over broad areas of the Northern Gulf of Alaska, i.e., across coastal, shelf, and slope regions (Hatch 2013, Arimitsu et al. 2021, Appendix A). An in-depth analysis of rhinoceros auklet (*Cerorhinca monocerata*) diets, supplemented with data from GPS tags attached to foraging birds, showed that the seabirds can detect prey species in foraging areas where other survey types have found the prey to be sparse or absent (Cunningham et al. 2018). Seabird diets, including those from Middleton, are useful indicators of spatial and interannual variability in forage species in Alaska (Sydeman et al. 2017, 2021, Piatt et al. 2018, Thompson et al. 2019).

Seabird diet samples at Middleton Island were collected from 8 April to 30 August 2022. This included a total of 1129 diet samples from black-legged kittiwakes (*Rissa tridactyla*) and 369 diet samples from rhinoceros auklets. In 2022, invertebrates (especially squid) and myctophids were important in the kittiwake diet during the pre-laying period (Apr-May), indicating extensive foraging off the continental shelf at that time (Fig. 2). To the extent the birds foraged over the shelf in spring, age-1 and older herring were the main fish prey in 2022. Capelin (*Mallotus villosus*) were scarce in kittiwake diets throughout the season, present in only trace amounts during spring and summer. Pacific sand lance (*Ammodytes hexapterus*) indices were moderate and relatively stable in kittiwake and auklet diets (Figs. 2 and 3). Pacific herring (*Clupea pallasii*) continued to be an important prey for Middleton seabirds in 2022. Hexagrammid species (kelp and rock greenlings [*Hexagrammos decagrammus* and *H. lagocephalus*, respectively], lingcod [*Ophiodon elongatus*], and Atka mackerel [*Pleurogrammus monopterygius*]) declined after a post-heatwave peak (2018-2020). Two species of interest, both included as "other fish" in Figs. 2 and 3 for 2022, were Pacific saury (*Cololabis saira*) and chub mackerel (*Scomber japonicus*). Both species are associated with warmer waters than usually found in the northern Gulf of Alaska. Sauries, taken by rhinoceros auklets late in chick-rearing, had previously been encountered as a single specimen in 2014, at the height of the marine heatwave. In 2022, sauries occurred in 9 of 15 samples collected 19-21 August. Chub mackerel, taken only by black-legged kittiwakes, also appeared in mid-August, with 15 occurrences among 51 kittiwake samples collected 13-30 August 2022. Previously, chub mackerels were encountered at Middleton only in 2019 (4 occurrences) and 2020 (15 occurrences).

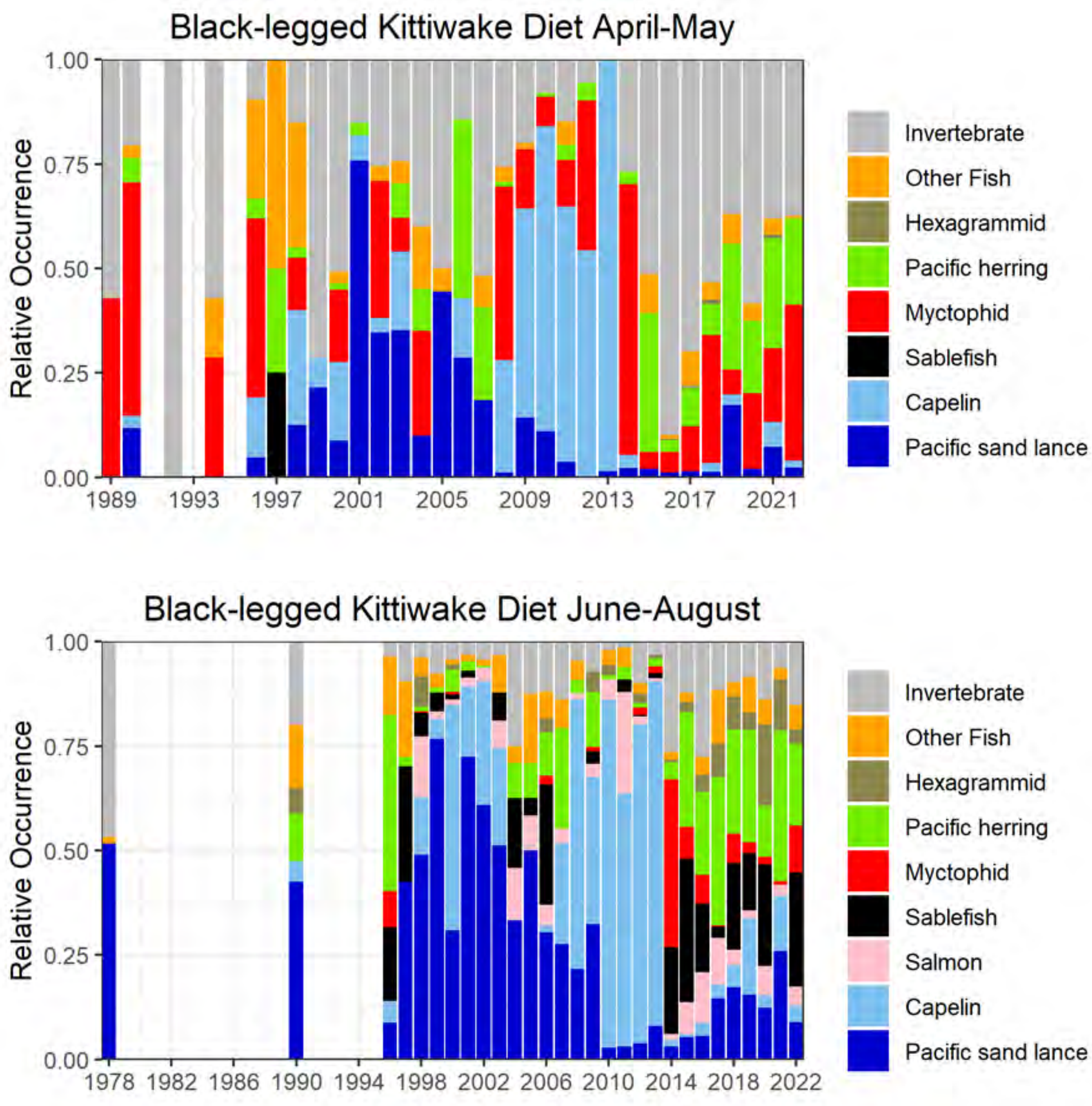

Figure 2. Interannual variation in diet composition of black-legged kittiwakes during spring (top) and summer(bottom) on Middleton Island.

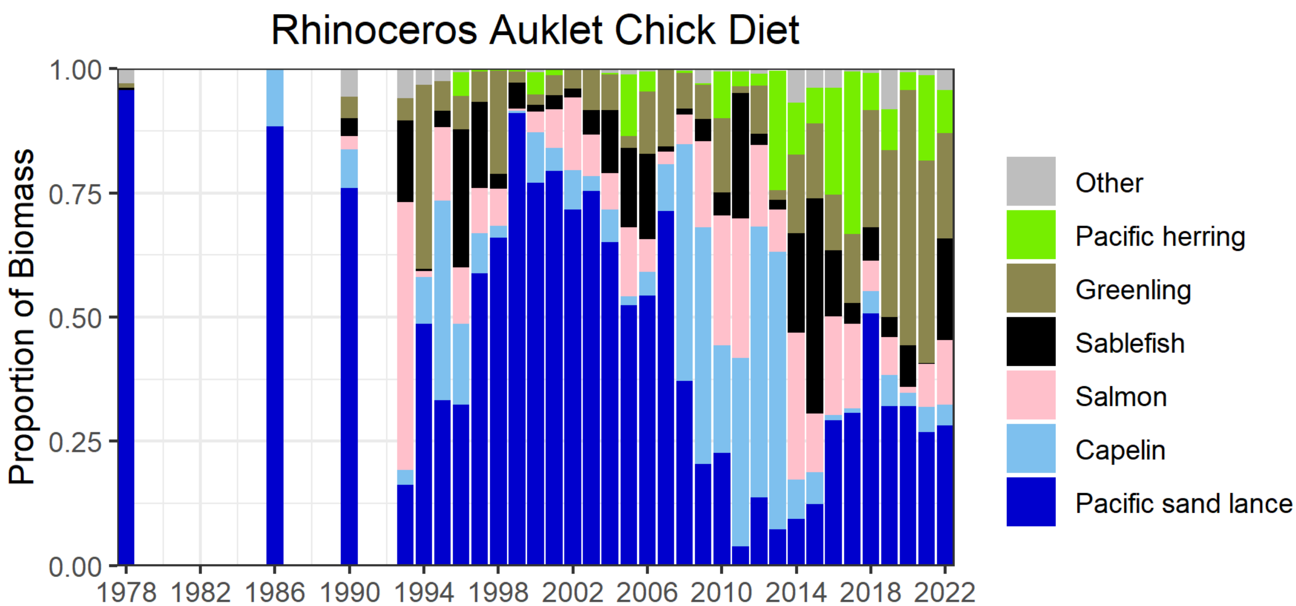

Figure 3. Interannual variation in rhinoceros auklet chick diets at Middleton Island.

NOAA Alaska Fishery Science Center has determined that age-0 sablefish (*Anoplopoma fimbria*) growth information from seabird diets at Middleton Island may provide a useful indicator of sablefish recruitment. NOAA has requested annual updates from US Geological Survey (USGS) on this sablefish data for use in their sablefish stock assessment efforts each fall. Sablefish made up 20% of the total biomass in rhinoceros auklet chick diet samples during summer 2022 (date range: Jun 22-Aug 21), which is well above the long-term mean (8.7%). The large proportion of sablefish represented in chick diets (n sablefish = 284, catch per unit effort = 0.77 fish/sample, frequency of occurrence = 0.35) during 2022 suggests sablefish were widely available within the ~100 km radius foraging area around Middleton Island.

Because the chick diet samples are collected over the course of a ~2-month chick-rearing season, an index of age-0 sablefish growth can be calculated using the relationship between mean length and Julian day for each year (Ordinary Least Squares regression: $F = 24.44$; $R^2 = 0.85$; $p < 0.001$). From this relationship we predicted size on the median date of sampling for all years (i.e., July 24) from the relationship $y = a + b*date$, where y is length in mm, a is the intercept, and b is the coefficient for each year. Annual anomalies of growth (change in size over time, mm d^{-1}) and size (length, mm) were calculated by subtracting the average growth and size indices across all years. For 2022, the average growth index was 1.54 mm/day, which was slightly below the long-term average of 1.88 mm/day. Predicted size on the median sample date was 107 mm, which was 6 mm above the long-term mean (Fig. 4).

Age-0 sablefish were larger in 2022 than they were in 2021, when predicted size (71 mm) on the median sampling date was 29 mm below the long-term (1978 – 2022) mean (Fig. 4) and only six individual sablefish were sampled by seabirds despite above average diet sampling effort (n samples = 306). It is unlikely that age-0 sablefish during summer 2021 were large enough to be targeted by seabirds as suitable prey for their chicks, which may explain why so few individuals were sampled that year. In 2019 the growth anomaly was high but size was only moderately above average because fish were small at the beginning of the sampling period and grew unusually fast that year (Fig. 4).

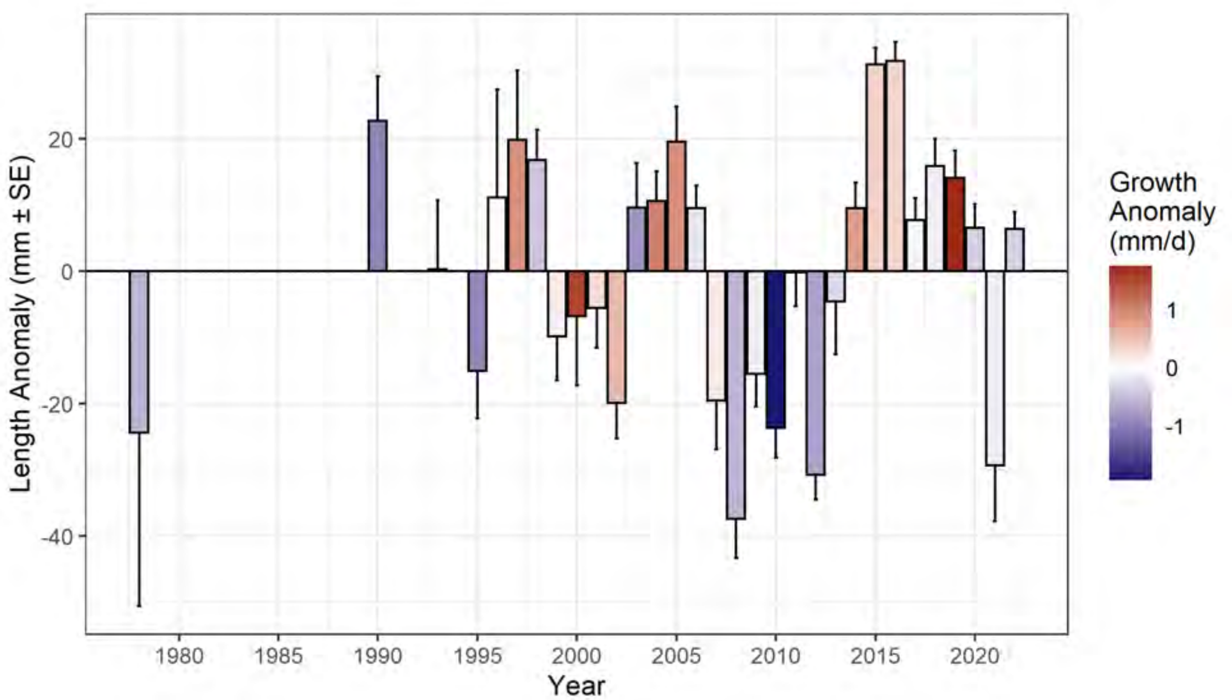

Figure 4. Interannual variability in predicted length anomaly (y-axis) and growth anomaly (color) for age-0 sablefish in seabird diets at Middleton Island, Alaska.

Fall Integrated Predator Prey Survey

The Fall IPP survey occurred on schedule during the second two weeks of September. We conducted acoustic transects, trawl, and habitat sampling in Bainbridge Passage, Montague Strait, and Port Gravina as planned. We also conducted focal follows of humpback whales whenever possible. We encountered notable concentrations of adult herring near three feeding humpback whales at Glacier Island on 21 Sep 2022. Macrozooplankton acoustic biomass indices for 2022 were highest of any year sampled between 2017 and 2022 (Fig. 6). Other datasets from this cruise are still being processed.

