Coastal Lagoon Monitoring in the Southern Chukchi Sea National Park Units

Fieldwork Summary
2021

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Title page photo: WCS Fisheries Ecologist Kevin Fraley measures the length of a humpback whitefish caught in an onshore gillnet at the freshwater inlet sampling site of Krusenstern Lagoon in June 2021.

EXECUTIVE SUMMARY

Wildlife Conservation Society (WCS) has worked with the National Park Service since 2012 to design and implement the Coastal Lagoon Vital Signs component of the Arctic Inventory and Monitoring Network. This program is intended to establish biotic and abiotic reference conditions for assessing long-term changes in the coastal lagoons of Cape Krusenstern National Monument and Bering Land Bridge National Preserve. The Vital Signs program focuses on monitoring both the structure and ecological function of lagoons, as well as the fish resources used for subsistence by coastal communities. A standardized Vital Signs Protocol was developed for these lagoons, informed by our field efforts throughout 2015-2018. Our 2021 Vital Signs fieldwork sought to build upon the pre-existing database of in-depth temporal and spatial information on lagoon ecology.

There are nine coastal lagoons described in the boundary of Cape Krusenstern National Monument – Aukulak, Imik, Ipiavik, Kotlik, Krusenstern, Port, Sisualik, Tasaycheck, and Atilagauraq. We collected seasonal physical and biological data at three Cape Krusenstern lagoons including Kotlik, Krusenstern and Aukulak, which have been previously sampled in 2012 and 2015-2018. We measured physical and chemical water properties, primary productivity, and performed benthic Mysidae tows at all three lagoons. We also assessed lagoon fish assemblage diversity and abundance, sampled a variety of fish to evaluate contaminant loads in subsistence-harvested species, and collected stickleback species for proximate composition and food web analyses. Additionally, we conducted sampling at the mouth of the Tukrok River, a riverine matrix which acts as the connection between Krusenstern Lagoon and the Chukchi Sea, with the outlet to the marine environment located 14 km away from the main body of the lagoon. Given the significant distance between the two sampling locations we treated the Tukrok River mouth as an entirely different sampling site than Krusenstern Lagoon.

While ease of access and logistics allowed for two sampling efforts at Cape Krusenstern lagoons via wheeled airplanes (June and August), the lack of a floatplane or a helicopter prevented sampling efforts at Bering Land Bridge lagoons during the 2021 field season. We generally accessed the various Park unit lagoons via fixed-wing plane equipped with tundra tires. Within and among each visited lagoon, we used a small inflatable boat equipped with a 9.9 horsepower outboard motor. Four long-term stations (center, outflow, inflow, and marine edge) and three random sampling stations were sampled at each lagoon. At each station and during each season we collected water quality and primary productivity data (YSI Sonde instrumentation) at all long-term and random sites. Fish sampling occurred at the outflow, marine edge, and inflow sites during both seasons, including a total of 40 beach seine pulls, 14 2-hour fyke net sets, and 74 gillnet sets (varying durations). Additionally, certain stations were sampled for Mysidae diversity and abundance using a benthic tow net. These investigations will supplement results from ongoing and future laboratory analyses of fish and Mysidae samples in collaboration with the University of Alaska Fairbanks.

Lagoons varied in their seasonal connectivity with the ocean. Krusenstern and Kotlik Lagoons were open to the marine environment during the first round of sampling in June, and closed during the second round of sampling in August. Aukulak Lagoon remained closed throughout the 2021 summer season. Evaluation of water quality data indicates that physical water properties varied by lagoon and season. Seasonal salinity levels tracked those of previous years, and were related to a lagoon's connection with the marine environment; the more directly connected the lagoon is to the Chukchi Sea, the higher its salinity. Average salinity levels at all lagoons dropped between the first and second sampling rounds, likely because of closure to the marine environment and significant rainfall that preceded the final sampling excursion. Because Aukulak Lagoon remained closed to the ocean, and Krusenstern is 14 km distant from the marine opening, they exhibited low salinity throughout the year. Mean water temperatures at all three lagoons decreased over the course of the field season and were largely comparable to temperatures from previous years. However, average temperatures in Aukulak and Kotlik Lagoons in the early season (20.30 and 16.47 C, respectively) were higher than any from 2012-2018, indicating a warmer-than-average June