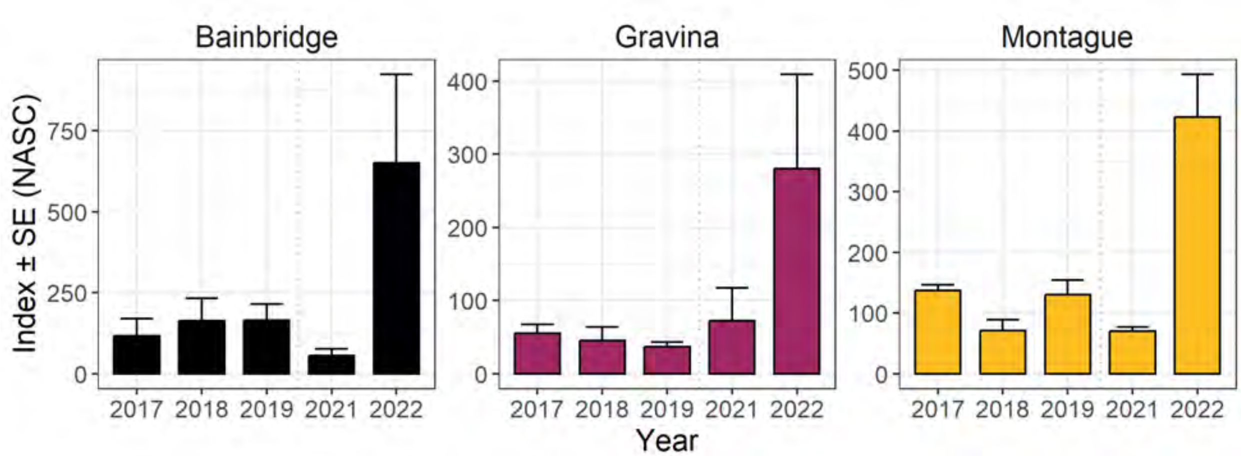

Figure 5. Interannual variability in macrozooplankton acoustic biomass indices during fall surveys in three regions (color) within Prince William Sound.

Summer Forage Fish Sampling

Validation surveys were conducted from Cordova, AK in support of the continuing GWA aerial forage fish surveys during the second week of June when aerial surveys were conducted by Scott Pegau and Mike Collins. A boat-based team departed from Cordova, AK to the general area identified beforehand by the aerial spotters. When both the aerial spotter plane and boat-based crew were on station, the spotter plane would locate a school of forage fish, make a visual identification of that school, and guide the boat-based crew to the school by giving verbal instructions over marine VHF radio. Once the skiff was over a school, the boat crew would identify fish either by catching fish with jigs, or by crewmembers seeing fish at the surface, or below the surface with a drop camera. The spotter plane identified three forage fish schools in Simpson Bay, five schools along Hawkins Island near Windy Bay, and three schools in Eaglek Bay that were validated with the help of Rob Campbell (PWSSC). The boat crews identified all but three of the schools observed by the aerial survey team, and all eight schools identified by the boat-based crew agreed with the identification provided by the spotter plane. In 2022, relative density of forage fish schools during the June aerial surveys was greatest in Port Gravina where observers noted large concentrations of small schools on a single day (Fig. 6).

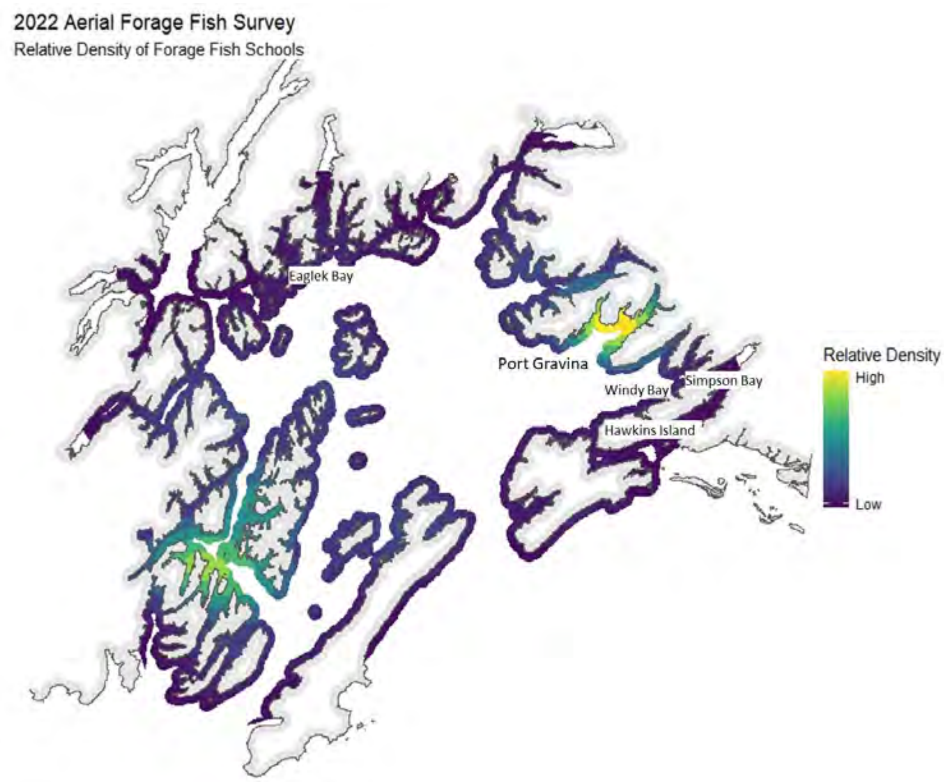

Figure 6. Weighted relative density of all forage fish schools observed June aerial surveys during 2022.

Summer Forage Fish Condition

We collected forage fish from the *R/V Alaskan Gyre* in July 2022. Pacific sand lance were collected with a small mesh purse seine at Cabin Bay for bomb calorimetry analysis. Although we visited Port Etches and looked for spawning capelin over several tidal cycles, we did not encounter any spawning capelin activity in the area. We also worked with John Johnson who runs the Nuuciq Spirit Camp, and contracted Rob Campbell (PWSSC) to search for spawning capelin in Port Etches in July but none were observed that summer. We have developed a flier to help crowd source information on spawning capelin from Port Etches and other locations around Alaska (Appendix B). Spawning capelin samples were obtained from Kodiak (May) and Sitka National Park (Sep) in 2022, and these samples will be subsampled to better understand variability in spawn timing and age structure in the Gulf of Alaska.

Juvenile Salmon Otoliths

In March 2022, juvenile salmon were removed from archived Rhinoceros auklet bill load samples stored in freezers at the NOAA Ted Stevens Marine Research Institute (Juneau, AK). Bill loads were collected from nesting rhinoceros auklets on Middleton Island between 2010 and 2021 and have been stored frozen. Otoliths were successfully recovered from 502 individual pink and chum salmon found in the bill load samples. Preparation and reading of otoliths follow procedures described in the Alaska department of fish and game's Cordova otolith lab procedure manual (ADFG 2017). Currently, we are in the process of mounting otoliths on microscope slides, polishing otoliths to expose thermal marks, and imaging otoliths to facilitate reading by a second observer. Next steps will include completing workup of the archived otoliths and inspecting for thermal marks and continuing on to juvenile salmon samples collected in the summer of 2022.

Acknowledgements

We thank Scott Hatch (ISRC), Shannon Whelan (ISRC), Dan Donnelly (USGS), and Caitlin Marsteller (USGS) for their dedicated work in the field and also for key contributions to this report including data collection, data management, graphics, and project summaries. We are grateful for the efforts of the captain of the *R/V Alaskan Gyre*, Paul Tate, and for help in the field from Sam Stark (USGS), Sarah Schoen (USGS), John Moran (NOAA), Bree Whiteveen (University of Alaska Fairbanks), and Rob Campbell (PWSSC). We thank the scientific team of the GWA-Long Term Research and Monitoring program for their expertise and resources in support of this work.

The research described in this report was supported by the *Exxon Valdez* Oil Spill Trustee Council. However, the findings and conclusions presented by the authors do not necessarily

reflect the views or position of the Trustee Council. Any use of trade, firm, or product names is for descriptive purposes and does not imply endorsement by the US Government.

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Sydeman, W. J., S. A. Thompson, J. F. Piatt, S. G. Zador, and M. W. Dorn. 2021. Integrating seabird dietary and groundfish stock assessment data: Can puffins predict pollock spawning stock biomass in the North Pacific? Fish and Fisheries 1–14.

Thompson, S. A., M. García-Reyes, W. J. Sydeman, M. L. Arimitsu, S. A. Hatch, and J. F. Piatt. 2019. Effects of ocean climate on the length and condition of forage fish in the Gulf of Alaska. Fisheries Oceanography 28:658–671.

2. Products:

Peer-reviewed publications:

Robinson, C. L. K., D. F. Bertram, H. Shannon, V. R. von Biela, W. Greentree, W. Duguid, and M. L. Arimitsu. In press. Reduction in overwinter body condition and size of Pacific sand lance has implications for piscivorous marine predators during marine heatwaves. Marine Ecology Progress Series.

Schoen, S., M. Arimitsu, C. Marsteller, and J. Piatt. 2022. Lingering impacts of the 2014-2016 northeast Pacific marine heatwave on seabird demography in Cook Inlet, Alaska. Marine Ecology Progress Series. https://doi.org/10.3354/meps14177

Thorson, J. T., M. L. Arimitsu, T. Levi, and G. H. Roffler. 2022. Diet analysis using generalized linear models derived from foraging processes using R package mvtweedie. Ecology e3637

Reports:

Arimitsu, M., and S. Hatch. 2022. Age-0 sablefish growth index time series from seabird diets. *In*: K. Shotwell, B. Fissel, and D. Hanselman. 2022. Appendix 3C Ecosystem and socioeconomic profile of the sablefish stock in Alaska. Report to the North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501. https://apps-afsc.fisheries.noaa.gov/refm/docs/2020/sablefish.pdf

Arimitsu, M., S. Schoen, J. Piatt, C. Marsteller, and G. Drew. 2021. Monitoring the recovery of seabirds and forage fish following a major ecosystem disruption in Lower Cook Inlet. Anchorage, Alaska: U.S. Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2021-031. 50 p. Anchorage, AK: U.S. Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2021-031. 50 p.

Popular articles:

None to report.

Conferences and workshops:

Arimitsu, M. 2022. Sentinels of change. Keynote Address. American Fisheries Society Alaska Chapter. March 2.

Arimitsu, M. 2022. Forage fish research and monitoring activities in the Northern Gulf of Alaska. Invited Oral Presentation. NOAA's Forage Species Workshop. Virtual. March 30.

Arimitsu, M., and J. Piatt. 2022. Shifting baselines as forage fish respond rapidly to climate change stressors in Alaska. Oral presentation. USGS Pacific Coast Diadromous and Marine Fish Symposium. September 21.

Arimitsu, M., D. Cushing, J. Durban, S. Hatch, R. Kaler, K. Kuletz, L. Labunski, C. Matkin, J. Moran, D. Olsen, S. Pegau, J. Piatt, J. Straley, and S. Whelan. 2023. Changes in marine predator and prey populations in the Northern Gulf of Alaska: Gulf Watch Alaska Pelagic update 2022. Poster. Alaska Marine Science Symposium. Anchorage, Alaska. January 24.

Donnelly, D., M. Arimitsu, S. Pegau, J. Piatt. 2022. Spatial and temporal variation in forage fish using broad-scale and cost-effective aerial surveys in Prince William Sound 2010-2021. Oral presentation. American Fisheries Society Alaska Chapter. March 2.

Donnelly, D., M. Arimitsu, S. Pegau, and J. Piatt. 2023. Detecting spatial and temporal variation in forage fish school densities using broad-scale aerial surveys. Poster. Alaska Marine Science Symposium. Anchorage, Alaska. January 24.

Marsteller, C., M. Arimitsu, J. Piatt, V. von Biela, and D. Donnelly. 2022. Pacific capelin age-at-spawning and energy content following a prolonged marine heatwave. Oral presentation. Capelin Symposium Bergen, Norway. October.

Marsteller, C., M. Arimitsu, J. Piatt, V. Von Biela, and D. Donnelly. 2023. Age-at-spawning and energy density of Pacific capelin across a regional gradient following NE Pacific marine heatwave. Poster. Alaska Marine Science Symposium. Anchorage, Alaska. January 24..

Murphy, H., and M. Arimitsu. 2022. Marine heatwaves and cold-spells: Persistent capelin stock collapses at opposite ends of the thermal optima. Keynote Address. Capelin Symposium Bergen, Norway. October.

Turner, L., C. Cunningham, and M. Arimitsu. 2022. Combining forage fish datasets to understand spatial and temporal patterns for management. Oral presentation. American Fisheries Society Alaska Chapter. March 2.

Turner, L., C. Cunningham, and M. Arimitsu. 2023. Combining predator diet and survey data to understand spatial and temporal patterns of forage fish in Alaska. Poster. Alaska Marine Science Symposium. Anchorage, Alaska. January 24.

Public presentations:

None to report.

Data and/or information products developed during the reporting period:

None to report.

Data sets and associated metadata:

Arimitsu, M. L., Piatt, J. F., Heflin, B. and Marsteller, C. E. 2017 Gulf Watch Alaska - Pelagic Ecosystems Forage Fish Component - data from Prince William Sound: distribution, abundance, and morphology of fish, zooplankton, and predators and oceanographic Conditions (ver. 3.0, March 2023): U.S. Geological Survey data release, https://doi.org/10.5066/F74J0C9Z.

Additional Products not listed above:

Arimitsu, M. L., Piatt, J. F., Thorson, J. T., Kuletz, K. J., Drew, G. S., Schoen, S. K., D. Cushing, C. Kroeger, and W. Sydeman. 2023. Joint spatiotemporal models to predict seabird densities at sea. Frontiers in Marine Science. doi: 10.3389/fmars.2023.1078042.

Crowell, A. L., and M. L. Arimitsu. In revision. Climate change and pulse migration: Intermittent Chugach Inuit occupation of glacial fiords on the Kenai Coast, Alaska. Frontiers in Environmental Archeology.

3. Coordination and Collaboration:

The Alaska SeaLife Center or Prince William Sound Science Center

We work closely with Scott Pegau at PWSSC on validation of aerial surveys, and with Mary Anne Bishop and Anne Schaefer on fall/winter marine bird data. We have also had recent planning discussions with Kristen Gorman (University of Alaska Fairbanks) and Pete Rand at PWSSC, as well as Jenni Morella (Alaska Department of Fish and Game) regarding juvenile salmon samples, otolith protocols, and opportunities for sharing information and resources across projects.