in 2021. Dissolved oxygen saturation decreased at all lagoons over the course of the season, but saturation was higher than 96% at all times, indicating normoxic conditions. Lagoon pH was lower in 2021 compared to previous years, and lower in the late season. This indicates a shift towards greater acidity, yet levels are comparable to adjacent environments and remain well above thresholds of concern for biota. Turbidity of lagoons was low overall (0.71-11.44 FNU), and increased from the early to late sampling season, likely a result of suspended sediment entrained by persistent storms in August 2021. As in previous years, Krusenstern Lagoon exhibited the highest turbidity, likely due to wind-driven turbation caused by the lagoon's considerable fetch.

Primary productivity was low during the 2021 season, likely due to an uncommonly stormy and cloudy summer that was not conducive for optimal autotrophic growth and reproduction. Total chlorophyll ranged from 1.01 – 3.56 RFU and blue-green algae concentration ranged from 0.17 – 0.92 RFU. Algal blooms were not observed visually like they had been during previous sampling years. Experimental Mysidae sampling with a benthic tow net was effective in lagoons where Mysidae were present (Krusenstern and Kotlik) and yielded ample sample volumes, which have been frozen and are being held by WCS for future taxonomic sorting, counting, proximate composition analyses, and food web studies.

We captured and processed 1,726 fish at the lagoons and the Tukrok River mouth, which represented much lower overall abundance than previous years. We attribute this to fewer small-bodied forage fish being present across sites, and the near-absence of fish in Aukulak Lagoon due to winterkill. Species richness of fishes and their abundance in lagoons fluctuated during the course of each field season with population composition and relative abundance varying between both season and lagoon. We recorded a total of 20 different fish species, including the typical suite of key forage and important subsistence species. This was similar to species diversity in 2018, but lower than the most speciose year in 2016 (25 species). Diversity was highest at Kotlik Lagoon, and diversity and abundance were lowest at Aukulak Lagoon with only four individuals of two species encountered because of winterkill and lack of lagoon marine connectivity. Several species that had rarely or never been encountered in previous lagoons investigations were caught, including broad whitefish, yellowfin sole, Arctic grayling, Alaska blackfish, and slimy sculpin. Conversely, notable absent taxa included Pacific salmon species, belligerent sculpin, capelin, and sand lance. Interestingly, the largest Dolly Varden and Arctic grayling ever recorded in the lagoons by WCS were captured in Kotlik Lagoon in June 2021.

Overall, our research builds on prior lagoon ecology monitoring and research, providing information vital for understanding long-term change, monitoring and managing Arctic lagoons of these Park units. This data will help prioritize spill contingency planning (by establishing the most productive lagoons), and will continue to inform a comprehensive understanding of the *Story of the Lagoons* – a key priority for the Native Village of Kotzebue, Wildlife Conservation Society, and the National Park Service. Future planned efforts include evaluation of lagoon basal prey resource taxonomy and food web ecology, fish seasonal movements and life history chronology investigations, and community outreach efforts through film and other media.

INTRODUCTION

In order to fulfill the National Park Service (NPS) mission of conserving parks unimpaired, NPS managers are directed by federal law and NPS policies and guidance to know the status and trends in the condition of natural resources under their stewardship. The 2006 NPS Management Policies specifically directed the NPS to inventory and monitor natural systems. NPS has used the term "vital signs monitoring" since the early 1980s to refer to a relatively small set of information-rich attributes. This subset of physical, chemical, and biological elements and processes of Parklands ecosystems are selected to represent the overall health or condition of Park resources, known or hypothesized effects of stressors, or elements that have important human values. Vital Signs can provide managers with an early warning of situations that require intervention in National Parklands. The mission of the NPS Arctic Network (ARCN) Inventory and Monitoring Program includes monitoring 28 specific Vital Signs in the five northern Alaska NPS units, including the coastal lagoons of Cape Krusenstern National Monument and Bering Land Bridge National Preserve (Lawler et al., 2009).

In 2007, the Arctic Network Inventory and Monitoring Program began developing a monitoring protocol for coastal lagoons located in Cape Krusenstern. Using monitoring data to inform management decisions is clearly outlined in both the General Management Plan (GMP) for Cape Krusenstern National Monument (NPS, 1986a): "…monitoring will be conducted so that thorough information about the condition of resources will be available to monument managers"; and Bering Land Bridge National Preserve (NPS, 1986b) which notes the: "positive effects on natural and cultural resources within the preserve as a result of natural resource research and monitoring." More specifically, the Cape Krusenstern GMP states the importance of monitoring water quality within the Monument. The National Park Service will establish a monitoring program: "…to provide baseline data on water quality of the Monument against which future sampling can be compared."

Coastal lagoons are a dominant landscape feature of the Arctic coastline; over a third (37%) of the coastline between Wales and the Canadian border is adjacent to coastal lagoon habitat (Figure 1, Table 3). The coastal lagoons of the NPS Arctic Network represent a critically important ecosystem type in the region, and are vulnerable to both climatic change and development impacts. They are also highly dynamic, with both intra- and inter-lagoon dynamics only partially understood. From a climate change perspective, increased coastal erosion and ocean acidification has the potential to profoundly alter the physical and biological dynamics of the lagoons. New dynamics of lagoon breaching will alter fish community patterns and the availability of important subsistence fish species. Changes in pH are projected to be most drastic in Arctic surface waters (Steinacher et al., 2009). Additionally, projected acidification has the potential to have a strong negative impact to calcifying organisms including mollusks and phytoplankton (Comeau et al., 2009). Coastal lagoons are also facing potential threats from increased development in the Arctic including potential oil and gas development in the northern Chukchi Sea, deep-water ports in the northern Bering Sea and increased international shipping along the Northern Sea Route. Lagoon Vital Signs efforts address the need for baseline information about the structure and function of lagoons, as well as the dearth of information about the local fish resources utilized for subsistence (Lentz et al., 2001). Without a clear understanding of baseline conditions in the lagoons, including the seasonality and inter-annual variability of physical and biotic components, and relative productivity, it is impossible for managers to detect long-term changes that result from climate change, to quantify the impacts of human-caused accidents, or develop appropriate management plans that protect the key functions that these lagoons provide for ecological health and subsistence economies.

Coastal Lagoons in Northern Alaska

Lagoons on the Beaufort Sea coastline have been comprehensively studied due to the relatively greater interest as part of oil and gas environmental assessment activities. Common to all the more northern studies is the significant interannual, seasonal, and geographical differences in lagoon physical conditions and fish assemblages. Lagoon conditions can vary from fresh to saline, sometimes within a season depending on connectivity with the Beaufort Sea. Jarvela and Thorsteinson (1999) found Arctic cod, capelin, and liparids (snailfish) to be the most abundant marine fishes in catches, while Arctic cisco was the only abundant diadromous (life cycles in fresh water and in marine water) freshwater species. Johnson et al. (2010) found capelin, Arctic cod, juvenile pricklebacks and juvenile sculpins to be the most common taxa in the Beaufort Sea around Cooper Island. In Elson Lagoon (Beaufort Sea coast), least cisco and juvenile sculpin were most common. Johnson et al. (2010) also concluded that species occupying coastal waters of the Beaufort Sea remained relatively unchanged over the past 25 years.

Between North Slope efforts and the Cape Krusenstern and Bering Land Bridge NPS units, the most significant lagoon research efforts have been conducted between Kivalina and Cape Thompson in the 1950s as part of the Project Chariot environmental assessment (Johnson, 1961; Willimovsky and Wolfe, 1966; Tash and Armitage, 1967; Tash, 1971) and at Port Lagoon just to the south of Kivalina as part of the Environmental Assessment for the Red Dog Mine port facility. Cape Thompson lagoons were visited by WCS crews in 2018 and 2021 to assess ecological changes that occurred since these historical studies were conducted (Smith et al., 2018c; Pinchuk and Robards 2020; WCS 2021 unpublished data).