EVOSTC Long-Term Research and Monitoring Projects

Mayumi Arimitsu is on the GWA-LTRM science coordinating committee serving as lead for the GWA-LTRM pelagic component, which includes five monitoring projects including marine birds, humpback whales, killer whales, and forage fish. Her duties in this role have included leading science synthesis activities, coordinating pelagic program science products and information transfer, leading presentations at conferences and principal investigators meetings, and facilitating communications between the program management team and the pelagic component project leaders.

Under the pelagic component of the GWA-LTRM program, the forage fish project shares a research platform and common goals of the humpback whale project (22120114-O) also associated with the IPP surveys. Summer forage fish surveys and information regarding Middleton Island seabird diets also provide a means to understand trends in piscivorous marine birds (project 22120114-M).

EVOSTC Mariculture Projects

Although the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) mariculture projects are just getting up to speed, we engaged with this group at the GWA-LTRM principal investigator (PI) meetings in November 2022 and January 2023 and we are looking forward to working with the mariculture team as our sampling goals and geographic regions are complimentary.

EVOSTC Education and Outreach Projects

Although the EVOSTC education and outreach projects are just getting up to speed, we engaged with this group at the GWA-LTRM PI meetings in November 2022 and January 2023 and we are looking forward to working with them to expand our capacity for bringing our science to new audiences.

Individual EVOSTC Projects

We are working with the Northern Gulf of Alaska Long Term Ecological Research (NGA LTER) team (Russ Hopcroft, Kathy Kuletz, Dan Cushing) to assess connectivity between our collective ecosystem monitoring efforts. For example, this work will facilitate a better understanding of the relationship between seabird diets at Middleton and the distribution for forage fish in trawls that overlap in time and space with Middleton Island seabirds.

Trustee or Management Agencies

Data and fish samples gathered as part of the GWA-LTRM forage fish study will be used by NOAA National Marine Fisheries Science annual stock assessments (e.g., Bridget Ferriss and Stephani Zador Ecosystems Considerations Chapter to the Northwest Pacific Fisheries

Management Council, Kalei Shotwell et al. Sablefish Ecosystem and Socioeconomic Profile). We also provided forage fish and macrozooplankton samples for studies on harmful algal blooms (USGS study PIs: Sarah Schoen, Matt Smith, and Caroline van Hemert). The GWA forage fish work is also complimentary to a related USGS-Bureau of Ocean Energy Management study of forage fish and seabird trends in areas of oil and gas development in Cook Inlet (Arimitsu and Piatt, USGS). This continued coordination and collaboration with GWA-LTRM PIs and other researchers (Liz Labunski and Kathy Kuletz, US Fish and Wildlife Service; Kris Holderied, NOAA) in Cook Inlet and Kachemak Bay increases the scope of ecosystem monitoring in the Northern Gulf of Alaska.

Native and Local Communities

We are working with John Johnson (Chugach Alaska Corporation) regarding sample collection and spawning capelin observations in Port Etches. We look forward to increasing our engagement with native and local communities in the coming year. We have plans to present information on this work and related projects at the upcoming Chugach Regional Resources Commission Subsistence Memorial Gathering.

4. Response to EVOSTC Review, Recommendations and Comments:

May 2021 EVOSTC Science Panel Comment: This proposal seeks to continue a long-term study on forage fish in Prince William Sound (PWS) and nearby waters as one project in the multidisciplinary Gulf Watch Alaska Long-Term Monitoring Program: Pelagic Ecosystem Monitoring Component. The PIs identify an additional $4,825,000 in matching funds. The project is one of five projects in the Pelagic Ecosystem Monitoring Component, with the other projects focusing on killer whales, seabirds (2), and humpback whales; and it is a partner in the Integrated Predator Prey (IPP) project in the Pelagic Ecosystem Monitoring Component of the program. The objectives of this project are to continue to provide indices of forage fish abundance, including species composition and biomass within persistent predator foraging areas using shipboard hydroacoustic profiling, trawls, and other sampling methods, and by following foraging humpback whales; continue to provide indices of forage fish abundance/availability by sampling seabird diets on Middleton Island; continue to measure physical and biological parameters in PWS during integrated surveys using CTDs, nutrient sampling, and zooplankton sampling; continue to assess the quality of forage fish as prey, such as age, size, growth, and body condition by targeted sampling of sand lance and spawning capelin in two areas of predictable aggregations in PWS; and continue shipboard validation of the species composition of forage fish schools located during aerial surveys by a separate project.

The team proposes to analyze archived samples of juvenile pink and chum salmon (wild and hatchery fish) obtained from prey returned by rhinoceros auklets to provision chicks at Middleton Island since 2010 to produce a 21-year time series of body condition indices for these species. These analyses may help understand interannual variability in juvenile salmon growth in relation to environmental variability and competition between wild and hatchery stocks.

The proposers are very competent, have been highly productive, and have strong collaborations within the GWA LTRM Program and with other studies in the Gulf of Alaska. The results to date have been invaluable to the current understanding of ecosystem variability in PWS and the Gulf of Alaska, particularly as it is related to atmospheric forcing.

PI Response: *We thank the reviewers for these positive comments on our work thus far and look forward to continuing this work in the future should the GWA-LTRM program funding be awarded.*

May 2021 EVOSTC Science Panel Comment: While we agreed that this is a strong proposal by a reliable and productive team, we do have some questions about methodology that should be addressed.

1) It is not clear what will become of the fish they catch to validate the composition of schools located by the aerial surveys. Certainly, the fish will be identified to species. Will some of these samples also be measured and weighed, and aged using otoliths? If so, how many? Will the energy density of fish captured in June be calculated for comparison with capelin and sand lance collected for body condition analysis in July?

PI Response: *The main purpose of the aerial validation work is to identify species and age of the schools observed in the plane. The majority of schools encountered thus far on the aerial validation trips are herring. Although sand lance are also observed from the airplane, that species is typically verified by camera because sand lance are best collected with a purse seine or mid-water trawl, and neither of these methods are fast enough to deploy while the airplane is circling overhead. Capelin are rarely encountered during aerial surveys. Therefore, no, we will not catch fish during aerial validation efforts that could be compared to July sand lance or capelin samples.*

We clarified details of how the fish would be measured by adding the following text to the second paragraph on page 12 (Section 4, Project Design, B. Procedural and Scientific Methods):

Herring, which is the only species classified by age class during surveys, will be captured during aerial validation and identified to species, aged with scales, and measured for length and weight. Other schools will be verified to species at least, and any fish caught will be measured for length and weight. Approximately 10% of flight time (4-6 hours) will be dedicated to validation effort on an annual basis.

In the same paragraph we added a brief summary on the validation results from 2014-2021: A total of 80 schools were validated between 2014 and 2021 (average: 13 schools/year, range: 2 in 2020 due to low effort during the pandemic to 25 schools in 2021). Of those, 85% of schools were correctly classified by species, and 75% of herring schools were correctly classified by age-class. One school was incorrectly classified to species because it was determined to contain both age-0 herring and age-0 sand lance, and 8% of herring schools were incorrectly classified to age-class because of mixed-age schools (e.g., schools composed of age-1 and age-2+ fish).

<u>May 2021 EVOSTC Science Panel Comment:</u> 2) 200 capelin and 200 sand lance will be weighed, measured and frozen in the field during targeted sampling to determine body condition and later aged in the lab using otoliths. Energy density of a random sample of 10 aged fish of each species will be calculated. It is not clear if this will be a total of 10 fish of each species, or 10 each of known ages (e.g., 10 age 0, 10 age 1, etc.). Apparently, they will not be stratified by sex or date—does that matter? Will a sample of just 10 fish/summer be sufficient to characterize the condition of the capelin and sand lance populations in PWS?

<u>PI Response:</u> We have previously shown that total energy of age-1 sand lance were sensitive to the marine heatwave, while age-0 sand lance did not vary over time (von Biela et al. 2019). This is because age-0 fish typically put their energy towards somatic growth rather than lipid storage. For capelin, sex and maturity determine variability in lipid content (Montevecchi and Piatt 1984), so we will sample energy density of mature males for that species. In Section 4, Project Design, B. Procedural and Scientific Methods, paragraph 1 on page 13, we clarified that 10 age-1 sand lance and 10 mature male capelin will be assessed for energy density.

Montevecchi, W.A. and J. Piatt. 1984. Composition and energy contents of mature inshore spawning capelin (Mallotus villosus): Implications for seabird predators. Compend. Biochem. Physiol. 78A:15-20.

von Biela, V.R., M.L. Arimitsu, J.F. Piatt, B. Heflin, S.K. Schoen, J.L. Trowbridge, and C.M. Clawson. 2019. Extreme reduction in nutritional value of a key forage fish during the Pacific marine heatwave of 2014-2016. Marine Ecology Progress Series 613:171-182.

May 2021 EVOSTC Science Panel Comment: 3) A similar question was raised about sample sizes for the juvenile pink and chum salmon collected from provisioning auklets at Middleton Island. Will 10 wild and 10 hatchery fish collected over a period of a month or so be sufficient to characterize the annual condition of these species? The example of pink salmon growth (Fig. 8) shows that they do indeed grow in some years, but maybe not all years, and that in all years the data are very noisy and not compelling. Apparently, the fish in those samples were not stratified as wild or hatchery. How confident are the PIs that all of these fish, past and future, originated in PWS? In short, this addition to the bigger project requires significantly greater explanation and justification. It also would be helpful to know the cost of this new work to better evaluate it in the larger context of the budget.

PI Response: We agree that the new salmon project could be better justified and have added more details to this section. For example, we clarified the answer to the energy density sample size question in Section 4, Project Design, B. Procedural and Scientific Methods on page 14 with the following text:

Sample size of 10 fish is based on the sample size we use for similar analysis of sand lance (von Biela et al. 2019). Analyses of juvenile chum from Bristol Bay found relatively low CVs (3%) in energy density measures (Burrill et al. 2018), and therefore we anticipate that our sample size will be successful in detecting change over time.

It is true that this index of growth may not be as informative as we'd like, but we intended it to be a starting point and example of the data we already have in hand. To reduce the noisy data in the original version of Figure 8, we revised the analysis to use the mean of samples on each day as the response, which produced a much better fit (R2 = 0.53, p < 0.001). We will not know if these fish are hatchery or wild until we look for hatchery marks on the otoliths, but it's possible that stratifying could help improve the fit of the growth index. We clarified this and the specific issue of cost in Section 4, Project Design, B. Procedural and Scientific Methods, at the bottom of page 14 and top of page 15 by adding the following text: Because the samples are collected over the course of the chick rearing period (ca. 5- 6 weeks), existing information on size may be useful for understanding interannual variability in growth of juvenile salmon (Fig. 8), as previously documented in juvenile salmonids measured over time in southeast Alaska (Orsi and Ferguson

2017). We found the interaction between Julian day and year explain 53% of the variation in the mean length per day ($p < 0.001$). This relationship could be strengthened once we process otoliths to know which samples originate from wild vs. hatchery populations. The bulk of the costs for this part of the work (i.e., $34K in year 1 of the project) will support GS9 salary for lab work associated with processing 11 years of archived samples. After year 1 no extra costs are incurred to process annual samples in the lab as we are already planning similar work for other forage fish species. We are working closely with Pete Rand (PWSSC) and Jennifer Morella (ADF&G) to ensure that methods are complementary.

We also revised Figure 8 as follows: Figure 8. Juvenile pink salmon mean length by Julian day and year (OLS: $R_2 = 0.53$, $p < 0.001$). Samples were collected by seabirds at Middleton Island.

September 2021 EVOSTC Science Panel Comment: This proposal seeks continued funding over an additional ten years for the long-term study of forage fish in Prince William Sound (PWS) and nearby waters, as one project in the multidisciplinary Gulf Watch Alaska Long-Term Monitoring Program: Pelagic Ecosystem Monitoring Component. The objectives of this project are to provide indices of forage fish abundance, including species composition and biomass, within persistent predator-foraging areas using shipboard hydroacoustic profiling, trawls, and other sampling methods, and by following foraging humpback whales; continue to provide indices of forage fish abundance/availability by sampling seabird diets on Middleton Island; continue to measure physical and biological parameters in PWS during integrated surveys using CTDs, nutrient sampling, and zooplankton sampling; continue to assess the quality of forage fish as prey, such as age, size, growth, and body condition by targeted sampling of sand lance and spawning capelin in two areas of predictable aggregations in PWS; and continue shipboard validation of the species composition of forage fish schools located during aerial surveys by a separate project. The PIs are highly qualified to undertake this important work and have been extremely productive, and the proposal in general is strong.

We had concerns from the March 2021 review that were, overall, adequately addressed. We asked for clarification regarding the fate of the fish captured for validation of aerial survey observations. The PIs responded that herring only will be targeted, as sand lance and capelin are difficult to capture under the time constraints of the aerial survey. Results from prior validations for herring were summarized. We also asked for clarification of analyses to be conducted on sand lance and capelin collected during dedicated sampling. We also wondered if a total of ten individuals of each species would suffice as an index of the energy density of those populations.

The PIs clarified that only age-1 sand lance and adult male capelin would be analyzed. They addressed the other, more important, question of sample size by citing a prior publication of their group (von Biela et al. 2019) that appears to justify the sample size. Finally, we had a similar question about the justification for sample sizes of juvenile pink and chum salmon to be collected from seabirds at Middleton Island and analyzed for body condition – will ten fish of each species be sufficient to characterize condition when they are collected over a period of 5-6 weeks, particularly if as they say, they will stratify the samples between wild and hatchery origin? The response of the PIs was that this is the sample size they use for sand lance, and that salmon sampled from Bristol Bay had low CVs (3%) in energy density measures. This answer was not compelling, however, the cost for this aspect of the overall project is negligible and not a distraction from the larger goals.

PI Response: *We understand the EVOSTC science panel's concerns that the proposed samples size for juvenile salmon energy density (i.e., up to 40 fish per year) may be too small to adequately evaluate interannual variability in condition of hatchery vs. wild pink and chum salmon, particularly if samples are collected by seabirds during a ~6-week period in summer. To reduce variability within this relatively long sampling window, we will select juvenile salmon samples that are within 1 week of the median date of sampling (i.e., July 25) for bomb calorimetry analysis if samples are available to do so. If enough samples aren't available within the narrower timing window, we will incorporate Julian date into the model to assess differences among years. We agree with the science panel that the salmon otolith and bomb calorimetry analyses constitute a relatively minor aspect of the budget and study overall, but we hope that these juvenile salmon samples might also provide information valuable to other researchers studying salmon in the region. To that end, we are coordinating with Jenni Morella, Pete Rand, Kristen Gorman, Ron Heintz, and others to make sure methods are standardized and data are comparable.*

5. Budget:

***EXXON VALDEZ* OIL SPILL TRUSTEE COUNCIL**
PROJECT BUDGET PROPOSAL AND REPORTING FORM

Budget Category:		Proposed FY 22	Proposed FY 23	Proposed FY 24	Proposed FY 25	Proposed FY 26	5- YR TOTAL PROPOSED	ACTUAL CUMULATIVE
Personnel		$155,284	$126,623	$132,135	$137,923	$144,000	$695,965	$118,190
Travel		$14,492	$14,854	$15,226	$15,606	$15,996	$76,175	$15,229
Contractual		$106,800	$109,470	$112,207	$115,012	$117,887	$561,376	$102,250
Commodities		$32,000	$32,000	$32,000	$32,000	$32,000	$160,000	$17,760
Equipment		$10,650	$10,916	$11,189	$11,469	$11,756	$55,980	$10,718
Indirect Costs	Rate = 0%	$0	$0	$0	$0	$0	$0	$0
SUBTOTAL		$319,226	$293,864	$302,757	$312,010	$321,639	$1,549,495	$264,148
General Administration (9% of subtotal)		$28,730	$26,448	$27,248	$28,081	$28,947	$139,455	N/A
PROJECT TOTAL		$347,956	$320,312	$330,005	$340,091	$350,586	$1,688,950	
Other Resources (In-Kind Funds)		$482,500	$482,500	$482,500	$482,500	$482,500	$2,412,500	

COMMENTS:
Expenditures of personnel and commodities in FY22 were lower than anticipated, in part due to the differences in fiscal year periods between EVOSTC and USGS, and because less was spent on vessel charter and personnel costs were split between FY22 and FY20-21 budgets that were complicated by the COVID-19 pandemic. We anticipate that spending categories will ultimately reflect our proposed amounts as the project progresses. USGS will make a substantial in-kind contributions of salary for pelagic component lead and PIs, field equipment required to conduct the work. ISRC will also make substantial in-kind contributions for the use of facilities at Middleton Island. However, USGS funds included as in-kind or as contributions are included for planning purposes only and nothing contained in this proposal shall be construed as binding the USGS to expend in any one fiscal year any sum in excess of its appropriations or funding in excess or what it has received for the collaborative work outlined in this proposal or involving the Federal government in any obligation to pay money before funds have been appropriated for that purpose unless otherwise allowed by law.

FY22-26	**Project Number: 22120114-C** **Project Title: Forage Fish Monitoring** **Primary Investigator: Arimitsu & Piatt (USGS)**	**TRUSTEE AGENCY SUMMARY PAGE**

Expenditures of personnel and commodities in FY22 were lower than anticipated, in part due to the differences in fiscal year periods between EVOSTC and USGS, and because less was spent on vessel charter this year and personnel costs were split between FY22 and the FY20-21 budgets that were complicated by the COVID-19 pandemic. We anticipate that spending categories will align closely with our proposed amounts as the project progresses. USGS will make substantial in-kind contributions of salary for pelagic component lead and PIs (6 months GS-13 at 74K, 2 months GS-15 at 35K), and field equipment required to conduct the work including hydroacoustic echosounders (141K), oceanography sampling equipment (55K), a trawl depth monitor system (21.5K), small boats (20K), a marine scale (10K), and net sampling and camera gear (6K) for forage fish work in Prince William Sound. ISRC will also make substantial in-kind contributions for the use of facilities (120K) at Middleton Island. However, USGS Funds included as in-kind or as contributions are included for planning purposes only and nothing contained in this proposal shall be construed as binding the USGS to expend in any one fiscal year any sum in excess of its appropriations or funding in excess or what it has received for the collaborative work outlined in this proposal or involving the Federal government in any obligation to pay money before funds have been appropriated for that purpose unless otherwise allowed by law.

Appendix A. Middleton Field Report

BACKGROUND

The Middleton Island Marine Biological Station is a facility owned and managed by the Institute for Seabird Research and Conservation (ISRC) in support of long-term seabird research and monitoring in the Gulf of Alaska. ISRC partners with academic organisations to continue long-term monitoring of the Middleton Island seabird community, conduct fundamental and applied research, and train the next generation of scientists. ISRC also executes field protocols for, and shares data with, organisations that are not able to visit the island.

In 2017, ISRC entered into a cooperative agreement with the U.S. Geological Survey, Alaska Science Center, to continue field studies of seabirds on Middleton Island as part of GulfWatch Alaska. The latter program, funded by the Exxon-Valdez Oil Spill Trustee Council, is intended to uncover and monitor natural and anthropogenic factors affecting ecosystem functioning in the Gulf of Alaska and Prince William Sound. The particular contribution of Middleton seabird monitoring is to quantify dietary shifts in predator species, especially black-legged kittiwakes and rhinoceros auklets, as indicators of forage fish dynamics in the region.

THE FIELD TEAM

In 2022, the Middleton research station was occupied by members of the field crew from 8 April through 15 August.

Dr. Scott Hatch
Dr. Marie Claire Gatt[4]
Don-Jean Léandri-Breton[3]
Chinatsu Nakajima[2]
Stella Solasz
Shannon Whelan[3] (Camp Leader)
Sierra Pete[2] (Camp Leader)
Gabby Dennis
Haley Gee
David Jadhon
Lauren Jackson[1]
Alexandre Turmaine[1]
Léo Marcouillier[2]
Éliane Miranda[2]
Dr. Shannon Leone Fowler[4]
Dr. Kyle Elliott
Dr. Morgan Benowitz-Fredericks
Mo Heim
Martha Hatch

[1]BSc honours student *[2]MSc student* *[3]PhD student* *[4]Post-doctoral fellow*

RESEARCH ACTIVITIES

Special lines of research in 2022 included:

- GPS-tagging to identify the principal foraging areas used by black-legged kittiwakes during pre-laying, incubation, and chick-rearing
- Video loggers to understand fine-scale foraging behaviour of kittiwakes
- Heart rate loggers and doubly labelled water to understand kittiwake energetics
- PIT-tagging and RFID monitoring of rhinoceros auklets breeding in artificial burrows to quantify adult survival and behaviour
- GPS-tagging to identify foraging areas and sub-colony partitioning of rhinoceros auklets during chick rearing
- GPS-accelerometer-depth tagging to continue long-term monitoring of pelagic cormorant movement during chick-rearing
- Geolocator-tagging of kittiwakes, rhinoceros auklets, and tufted puffins to understand migration, non-breeding behaviour, carryover effects, and ecotoxicology
- Blood sampling of various seabird species to understand physiology, contaminants, isotopes, oxidative stress, genetics, etc.
- Genetic sampling of sablefish found in the Middleton seabird diet
- Various other sampling efforts to understand contaminants, isotopes, and animal behaviour in the Middleton seabird community

These projects were collaborations with many organisations, including McGill University, Bucknell University, University of Tsukuba, University of Milan, University of Roehampton, Centre national de la recherche scientifique (CNRS), USGS, NOAA, and Environment and Climate Change Canada.

NOTEWORTHY EVENTS

Another seabird die-off affected primarily kittiwakes


Photo: Mo Heim

Another seabird die-off occurred from mid-June to mid-July 2022, following the die-off observed in 2021. Kittiwakes were the primary species affected, though glaucous-winged gulls and duck species were also observed behaving erratically and found dead during the same period. Fewer individuals were affected during the 2022 die-off, relative to the 2021 event. Symptoms followed what was observed during the 2021 die-off, which was tentatively attributed to avian botulism. Although symptoms were not consistent with avian influenza, we knew that the disease was affecting many North American avian populations so the field team immediately sampled affected birds for avian influenza (all samples tested negative). The team also collected mud samples from freshwater ponds at various locations around the island; one of these samples tested positive for *Clostridium* *botulinum* toxin type C. The National Wildlife Health Center received several carcasses but were not able to determine the cause of death.

Thank you to the US Fish and Wildlife Service, University of Alaska – Fairbanks, University of Alaska – Anchorage, Alaska Division of Environmental Health, and the National Wildlife Health Center for your collaboration during and after the die-off.

First record of Leach's storm petrel breeding on the island

Photo: Chinatsu Nakajima

Leach's storm petrels are occasionally heard and seen by field team members on the island but were not expected to breed on the island due to high densities of introduced European rabbits.

Following the chance discovery of an adult in a burrow during 2018 and the location of a potential breeding colony in 2021, the 2022 team looked for and monitored the area for potential burrows. At long last, an incubating Leach's storm petrel was located in June and that same burrow contained a healthy chick in July.

Thanks to 2018-2022 field team members for their hard work and enthusiasm to discover a new breeding species on Middleton Island!

Feasibility assessment for removal of introduced European rabbits: eradication is possible

Photos: Island Conservation

In late August 2021, following the regular seabird monitoring field season, representatives of Island Conservation (Mele Khalsa, Tommy Hall), USDA APHIS WS (Spencer Atkinson) and ISRC (Scott Hatch, Shannon Whelan) visited the island to assess the feasibility of rabbit eradication. Introduced rabbits were found in every habitat type on the island, including islets separated from the main island by sand bars.

The final report prepared by Island Conservation and USDA APHIS WS indicated that removal of the introduced rabbits is feasible through hunting and trapping methods, but would require multi-year, year-round effort to complete. There are no immediate plans to conduct an eradication and to do so would require extensive consultation and funding. However, the feasibility assessment is an important first step to restoration of Middleton Island.

ANNOUNCEMENTS

- ***Congratulations to Jenna Schlener for completing her MSc on Middleton kittiwakes!*** Jenna completed her thesis, entitled *Consequences of individual variation in foraging behaviour in black-legged kittiwakes,* through McGill University in 2022. Jenna now works as the Seabird Research Coordinator at the Alaska SeaLife Center.
- ***ISRC has secured funding to restore more kittiwake nesting sites.*** The funding will be used to build additional artificial cliffs on the former US Air Force buildings. With continued erosion of natural cliffs around the island, the population is currently nest-site limited. This project is an important step to restore the breeding population and compensate for historic impacts of oil spills on seabirds in the North Pacific.

BLACK-LEGGED KITTIWAKES

Productivity

Since 1996, a long-term food-supplementation experiment has continued to supply an unlimited number of fish to ~72 breeding pairs of kittiwakes throughout each breeding seas. This experiment has yielded a diverse set of publications about how food availability affects productivity and more (e.g., life-history, behaviour, energetics).

Among fed pairs on the tower in 2022 (n = 72), production was 1.01 fledglings/nest, whereas 356 unfed pairs produced 0.65 chicks/nest (Figure 1; Table S1). That comparison of breeding performance in fed and unfed kittiwake pairs on Middleton furnishes a powerful indicator of ocean conditions, for the simple reason that kittiwakes prefer to feed themselves. In poor years, characterized by positive PDO, low capelin availability, and poor kittiwake breeding performance, the difference between fed and unfed treatment groups is accentuated, and vice versa (Figure 2; Table S2).

The difference between food-treatment and control groups in 2022 indicates improving foraging conditions for surface-feeding kittiwakes relative to 2021 and since a sharp decline in productive circa 2014. This closing of the gap between treatments confirms a decisive end to a period of poor breeding performance of kittiwakes that began with the 2014-2016 marine heatwave in the northeast Pacific.

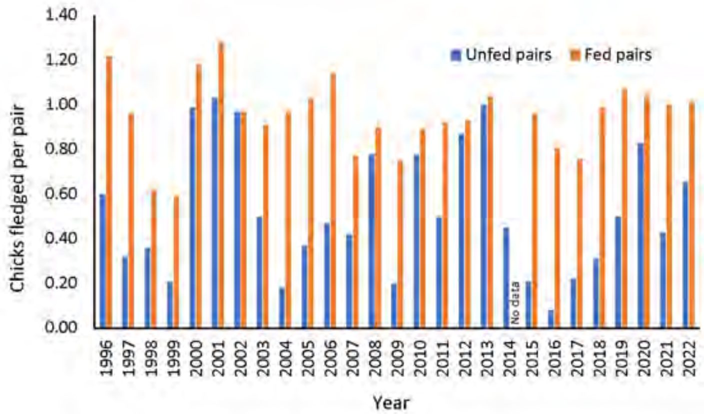


Figure 1. Annual production of kittiwake chicks from pairs breeding on the Middleton Island radar tower. Lower panel compares the breeding performance of kittiwakes subjected to supplemental feeding (ad libitum) at the nest site with control samples of naturally foraging pairs.

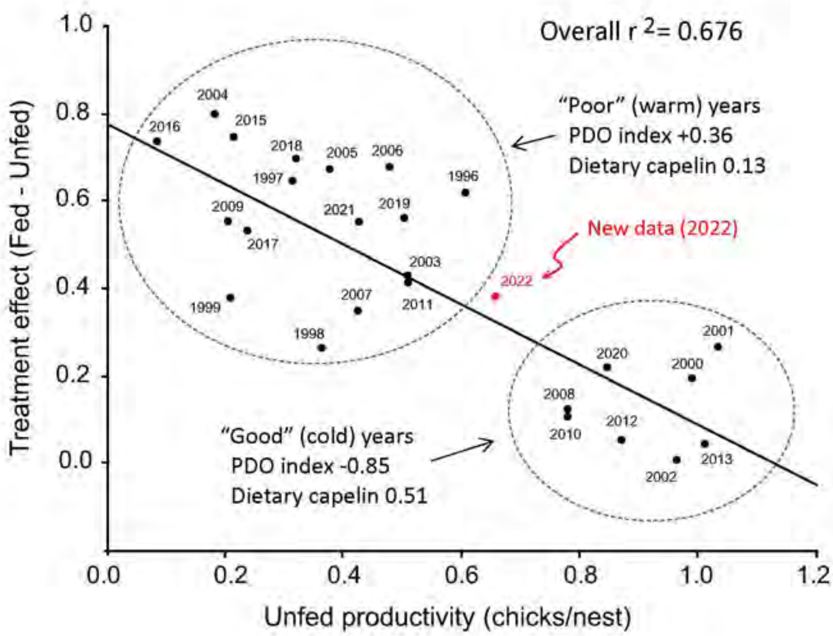


Figure 2. Effect of supplemental food treatment on kittiwake breeding performance on Middleton Island in 26 years since 1996. Productivity of unfed pairs is a proxy for quality of the foraging environment. Treatment effect is the difference in

productivity between supplementally fed and unfed pairs. "Bad" years are characterized by warm ocean conditions (PDO index June-August), a low proportion of capelin in the diet, and a marked effect of food treatment on kittiwake production. "Good" years have cool ocean conditions, a higher proportion of dietary capelin, and reduced or no difference in breeding performance of fed and unfed pairs.