Within the focal National Park Service land units, there are nine coastal lagoons described within the boundary of Cape Krusenstern National Monument – Aukulak, Imik, Ipiavik, Kotlik, Krusenstern, Port, Sisualik, Tasaycheck, and Atilagauraq; and four coastal lagoons within the boundary of Bering Land Bridge National Preserve – Espenberg, Kupik, Shishmaref, and Ikpek (Figure 1; Table 3). We note that Sisualik and Espenberg may not fulfill all the requirements of being classed as lagoons, being more representative of fully marine embayments or estuaries (Durr et. al., 2011; Tagliapietra et. al., 2009).

Villages in proximity to Cape Krusenstern National Monument include the Native Villages of Kivalina (17 km northwest of the monument boundary), Noatak (13 km east of the monument boundary), and Kotzebue (15 km southeast of the monument boundary). For Bering Land Bridge National Preserve, proximal villages include the Native villages of Deering (20 km east of the preserve boundary), Shishmaref (surrounded by the preserve at a distance of about 20-30 km), and Wales (36 km southwest of the preserve boundary). Many residents of these villages use camps along the coastline to conduct subsistence harvest activities, including around several of these lagoons. Red Dog Mine, one of the world's largest lead and zinc mines is located just north of Cape Krusenstern's boundary.

Of the lagoons in Cape Krusenstern, Atilagauraq is the smallest (<0.5 km^2) and Krusenstern Lagoon is the largest (56 km^2). Lagoons vary in the amount of water exchange with the surrounding marine environment. Aukulak, Krusenstern, and Sisualik are connected to Kotzebue Sound and Imik, Ipiavik, Kotlik, Tasaycheck, Atilagauraq and Port are connected to the more open Chukchi Sea. Aukulak, Imik, Kotlik, and Port are all intermittently open. Krusenstern, Atilagauraq, and Tasaycheck Lagoons are typically seasonally closed. Krusenstern Lagoon is connected to the ocean at the mouth of the Tukrok River, which is 14 km away from the main body of the lagoon itself. The mouth of the Tukrok opens in springtime as a result of snow and ice breakup in the rivers and lagoons feeding the river, which builds pressure at the beachhead, and ultimately in some years breaking through (sometimes helped by local fishermen who recognize that the opening of the lagoons allows fish to enter (and grow). The mouth of the Tukrok River routinely closes in mid to late summer as gravel is pushed up by wave action resulting from strong storms., but precipitation events in late summer often cause the connection to the marine environment to be temporarily restored. Sisualik, and Ipiavik are open year-round.