Other work

A multi-year carryover effects project (collaboration between University of Tsukuba, University of Milan, and McGill University) entered its second year. Geolocators and physiological samples were retrieved from over 200 kittiwakes, which will reveal non-breeding movements and much more.

Lauren Jackson and Alex Turmaine conducted BSc honours research projects throughout the summer and contributed another year to the long-term kittiwake tracking and physiology datasets. Kittiwakes used a diverse set of foraging locations, but many individuals continued to travel long distances to forage close to Prince William Sound and the Copper River Delta (Figure 3).

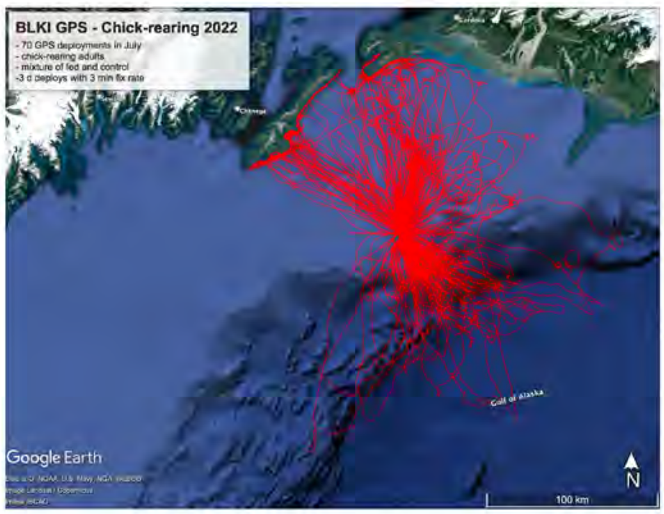


Figure 3. GPS-tagged black-legged kittiwakes used a diverse set of foraging areas during chick-rearing in 2022.

RHINOCEROS AUKLETS

Productivity

In general, rhinoceros auklets have consistently high breeding success on Middleton (Figure 4), and their population is increasing (last estimate ~20,000 individuals). At 0.66 chicks/egg laid (Table S3), production in 2022 was consistent with the long-term average of 0.63 (n = 25 years, 1997-2022).

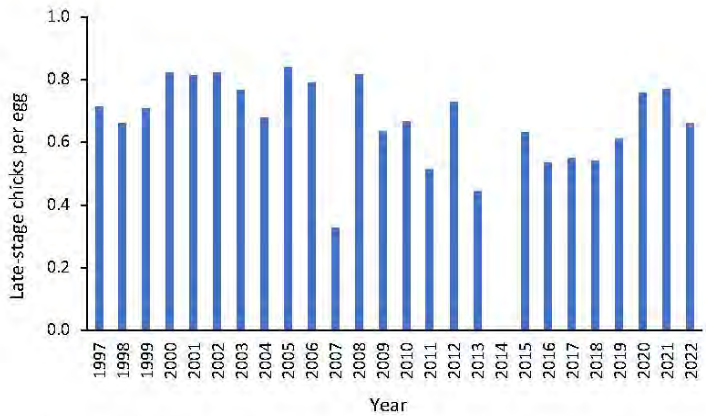


Figure 4. Annual production of rhinoceros auklet chicks from pairs monitored in natural burrow nests on Middleton Island.

Other work

Photo: Hannes Schraft

Since 2017, ISRC has installed 121 artificial nestboxes for rhinoceros auklets to facilitate monitoring and research. In 2022, Léo Marcouillier (University of Boulogne) and Éliane Miranda (McGill University) successfully piloted an RFID system developed by David Fifield (Environment and Climate Change Canada) on a subset of birds breeding in the artificial burrows.

Chinatsu Nakajima (University of Tsukuba) successfully deployed and retrieved geolocators and GPS devices to understand year-round movement behaviour and sub-colony partitioning of the Middleton auklets.

PELAGIC CORMORANTS

Productivity

Since 2002, pelagic cormorants have been monitored in the tower colony. Numbers (31-145 nest-building pairs) have varied greatly (less so in recent years), whereas breeding success (from ~0.45 to 2.0 fledglings per nest built) is relatively constant (Figure 5, Table S4). Production in 2022 (1.9 fledglings/nest) was greater than the long-term average of 1.2 fledglings/nest. On average, about 90 nests are constructed annually by cormorants on the tower, versus 60 nests in 2022. Thorough banding of adults and chicks done annually on the tower will support a future analysis and report of cormorant survivorship spanning the years since 2002.

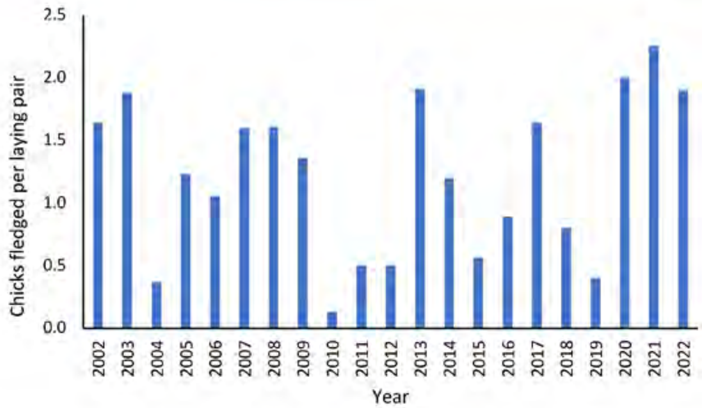


Figure 5. Annual production of pelagic cormorant chicks from pairs monitored on the Middleton Island radar tower.

Other work

A subset of pelagic cormorants was tagged with GPS-accelerometer-depth loggers during chick rearing to monitor foraging behaviour. Telemetry studies on Middleton cormorants in began in 2006 and ISRC has now accrued 9 years of movement data for this species. In 2022, tracked individuals used foraging areas in various locations around the island (Figure 6), while in several other years foraging was concentrated at the northern end of the island.

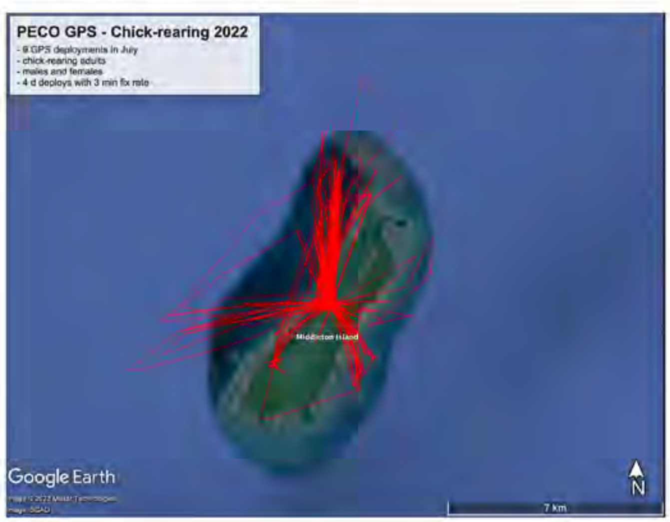


Figure 6. GPS-tagged pelagic cormorants used foraging areas north, east, and west of the island during chick-rearing in 2022.

TUFTED PUFFINS

Productivity

For 5 years prior to 2015, the virtual absence of fish-carrying adults seen around the island was a clear indication of scant chick production by tufted puffins on Middleton. Since that period, tufted puffin productivity has improved and 2022 was an exceptional year in particular: monitored burrows produced 0.54 chicks per egg in 2022 (Table S3).

FORAGE FISH

Black-legged kittiwake diet

In most years since 1996, kittiwake diet samples (regurgitations) have been collected from adults and/or nestlings on the tower from April or May through August (Table S5). On average, Middleton kittiwakes take about equal amounts of Pacific sand lance, capelin, and invertebrates, and lesser amounts of herring, sablefish, salmon, and myctophids, depending on stage of the season (Figure 7). A salient finding during the 2014-2016 marine heatwave was the virtual disappearance of capelin from the kittiwake diet on Middleton, following 6 prior years when capelin were abundant. Sampling in 2022 yielded 1129 kittiwake diet samples—the largest sample for kittiwakes throughout the time series (Table S5).

Rhinoceros auklet diet

Rhinoceros auklet diet samples are collected via bill-loads from chick-provisioning adults, usually once or twice a week from early July through early or mid-August. Overall, the auklet diet at Middleton is composed largely of a few species of forage fish, especially Pacific sand lance, capelin, salmon (including both pink and chum), and sablefish, in that order of importance (Figure 7). The years 2014-2017 saw significant breaks from the past, with historically dominant species—sand lance and capelin—being largely supplanted by sablefish, salmon, and herring. Sampling in 2022 yielded 369 auklet bill loads and ground samples, comprising over 11 kg of auklet prey in total (Table S6).

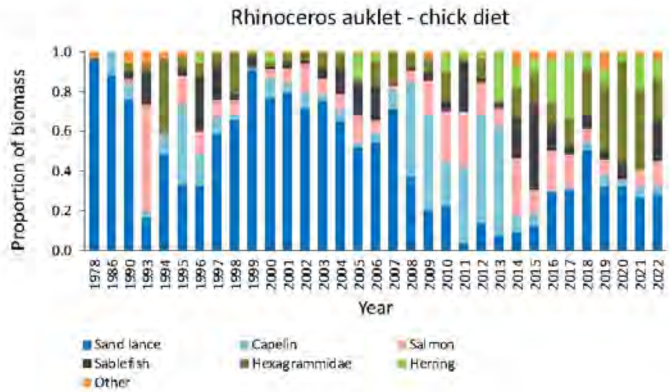
Overall diet patterns

The time series for kittiwakes and rhinoceros auklets since 1978 (Figure 7) shows general agreement vis-à-vis the decline of sand lance and, after 2008, the emergence of capelin as a dominant forage species. However, in several recent years, when neither sand lance nor capelin were prevalent, the diets of surface-feeding kittiwakes and diving auklets diverged substantially.

Following their notable absence in 2021, age-0 sablefish showed a strong comeback in 2022, comprising 20% of prey biomass in rhinoceros auklets and 27% relative occurrence in kittiwakes

(Figure 7). Pacific herring continued to be an important prey for Middleton seabirds in 2022. Hexagrammid species (kelp and rock greenlings, lingcod, and Atka mackerel) declined after a post-heatwave peak (2018-2020). Capelin remained infrequent, relative to pre-heatwave years, despite a shift towards negative Pacific Decadal Oscillation Index values (since ~January 2020) associated with relatively cold surface conditions in the Gulf of Alaska.

Two species of interest, both included as "other fish" in Figure 7 for 2022, were Pacific saury (*Cololabis saira*) and chub mackerel (*Scomber japonicus*). Both species are generally associated with warmer water than normally occurs in the northern Gulf of Alaska. Sauries, taken by rhinoceros auklets late in chick-rearing, had previously been encountered as a single specimen in 2014, at the height of the marine heatwave. In 2022, sauries occurred in 9 of 15 samples collected 19-21 August. Chub mackerel, taken only by black-legged kittiwakes, also appeared in mid August, with 15 occurrences among 51 kittiwake samples collected 13-30 August 2022. Previously, chub mackerels were encountered at Middleton only in 2019 (4 occurrences) and 2020 (15 occurrences).



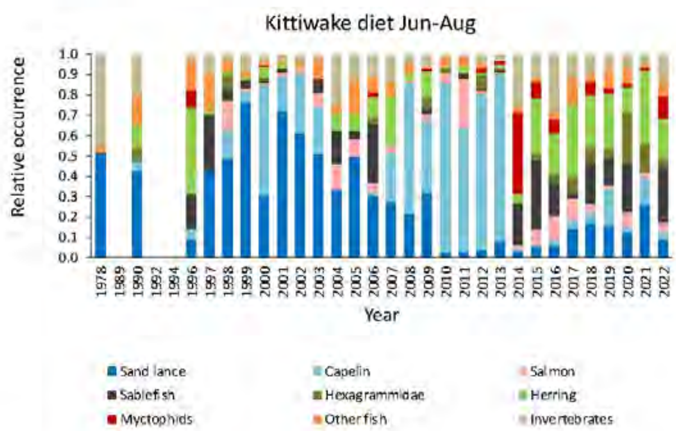


Figure 7. Interannual variation in diet composition of chick-rearing rhinoceros auklets on Middleton Island, 1978 to 2022 (upper panel), with a similar time series for black-legged kittiwakes (lower panel) for comparison.

RECENT PUBLICATIONS

2022

Benowitz-Fredericks, Z. M., Lacey, L. M., Whelan, S., Will, A. P., Hatch, S. A., & Kitaysky, A. S. (2022). Telomere length correlates with physiological and behavioural responses of a long-lived seabird to an ecologically relevant challenge. **Proceedings of the Royal Society B**, 289(1978), 20220139.

Kahane-Rapport, S. R., Whelan, S., Ammendolia, J., Hatch, S. A., Elliott, K. H., & Jacobs, S. (2022). Food supply and individual quality influence seabird energy expenditure and reproductive success. **Oecologia**, 199(2), 367-376.

Krishnan, K., Garde, B., Bennison, A., Cole, N. C., Cole, E. L., Darby, J., ... & Shepard, E. L. (2022). The role of wingbeat frequency and amplitude in flight power. **Journal of the Royal Society Interface**, 19(193), 20220168.

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FUNDERS

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Bucknell UNIVERSITY

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筑波大学 University of Tsukuba

UNIVERSITÀ DEGLI STUDI DI MILANO

ACKNOWLEDGEMENTS

Special thanks to Gulf Watch Alaska principal investigators John Piatt and Yumi Arimitsu for administering an ongoing Cooperative Agreement between the U.S. Geological Survey and ISRC and securing vital financial support through the EVOS Trustee Council and USGS. As always, the project benefitted from favors coming from many quarters and we are especially grateful to our friends and island neighbors from the Federal Aviation Administration.

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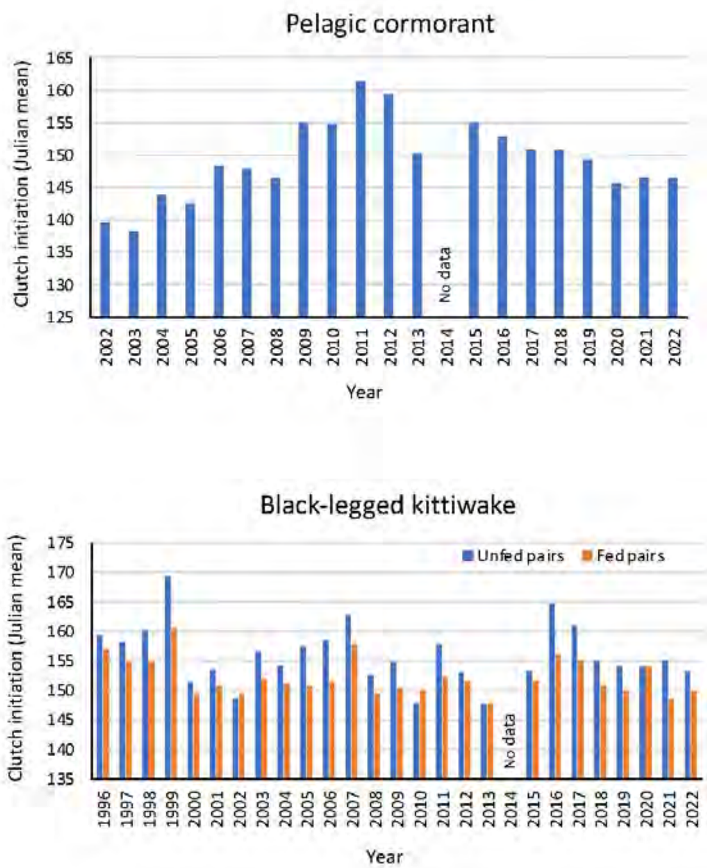

Figure S1. Breeding chronology of pelagic cormorants and black-legged kittiwakes on Middleton Island. On average, food-supplemented kittiwake pairs breed 4 days earlier than controls (lower panel).

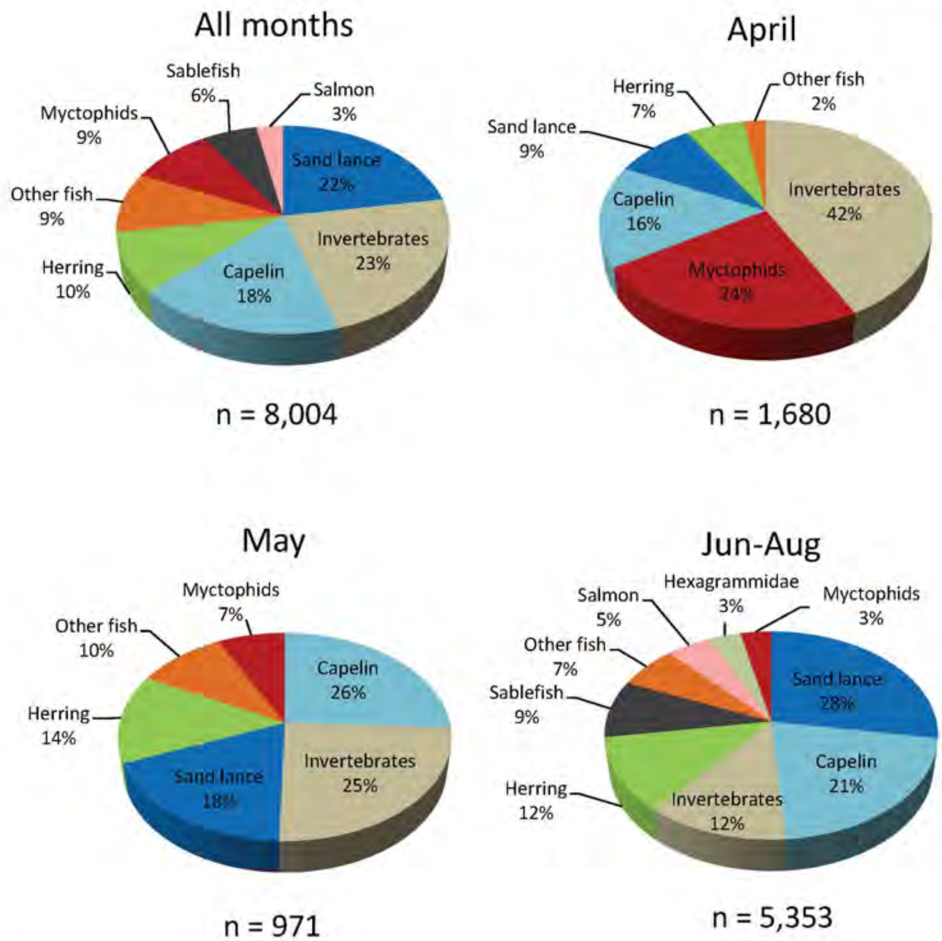

Figure S2. Overall composition of food samples obtained from black-legged kittiwakes (relative occurrence, April – August) on Middleton Island from 1978 to 2022.

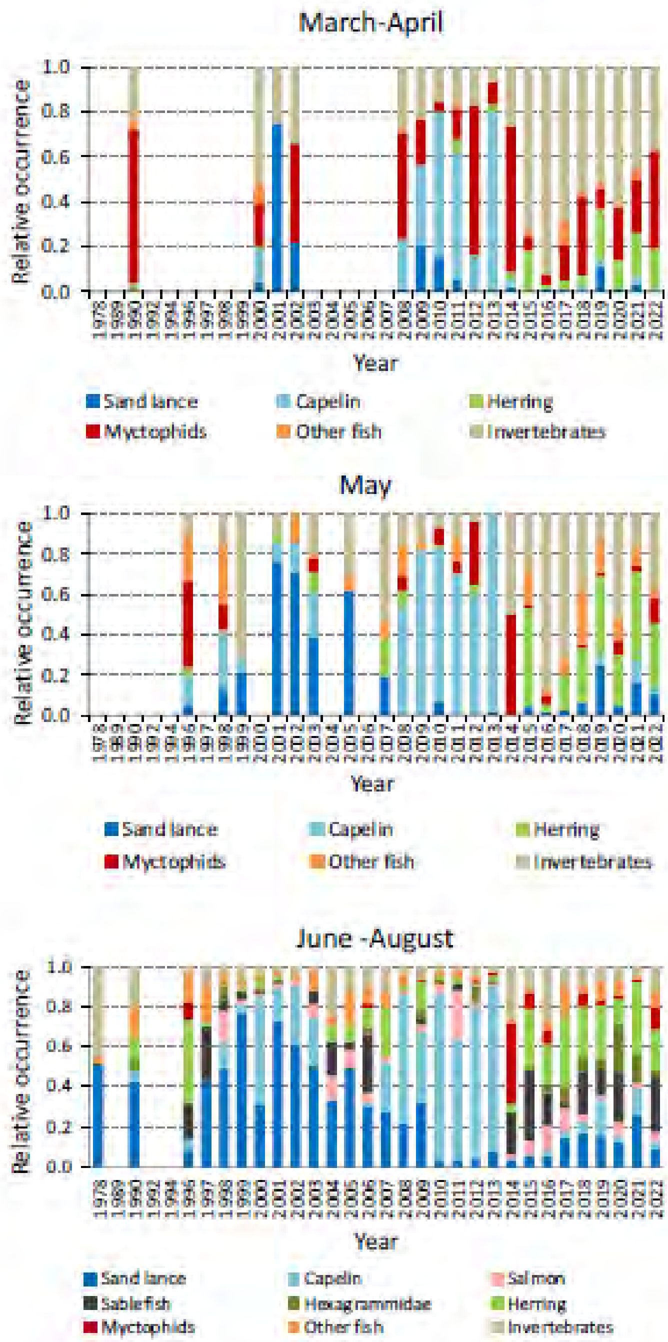

Figure S3. Interannual variation in kittiwake diet composition at three stages of breeding on Middleton Island, 1978 to 2022.

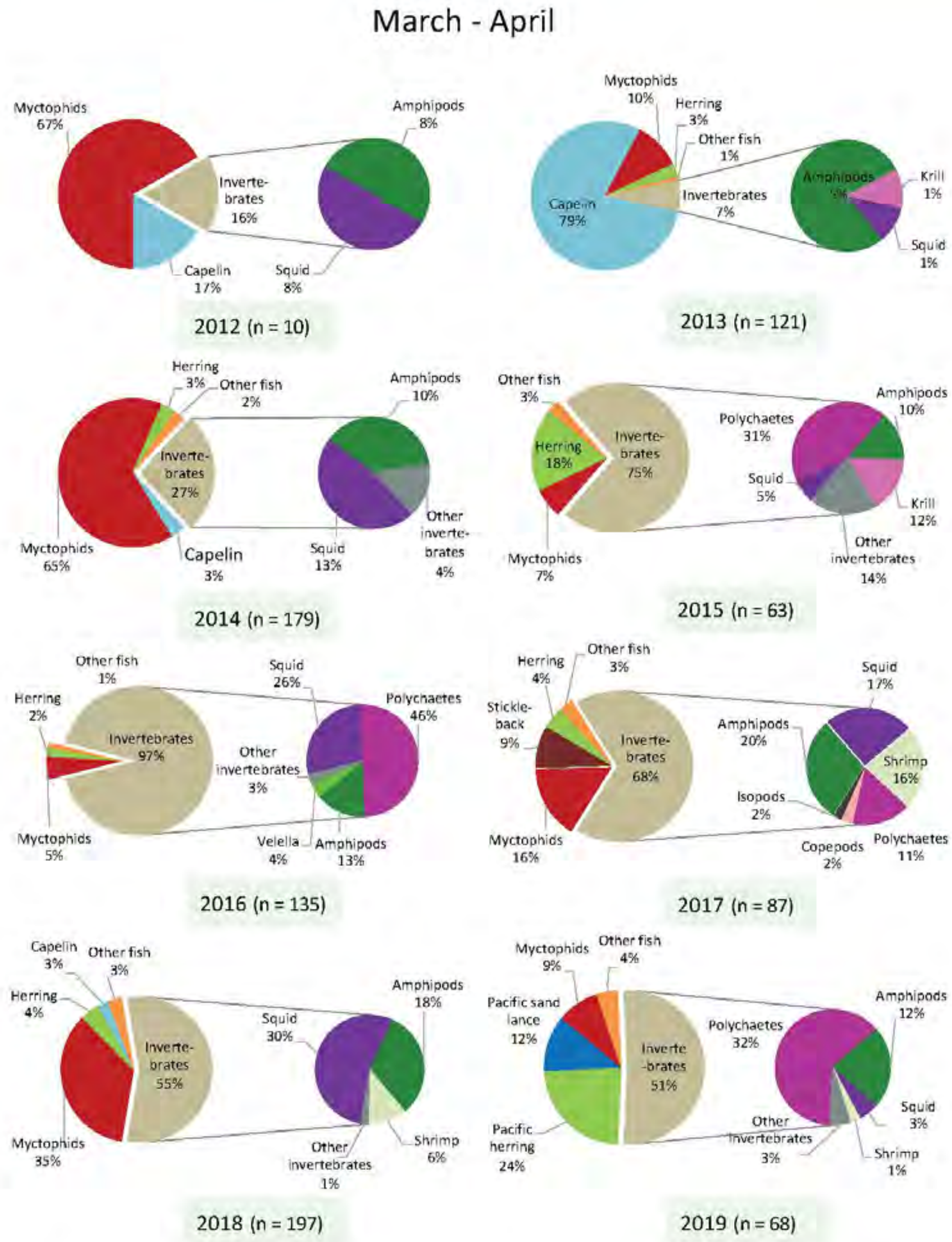

Figure S4. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island from spring arrival through April in 2012-2019.

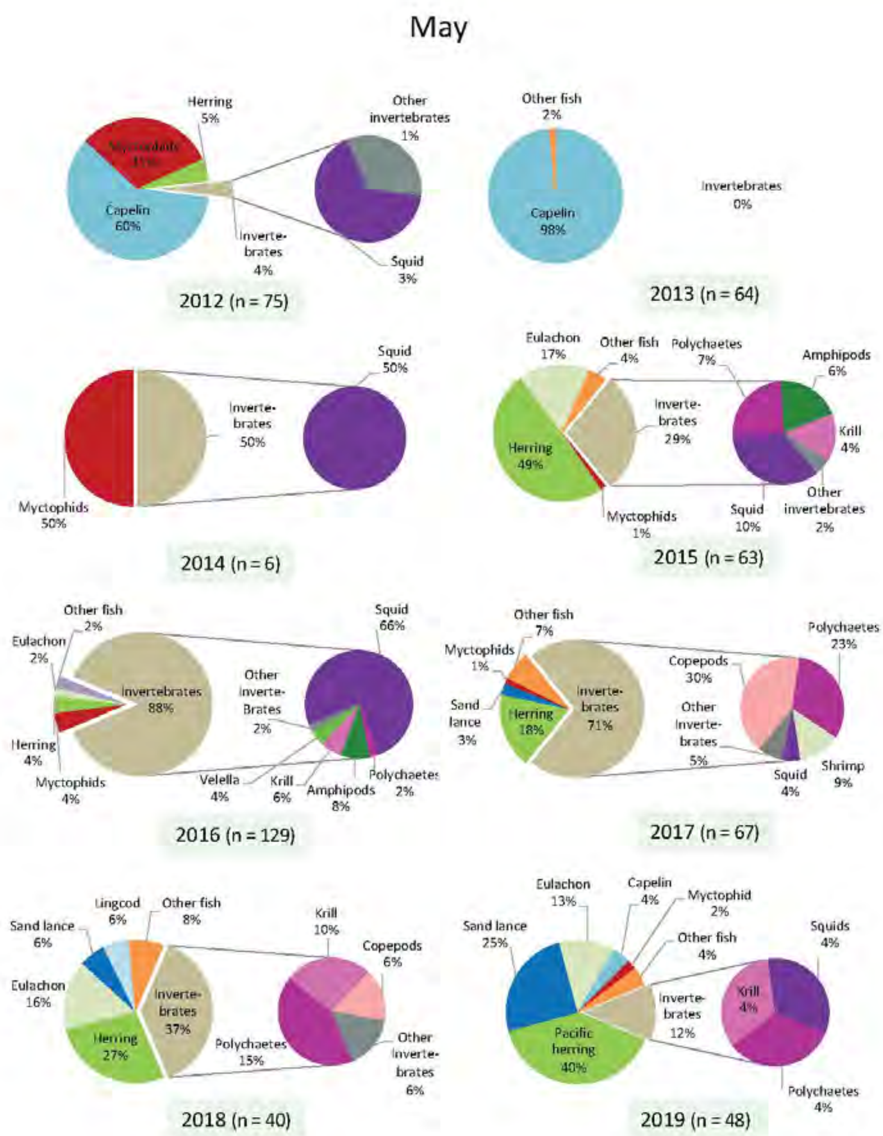

Figure S5. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island during May in 2012-2019.