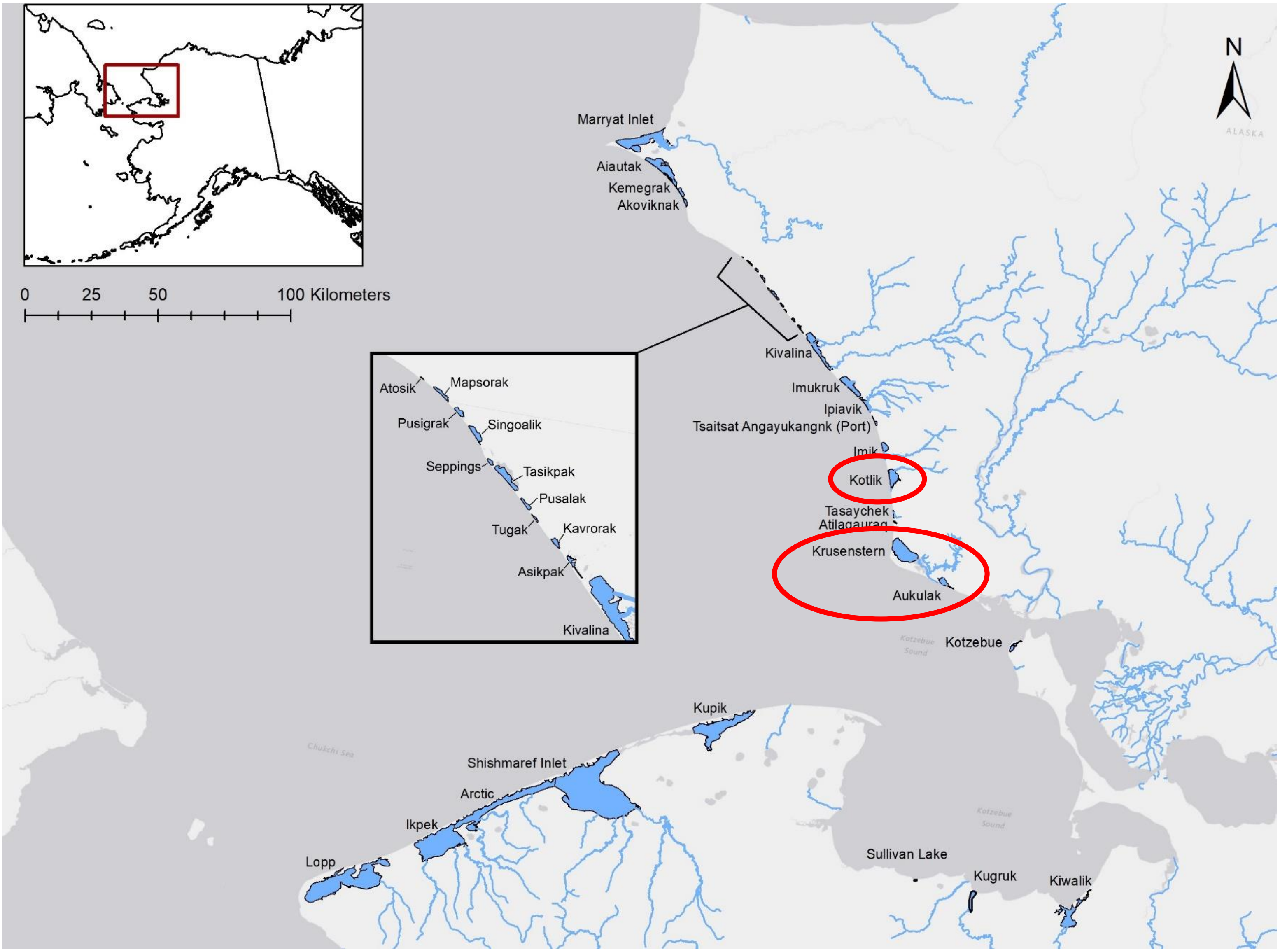

Figure 1: Map of named Southern Chukchi Sea coastal lagoons. 2021 study lagoons (Krusenstern, Kotlik, and Aukulak) are denoted by red circles.

Prior Coastal Lagoon Research in ARCN National Park Units and Overall Picture of Lagoons
There have been a number of prior research efforts investigating the ARCN national park units that include this report's study area. Throughout the 1970's, reports outlined avifaunal community composition and behavior surrounding the lagoons at Cape Krusenstern and Bering Land Bridge National Park. Additional insight from these predominantly avian studies included information on zooplankton community composition, which was found to be less diverse inside rather than outside the lagoons (Connors and Risebrough, 1977, 1978).

During the 1980's several reports were compiled that explored basic physical water quality parameters and fish and invertebrate community composition as well as fish abundance and size at study sites at Cape Krusenstern, Kotzebue Sound and the Tukrok River Channel (Raymond et al., 1984; Dames and Moore, 1983: Baylock and Erikson, 1983). Additional areas explored in these and associated reports included lagoon epibenthic regions, which were discovered to be highly variable and attributed to specific lagoon assemblages, timing, and location within lagoons by Blaylock and Erikson (1983). Findings from reports completed during this time period also suggested greater fish species diversity occur in lagoons open to marine environments rather than those closed off (Dames and Moore, 1983).

Research and data collection at lagoons in northwest Alaska National Park units continued into the 1990's, with one major study conducted at Krusentern Lagoon by Schizas and Shirley (1994). This study was in conjunction with a larger survey on benthic and epibenthic invertebrates of lagoons in Cape Krusenstern, and identified a new species of harpacticoid copepod (*Onychocamptus krusensterni)* among the benthic community at Krusenstern Lagoon.

During the early 2000's, additional information on physical and chemical (e.g. nutrients) and biological (e.g. zooplankton, epibenthos and fish) parameters was collected at six of the eight coastal lagoons located in Cape Krusenstern (Imik, Kotlik, Krusenstern, Aukulak, Sisualik,) (Reynolds et al., 2005). However, determining the general status and trends in conditions for these lagoons, in a manner comparable with future years, was not a feasible product of these studies, which acknowledged the absence of comprehensive baseline data for many coastal lagoons in the southern Chukchi Sea (Reynolds, 2012). A more limited sampling effort for the Cape Krusenstern National Monument lagoons in 2009 was conducted utilizing preexisting sampling sites with the intent of utilizing this in addition to data collected by Reynolds et al. (2005) to act as baseline information for Cape Krusenstern lagoons. Reynolds had sought to monitor coastal lagoons of Cape Krusenstern to document the long-term status and trends of physical, chemical, and biological components. In order to achieve that objective, Reynolds planned to collect: 1) physical and chemical water quality data in the five lagoons, 2) nutrient and chlorophyll A samples in five lagoons, 3) zooplankton samples in five lagoons, 4) benthic samples in three lagoons (Kotlik, Krusenstern, and Sisualik), 5) pelagic fish species in three lagoons (Kotlik, Krusenstern, and Sisualik), and 6) geomorphological data in five lagoons. These data, along with those previously collected (Reynolds et al. 2005), were intended to contribute to baseline water quality and species data for the five coastal lagoons in Cape Krusenstern. Additionally, field efforts during this sampling period were to be used to determine the feasibility of field-sampling methods for long-term sampling of these remote lagoon ecosystems (i.e., to develop a Vital Signs protocol).

Reynolds' efforts to seasonally sample multiple lagoons were ambitious given their remote nature and profound variability. While providing some valuable baseline data on basic conditions, a greater focus was still needed on a few lagoons to understand their temporal and spatial variability. Reynolds' protocols were not fully operationalized, and efforts to conduct in–field monitoring were thwarted by challenging logistics, creating a need and opportunity for NPS and Wildlife Conservation Society to collaborate towards common objectives and derive mutual benefit.

WCS-led field efforts have taken place over the course of the 2012 and 2015-2018 seasons (Robards, 2014; Haynes et al., 2017; Tibbles, 2018; Tibbles and Robards, 2018; Tibbles et. al., 2018; Smith et al., 2019 a-b). This report builds on information collected from these prior field efforts, which include baseline information for physical and chemical water properties, primary productivity, zooplankton diversity and abundance (Pinchuk and Robards 2020), and fish community dynamics. Results from these previous efforts indicate that both physical and biological dynamics vary greatly between both lagoon and season. Water quality parameters fluctuate in response to connectivity with the ocean; with salinity, temperature and dissolved oxygen levels varying across each season. In some cases, the synthesis of results from data collection indicate common trends as a result of this closure with both salinity levels and temperature decreasing over the course of the season in several cases. Fish communities were also highly variable with species abundance changing both across and between seasons. Results from fishing efforts indicate that seasonal dynamics of fish community composition change as the physical dynamics and characteristics of the lagoons undergo seasonal changes. Catches of migratory species (e.g. sheefish, humpback whitefish) generally decreased towards the end of the season as fish depart the lagoons, likely in response to the potential loss of connectivity to overwintering habitat as freeze-up approaches.

Table 1. Wildlife Conservation Society Southern Chukchi Sea lagoons ecological sampling efforts by year. Lagoons are arranged in order from north to south (See Figure 1 for geographic locations). "E" is defined as early summer sampling period from June-July and "L" refers to the late summer sampling period of August-September.

Land Management Unit	**Lagoon/location**	**2012**		**2015**		**2016**		**2017**		**2018**		**2021**	
		E	**L**	**E**	**L**	**E**	**L**	**E**	**L**	**E**	**L**	**E**	**L**
Alaska Maritime National Wildlife Refuge/ Cape Thompson	Kemegrak										X		
	Akoviknak										X		
	Atosik										X	X	
	Mapsorak										X	X	
	Singoalik										X	X	
Cape Krusenstern National Monument	Kotlik	X			X	X	X	X	X	X	X	X	X
	Tasaychek						X						
	Atilagauraq					X							
	Krusenstern	X		X	X	X	X	X	X	X	X	X	X
	Tukrok River mouth/Anigaaq			X	X	X	X	X	X	X	X	X	
	Aukulak			X	X	X	X	X	X	X	X	X	X
Bering Land Bridge National Preserve	Kupik	X		X		X							
	Ikpek	X		X		X							