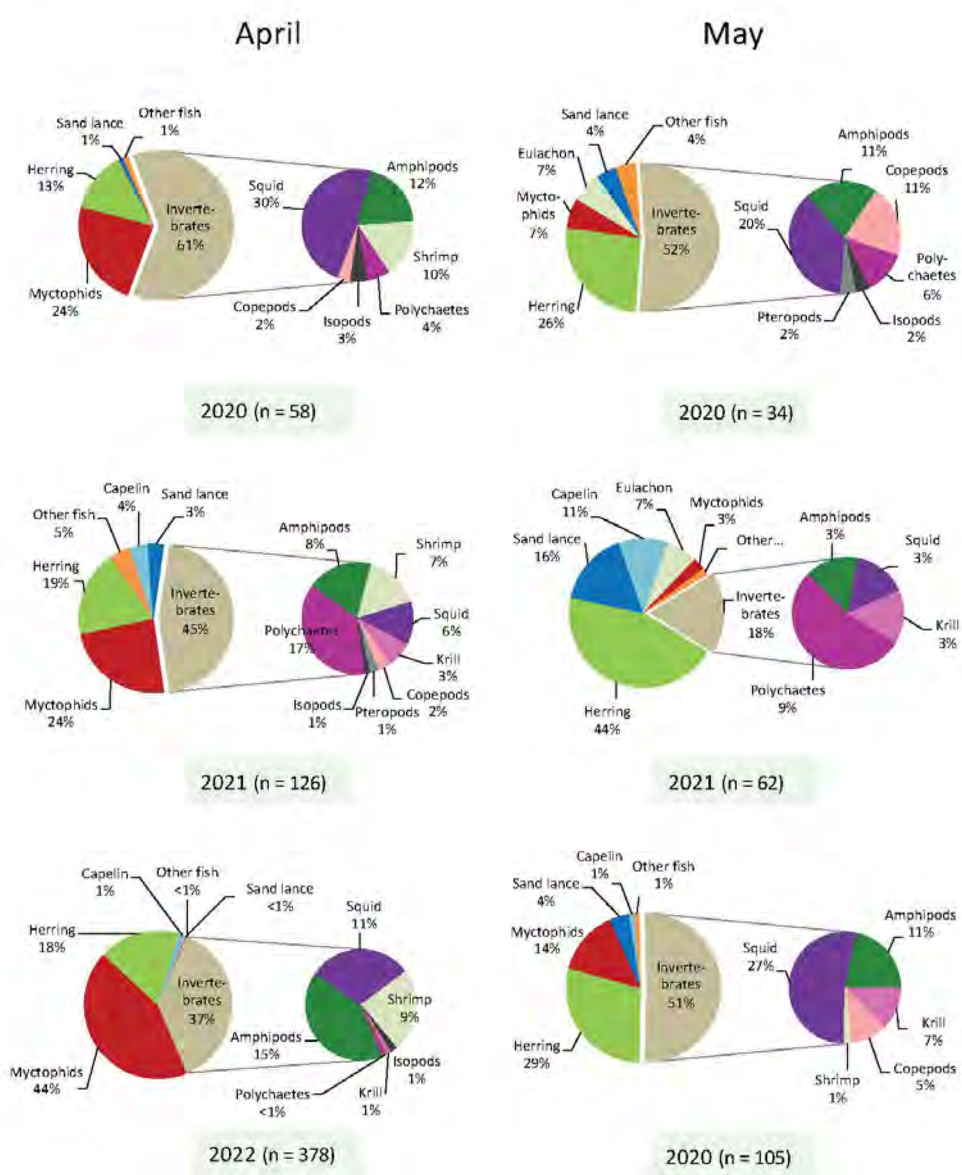

Figure S6. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island during April and May, 2020-2022.

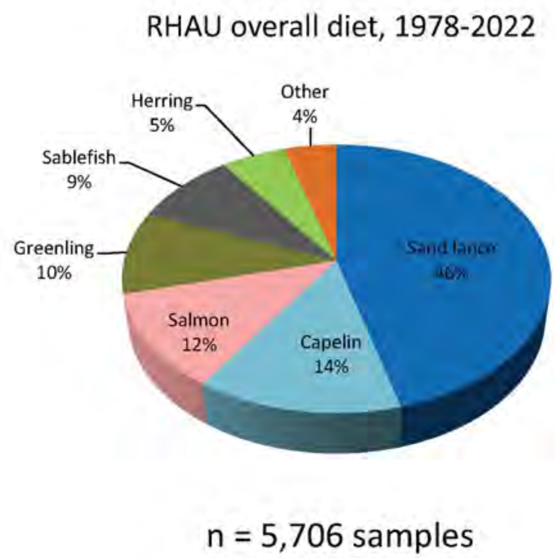

Figure S7. Overall composition of food samples obtained from chick-rearing rhinoceros auklets (% biomass, July-August) on Middleton Island from 1978 through 2022.

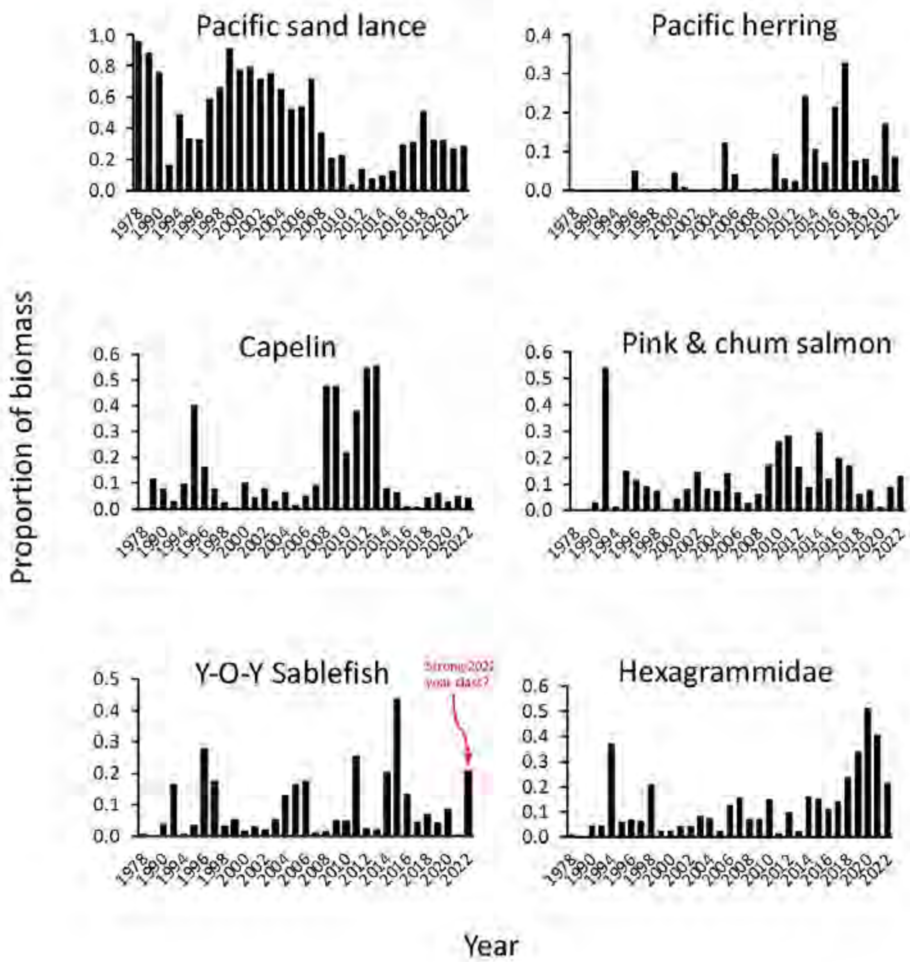

Figure S8. Indices of prey species occurrence in the nestling diet of rhinoceros auklets on Middleton Island from 1978 through 2022.

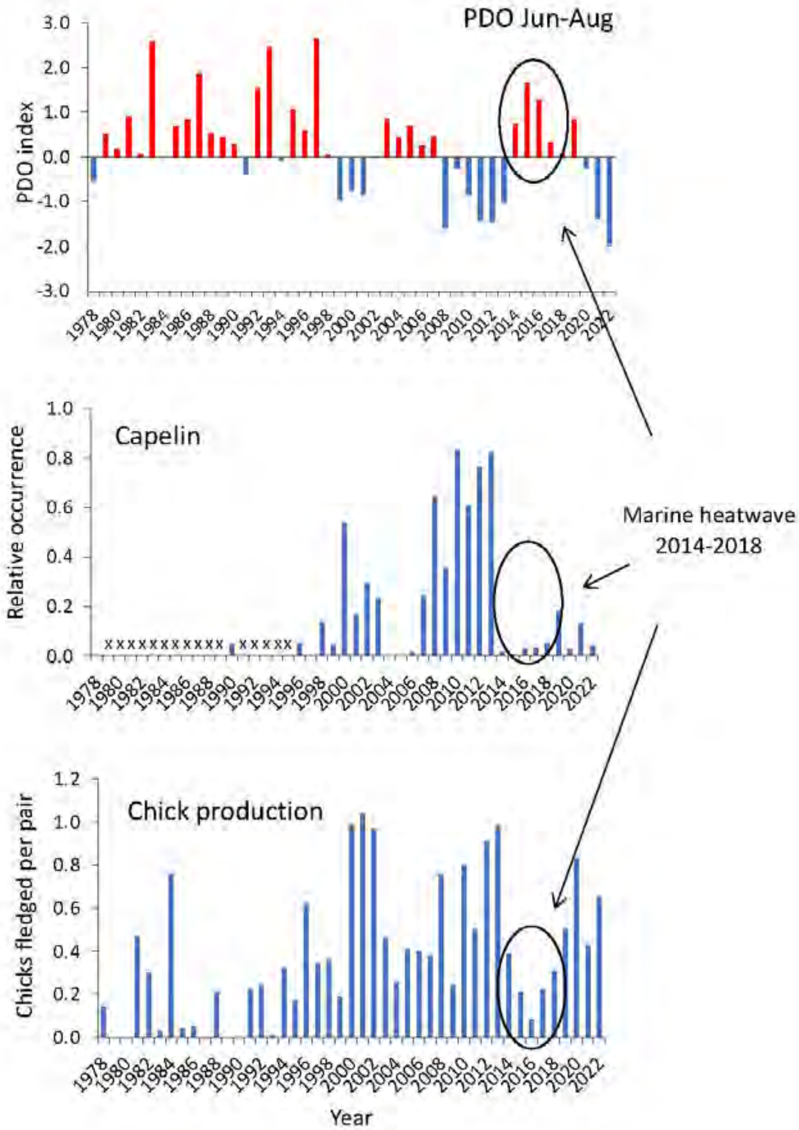

Figure S9. Relations among the Pacific Decadal Oscillation (PDO) index (June – August), relative occurrence of dietary capelin, and the annual production of kittiwake chicks on Middleton Island, 1978 to 2022. Missing data denoted by 'x'.

Table S1. Breeding performance of supplementally fed and unfed pairs of black-legged kittiwakes on the Middleton tower, 1996-2022.[a]

	Unfed pairs												Fed pairs											
	Julian lay date				Clutch size[a]				Chicks fledged				Julian lay date				Clutch size[a]				Chicks fledged			
Year	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.
1996	59	159	0.75	5.728	63	1.73	0.07	0.574	63	0.60	0.08	0.636	25	157	1.07	5.342	27	1.74	0.11	0.594	27	1.22	0.15	0.801
1997	59	158	0.44	3.386	65	1.48	0.08	0.664	65	0.32	0.06	0.503	25	155	1.09	5.427	25	1.80	0.08	0.408	25	0.96	0.16	0.790
1998	59	160	0.92	7.032	70	1.29	0.09	0.745	70	0.36	0.06	0.539	27	155	1.12	5.797	29	1.69	0.14	0.761	29	0.62	0.12	0.622
1999	65	169	0.59	4.771	156	0.47	0.05	0.606	156	0.21	0.04	0.468	44	161	1.01	6.684	46	1.61	0.09	0.614	46	0.59	0.11	0.717
2000	135	151	0.63	7.322	152	1.68	0.06	0.706	152	0.99	0.07	0.814	67	149	0.66	5.403	71	1.83	0.07	0.609	71	1.18	0.10	0.833
2001	166	153	0.46	5.942	174	1.78	0.04	0.560	174	1.03	0.06	0.853	67	151	0.41	3.342	71	1.93	0.07	0.569	71	1.28	0.10	0.848
2002	168	149	0.66	8.581	179	1.73	0.04	0.586	179	0.97	0.06	0.796	70	149	0.94	7.825	72	1.83	0.06	0.475	72	0.97	0.09	0.769
2003	95	157	0.47	4.600	102	1.67	0.06	0.603	102	0.50	0.06	0.609	66	152	0.74	6.003	69	1.81	0.07	0.550	69	0.91	0.10	0.836
2004	88	154	0.42	3.949	102	1.58	0.07	0.750	102	0.18	0.04	0.432	68	151	0.70	5.742	69	1.99	0.04	0.364	69	0.97	0.10	0.804
2005	214	157	0.30	4.321	221	1.67	0.04	0.553	221	0.37	0.04	0.553	71	151	0.57	4.775	72	1.86	0.05	0.421	72	1.03	0.08	0.712
2006	216	158	0.38	5.537	233	1.56	0.04	0.627	233	0.47	0.04	0.587	71	151	0.43	3.642	73	1.90	0.05	0.446	73	1.14	0.10	0.822
2007	172	163	0.43	5.606	197	1.34	0.05	0.693	197	0.42	0.04	0.606	63	158	0.74	5.900	73	1.58	0.08	0.725	73	0.77	0.10	0.874
2008	125	153	0.58	6.498	130	1.73	0.05	0.554	130	0.78	0.06	0.707	70	150	0.70	5.887	71	1.92	0.06	0.470	71	0.90	0.10	0.813
2009	90	155	0.57	5.439	98	1.69	0.07	0.649	98	0.20	0.04	0.405	75	150	0.81	7.056	76	1.89	0.04	0.386	76	0.75	0.08	0.656
2010	68	148	0.87	7.160	74	1.81	0.07	0.612	74	0.78	0.09	0.815	58	150	1.07	8.174	61	1.82	0.07	0.563	61	0.89	0.10	0.819
2011	41	158	0.64	4.092	42	1.62	0.08	0.539	42	0.50	0.09	0.552	47	152	1.26	8.624	48	1.83	0.07	0.519	48	0.92	0.11	0.794
2012	72	153	0.78	6.582	78	1.82	0.07	0.619	78	0.87	0.09	0.779	72	152	0.86	7.262	75	1.88	0.06	0.544	75	0.93	0.09	0.811
2013	63	148	1.06	8.413	68	1.84	0.06	0.507	68	1.00	0.10	0.792	67	148	0.97	7.965	70	1.97	0.06	0.538	70	1.04	0.10	0.842
2014	--	--	--	--	--	--	--	--	143	0.45	0.04	0.526	--	--	--	--	--	--	--	--	--	--	--	--
2015	296	153	0.29	4.986	352	1.51	0.04	0.762	352	0.21	0.02	0.422	70	152	0.47	3.895	72	1.90	0.05	0.449	72	0.96	0.09	0.740
2016	79	165	0.73	6.444	155	0.74	0.06	0.806	155	0.08	0.02	0.301	73	156	0.99	8.434	74	1.80	0.05	0.437	74	0.81	0.06	0.541
2017	72	161	0.52	4.407	104	0.95	0.07	0.755	104	0.22	0.04	0.417	72	155	0.58	4.938	74	1.82	0.04	0.371	74	0.76	0.08	0.679
2018	113	155	0.56	5.981	134	1.48	0.06	0.752	134	0.31	0.04	0.492	72	151	0.70	5.958	72	1.97	0.03	0.238	72	0.99	0.08	0.687
2019	326	154	0.30	5.471	368	1.61	0.04	0.691	368	0.50	0.03	0.586	73	150	0.46	3.922	73	1.99	0.04	0.311	73	1.07	0.09	0.770
2020	316	154	0.28	4.919	404	1.69	0.03	0.615	404	0.83	0.04	0.724	20	154	1.61	7.210	24	1.71	0.11	0.550	24	1.04	0.15	0.751
2021	217	155	0.45	6.693	217	1.76	0.03	0.441	217	0.43	0.04	0.532	72	149	0.50	4.275	72	1.97	0.04	0.335	72	1.00	0.09	0.732
2022	356	153	0.26	4.861	356	1.79	0.02	0.420	356	0.65	0.03	0.587	72	150	0.62	5.210	72	1.93	0.04	0.349	72	1.01	0.09	0.769

[a] Clutch size (and chicks fledged) include zero-egg nests, thus incorporating breeding propensity into clutch size and reflecting (for fledging) the overall productivity of site-holding pairs.