Traditional knowledge of local lagoon ecosystems has developed from a long history of subsistence fishing and is a vital monitoring system that supplements scientific data collection. Many residents of areas surrounding Cape Krusenstern rely on the lagoons for subsistence purposes, and have observed a range of significant changes to these resources linked to climate change (Moerlein et. al., 2015; Jones, A., 2006). These observations work to emphasize the importance of scientifically evaluating ecological functionality and health of lagoon systems, and incorporating local observations and expertise into these efforts. As Boswell et al. (2012) highlight for lagoons on the North Chukchi Sea coast, there is great importance in "developing a firm understanding of the value and role of these sensitive habitats with respect to fisheries productivity in the Arctic and their function as sources of nutrition and refuge for important fish, birds and mammals is imperative, especially in context of climate and environmental change."

Ultimately, the development of a workable protocol and recommendations for conservation are beneficial for land management agencies. For example, lagoons and their marsh areas are particularly sensitive to climate change or oil that once entrained in the lagoon system would be very difficult to remediate; so, assessing the ecological or subsistence value of different lagoons supports both an understanding of change in lagoons as well as prioritized contingency planning in the case of an oil spill. This report will contribute to the pre-existing body of information on Cape Krusenstern National Monument lagoons and will help to inform the ongoing development of sampling protocols and monitoring measures for Arctic lagoons more broadly.

2021 FIELD EFFORT

Objectives

The objectives of the Wildlife Conservation Society-led activities throughout the 2021 field season included the following:

1. Continue to test the viability of the National Park Service Coastal Lagoons Vital Signs Monitoring Protocol for the Arctic Network based on WCS led research efforts from the 2012 and 2015-2018 field seasons;
    a. Streamline logistics and provide feedback on standardized sampling protocol;
    b. Report findings from 2021 field season and incorporate data into comprehensive Arctic lagoons monitoring database;

2. Collect data from lagoon sites in Cape Krusenstern National Monument and Bering Land Bridge National Preserve including;
    a. Water quality parameters: temperature, pH, salinity, dissolved oxygen, turbidity, and specific conductivity;
    b. Primary Productivity including blue green algae and chlorophyll concentrations;
    c. Fish distributions, abundance, assemblage composition, life history, genetic information and contaminant levels;
    d. Species composition and behavior of animal communities interacting with lagoon ecosystems.

Study Design

The NPS sampling protocol (Jones et al. 2018) was followed to test for viability in the field, with alterations indicated in WCS monitoring efforts from 2015-2018 implemented where appropriate. Two sampling efforts were undertaken for three lagoons in 2021, one in June (termed "early season") and one in August ("late season").

Field Methodologies

Water Quality

Sampling methods used to collect physical and chemical data were based on the Environmental Protection Agency (EPA) National Coastal Assessment Field Operations Manual (U.S. EPA 2001). At each sampling point (7 sites per lagoon per visit) and at a depth of 50 cm, the following core water quality parameters were measured in situ using a YSI EXO 2 multiparameter sonde: water temperature, dissolved oxygen, salinity, specific conductivity, turbidity, and pH. Water depth was measured with a hand-held depth sounder.

Primary Production
Primary production was estimated using the YSI EXO 2 sonde to measure total chlorophyll and blue-green algae in the lagoons during the 2017 season. Reynolds (2012) and Robards et al. (2014) had used laboratory analysis for chlorophyll. However, the expenses for conducting this work are preclusive for a long-term monitoring project, particularly given the large number of below-detection samples over the course of the season. Primary productivity readings were conducted at all sites sampled for water quality.

Mysidae Tows
An experimental benthic Mysidae tow net was designed by WCS (Figure 2), with input from Alexei Pinchuk of the University of Alaska Fairbanks, and the aluminum net frame custom-fabricated by Interior Mobile Welding of Fairbanks, Alaska. The frame was designed to be assembled and disassembled using bolts and wingnuts for ease of transport via bush flights and small watercraft. The mouth of the net frame is ~75 cm wide and 25 cm tall. A custom Science Interactive Group 1000um-mesh net of dimensions 46 x 25 x 89 cm was hand-sewn to a tapered canvas hood using fishing line, and zip-tied to the net frame to capture Mysidae that were drawn into the net mouth. The net and canvas hood were tinted brown with natural fabric dye to camouflage the apparatus and prevent Mysidae from avoiding capture. A metal chain and eyelet across the front of the net was attached to a 50-m nylon rope to facilitate tows by personnel wading or in the boat.