Table S2. Effects of supplemental feeding on laying dates, clutch sizes and overall productivity of black-legged kittiwakes on the Middleton tower since 1996.

	Treatment effect (Fed - Unfed pairs)		
Year	Julian lay date	Clutch size	Chicks fledged
1996	-2.30	0.01	0.62
1997	-3.23	0.32	0.64
1998	-5.19	0.40	0.26
1999	-8.78	1.14	0.38
2000	-2.03	0.15	0.19
2001	-2.65	0.15	0.25
2002	0.79	0.10	0.00
2003	-4.58	0.14	0.41
2004	-2.87	0.41	0.79
2005	-6.67	0.19	0.66
2006	-7.09	0.34	0.67
2007	-4.90	0.24	0.35
2008	-3.13	0.19	0.12
2009	-4.40	0.20	0.55
2010	2.24	0.01	0.11
2011	-5.55	0.21	0.42
2012	-1.55	0.06	0.06
2013	0.15	0.13	0.04
2014	--	--	--
2015	-1.62	0.39	0.75
2016	-8.52	1.06	0.73
2017	-6.00	0.87	0.54
2018	-4.00	0.49	0.68
2019	-4.70	0.38	0.57
2020	0.10	0.02	0.21
2021	-6.55	0.22	0.57
2022	-3.37	0.14	0.36
Mean	-3.71	0.31	0.42

Table S3. Productivity of rhinoceros auklets and tufted puffins breeding on Middleton Island in 2015-2022.

Parameter	2015	2016	2017	2018	2019	2020	2021	2022	$\bar{x}$ ± se
				Rhinoceros auklet					
Burrows with eggs	60	61	62	61	72	62	100	108	
Eggs hatched	42	38	40	35	51	54	79	84	
Late-stage chicks	38	33	32	33	44	47	77	71	
Chicks/egg laid	0.63	0.54	0.52	0.54	0.61	0.76	0.77	0.66	0.63 ± 0.034
				Tufted puffin					
Burrows with eggs	52	82	71	71	60	32	78	97	
Eggs hatched	21	27	17	17	19	16	27	67	
Late-stage chicks	18	20	12	12	19	12	24	52	
Chicks/egg laid	0.35	0.24	0.17	0.43	0.32	0.38	0.31	0.54	0.34 ± 0.040

Table S4. Breeding performance of pelagic cormorants on the Middleton tower, 2002-2022.[a]

	A-egg date (Julian day)				Clutch size				Chicks fledged/nest built			
Year	n	Mean	SE	SD	n	Mean	SE	SD	n	Mean	SE	SD
2002	77	139.7	0.95	8.325	86	3.7	0.18	1.707	86	1.6	0.15	1.371
2003	78	138.2	0.97	8.540	80	4.0	0.16	1.441	80	1.9	0.16	1.400
2004	62	144.0	0.88	6.941	76	2.8	0.18	1.607	76	0.4	0.07	0.650
2005	31	142.5	1.32	7.352	31	3.5	0.18	1.028	31	1.2	0.23	1.283
2006	92	148.3	0.90	8.635	101	3.0	0.12	1.228	101	1.1	0.12	1.156
2007	142	147.8	0.93	11.130	144	3.8	0.11	1.275	144	1.6	0.12	1.425
2008	145	146.4	0.94	11.370	145	3.8	0.10	1.165	145	1.6	0.11	1.319
2009	113	155.0	0.68	7.223	128	2.9	0.11	1.232	128	1.4	0.10	1.175
2010	71	154.7	0.72	6.037	71	2.6	0.10	0.851	71	0.1	0.05	0.445
2011	95	161.3	0.96	9.314	109	2.5	0.12	1.281	109	0.5	0.07	0.741
2012	85	159.4	0.86	7.884	85	3.0	0.12	1.107	85	0.5	0.08	0.765
2013	89	150.3	0.73	6.842	90	3.4	0.09	0.880	90	1.9	0.12	1.167
2014	--	—	--	—	—	--	—	--	~87	~1.2	0.13	1.170
2015	58	155.0	0.91	6.910	85	2.1	0.16	1.470	85	0.6	0.09	0.823
2016	53	152.8	1.62	11.78	53	2.9	0.17	1.210	53	0.9	0.14	1.050
2017	69	150.9	1.08	8.951	69	3.3	0.10	0.845	69	1.6	0.16	1.306
2018	84	150.8	1.14	10.492	84	3.4	0.10	0.898	84	0.8	0.09	0.784
2019	75	149.3	1.03	8.918	75	3.6	0.10	0.841	75	0.4	0.10	0.838
2020	64	145.6	0.81	6.478	76	3.4	0.11	0.938	76	2.0	0.15	1.322
2021	59	146.5	0.77	5.946	59	3.6	0.11	0.828	59	2.3	0.17	1.308
2022	60	146.3	0.96	7.448	60	3.6	0.09	0.722	60	1.9	0.18	1.390
Totals	1,602	149.2	0.96	8.33	1,707	3.2	0.13	1.128	1,707	1.209	0.12	1.090

[a] Productivity data for 2014 based on final count of chicks in tower nests on 14 July. This is at least 3 weeks before final checks in other years, and thus the count of chicks does not include additional mortality that would have occurred before fledging. On the other hand, 10 nests were still being incubated on 14 July. Those nests assumed to produce zero fledged chicks, offsetting perhaps the premature count of late-stage chicks. Thus, the estimate of fledglings in 2014 is 102 chicks from 87 nests built, a relatively crude value that should not be taken as strictly comparable to other years.

Table S5. Temporal distribution of diet samples from black-legged kittiwakes on Middleton Island, 1978 – 2022.

	Adults			June			July			August			
Year	Mar	April	May	Adults	Chicks	Total	Adults	Chicks	Total	Adults	Chicks	Total	Total
1978								38	38		2	2	40
1989		2	2				5		5				9
1990		17	7	18		18	21	9	30				72
1992			1							3		3	4
1994		3											3
1996			19					37	37		17	17	73
1997			4	4	3	7	3	107	110	1	35	36	157
1998			32	11	16	27	13	130	143	7	64	71	273
1999			11	11		11	9	51	60	2	45	47	129
2000		41	7	13	1	14	4	87	91		29	29	182
2001		10	19	7	23	30	10	321	331		31	31	421
2002		26	14	2	22	24	1	193	194		22	22	280
2003		4	22	24	3	27	22	15	37	5	2	7	97
2004		9	8		1	1	11	7	18				36
2005		4	12	3		3	5	10	15	1	2	3	37
2006			6	6	8	14		100	100		19	19	139
2007		1	21	4		4	13	3	16	1	3	4	46
2008		44	10	4	2	6	2	40	42	2	13	15	117
2009		36	21	16	2	18	22	27	49	2	7	9	133
2010		39	51	39	34	73	27	128	155	4	36	40	358
2011		32	14	3		3	9	18	27	8	13	21	97
2012		10	75	5	10	15	60	238	298	11	67	78	476
2013	114	7	64	50	17	67	23	110	133	8	26	34	419
2014		179	6	1	1	2	3	100	103	14	14	28	318
2015		63	63	12	4	16	33	32	65	4	12	16	223
2016		135	129	27	5	32	42	123	165	3	26	29	490
2017		87	67	34	0	34	69	77	146	6	31	37	371
2018		197	40	18	5	23	27	92	119	4	53	57	436
2019		58	45	11	11	22	17	187	204	7	54	61	390
2020		58	34	1	18	19	1	351	352	4	142	146	609
2021		126	62	33	25	58	36	143	179	1	14	15	440
2022		378	105	13	36	49	61	373	434	1	162	163	1129
Total	114	1566	971	370	247	617	549	3147	3696	99	941	1040	8004

Table S6. Food samples (bill loads, partial bill loads, and ground samples) obtained annually from rhinoceros auklets on Middleton Island from 1978 through 2022.

Year	No. samples	TotalMass (g)
1978	72	3109.2
1986	4	97.7
1990	17	199.4
1993	70	1407.2
1994	190	3680.1
1995	146	2217.1
1996	78	1488.0
1997	138	1707.6
1998	315	7816.6
1999	100	2688.3
2000	106	2537.8
2001	126	3888.6
2002	95	2706.7
2003	121	3461.6
2004	107	2889.9
2005	95	2749.3
2006	113	4393.8
2007	100	2470.0
2008	130	4514.9
2009	111	3079.4
2010	175	6297.6
2011	115	3430.8
2012	260	7011.6
2013	248	8732.3
2014	180	5920.0
2015	334	9351.0
2016	306	8988.5
2017	328	10,056.8
2018	210	6,989.0
2019	319	10785.9
2020	322	9691.0
2021	306	9606.4
2022	369	11574.3
All years	5706	165,538.4

Table S7. Numbers of prey types identified in kittiwake food samples—the basis for computations of relative occurrence—by month on Middleton Island from 1978 through 2022.

Year	Prey type identifications						
	March	April	May	June	July	August	Total
1978	0	0	0	0	56	4	60
1989	0	4	3	0	10	0	17
1990	0	25	9	34	46	0	114
1992	0	0	1	0	0	4	5
1994	0	7	0	0	0	0	7
1996	0	0	21	0	38	19	78
1997	0	0	4	9	132	47	192
1998	0	0	40	34	190	111	375
1999	0	0	14	15	75	65	169
2000	0	64	7	16	108	41	236
2001	0	12	21	30	409	44	516
2002	0	41	14	24	222	28	329
2003	0	6	31	34	47	9	127
2004	0	11	10	2	22	0	45
2005	0	5	13	3	17	4	42
2006	0	0	7	17	143	24	191
2007	0	1	26	4	21	4	56
2008	0	69	13	6	44	15	147
2009	0	48	22	23	65	11	169
2010	0	45	58	78	160	48	389
2011	0	37	17	3	34	29	120
2012	0	12	80	20	339	89	540
2013	129	7	64	68	139	44	451
2014	0	218	6	2	156	39	421
2015	0	77	71	23	88	20	279
2016	0	202	158	45	260	46	711
2017	0	134	74	46	207	49	510
2018	0	329	51	29	190	70	669
2019	0	68	48	29	289	83	517
2020	0	98	46	23	543	200	910
2021	0	176	74	62	227	20	559
2022	0	546	134	60	716	225	1681
Total	129	2242	1137	739	4993	1392	10632

Table S8. Time series of kittiwake productivity, dietary capelin and PDO index during the breeding season on Middleton Island from 1978 through 2022.

Year	Mean PDO index (Jun-Aug)	Productivity	Capelin in diet (Jun-Aug)
1978	-0.55	0.14	0.0000
1979	0.51	--	--
1980	0.17	--	--
1981	0.90	0.47	--
1982	0.06	0.30	--
1983	2.57	0.03	--
1984	-0.01	0.76	--
1985	0.69	0.04	--
1986	0.83	0.05	--
1987	1.86	0.00	--
1988	0.52	0.21	--
1989	0.43	0.00	--
1990	0.27	0.00	0.0500
1991	-0.40	0.22	--
1992	1.53	0.24	--
1993	2.46	0.01	--
1994	-0.09	0.32	--
1995	1.06	0.17	--
1996	0.58	0.60	0.0526
1997	2.63	0.32	0.0000
1998	0.05	0.42	0.1373
1999	-0.97	0.19	0.0452
2000	-0.76	0.99	0.5394
2001	-0.85	1.03	0.1677
2002	-0.02	0.97	0.2956
2003	0.84	0.50	0.2333
2004	0.44	0.20	0.0000
2005	0.69	0.37	0.0000
2006	0.25	0.47	0.0163
2007	0.46	0.42	0.2414
2008	-1.57	0.78	0.6462
2009	-0.25	0.20	0.3535
2010	-0.85	0.78	0.8322
2011	-1.43	0.50	0.6061
2012	-1.44	0.87	0.7634
2013	-1.02	1.00	0.8247
2014	0.73	0.45	0.0152
2015	1.65	0.21	0.0076
2016	1.27	0.08	0.0313
2017	0.33	0.22	0.0332
2018	0.08	0.31	0.0519
2019	0.83	0.50	0.1820
2020	-0.25	0.83	0.0287
2021	-1.39	0.43	0.1336
2022	-2.00	0..65	0.0390

Table S9. Pearson correlations among the Pacific Decadal Oscillation (PDO) index (June to August), relative occurrence of dietary capelin, and kittiwake chick production on Middleton Island over 43 years between 1978 and 2022.

		Variable	
Variable	Statistic	Chick production	Capelin in diet
Capelin in diet			
	Pearson's *r*	0.616	---
	P (2-tailed)	<0.001	---
	n (years)	29	---
PDO (Jun-Aug)			
	Pearson's *r*	-0.589	-0.544
	P (2-tailed)	<0.001	0.002
	n (years)	43	29

Appendix B. Spawning Capelin Flier posted at the Nuuciq Spirit Camp at Port Etches and on social media.