Figure 2: Hauling the custom-fabricated aluminum Mysidae tow net onshore after conducting a 50-m tow at the freshwater inlet site of Kotlik Lagoon (Jade Creek) in August 2021.

When deployed in the field, the net was either towed (the boat was run in reverse and a technician held the rope in the bow) or walked at a speed of approximately 8 km/h for distances of 50-100 m, to ensure the net stayed on the lagoon bottom yet moved fast enough to entrain Mysidae, thereby optimizing catch. 50 or 100-m tow distances were employed to allow for quantitative measures of Mysidae abundance. At least two tows were attempted at each site that was also sampled for fish during the August 2021 visit. Catches were rinsed through the net mesh multiple times to filter out mud and debris. If catch volumes were large, they were subsampled (visually, by percentage) to ensure they would fit in plastic Nalgene containers. Sample containers were kept on ice or gel packs in a portable cooler in the field, until they could be frozen in Kotzebue. Samples are currently being held by WCS and will be sorted, species identified, abundance quantified, and stable isotope and proximate composition assessed at a later time by Alexei Pinchuk at the University of Alaska Fairbanks Juneau campus.

Fish Sampling
We captured fish in all lagoons using a beach seine, fyke net, experimental gillnets, and opportunistic angling. The 3.1x15 m beach seine was used to sample fish at any location where beaches allowed for deployment (e.g., sandy with no protruding rocks). We walked the net out to about 20m into the water then drew it parallel to shore the retrieved the net in a symmetrical manner with personnel drawing the wing lines attached to the net's ends simultaneously at a constant rate (per Robards et al., 1999). Where water depths did not allow deployment of the seine by wading, the net was deployed using the inflatable boat run in reverse.

We used fyke nets to collect larger volumes of fish only at lagoon outlet locations where the depth and substrate were favorable. Our fyke net was constructed with 3.1 mm stretch mesh, a 91.5 x 122 cm frame made of two rectangular conduit frames, 5 steel hoops, 2 throats, and a 15.2 m lead. The wings were anchored using rebar or driftwood with the main line attached perpendicular to shore and the wings set at approximately 45˚. Set time for fyke nets was more standardized than scientific gillnets throughout the field season, but number of sets varied to avoid mortality where catches were large. Set time for fyke net sets during the 2021 season was 2 hours.

Experimental gillnets consisted of 5 panels, each 25ft in length, for a total net length of 125ft. Stretch measurement of the individual panels were: 1 inch, 1.5 inch, 2 inch, 3 inch, and 4 inch. Set sites were selected in areas near the inflow, outflow (regardless of whether the connection was open or closed), and marine edge. Soaking nets were continuously monitored in order to minimize risk of a) birds or other unintended animals being caught, and b) unnecessarily heavy fish mortalities. Set time for gillnets during the 2021 field season ranged from 15 minutes to 1 hour, depending upon number of fish captured and wave action, to avoid unintended mortalities.

Angling via fly rod was attempted opportunistically by two crew members when large-bodied, elusive fishes such as Dolly Varden, sheefish, and Arctic grayling were visually observed at sampling sites but evaded capture by other gear.

We identified all fish to species and measured each individual to fork length. A subset of fish were weighed on a digital scale, when wind conditions allowed. We euthanized a subset of large-bodied fish of subsistence harvest importance for contaminants and otolith microchemistry analyses and a sample of ninespine and threespine stickleback for proximate composition and stable isotope analysis using an overdose of anesthetic (AQIUI-S). For a subset of Coregoninae, we took one fin clip from each individual (right pelvic fin) and placed the sample in a 1.8 mL cryo tube containing preservative for storage, then were delivered to Professor Andres Lopez at UAF. Fish samples were stored in a portable cooler with ice or frozen gel packs until they could be frozen in Kotzebue.

Field logistics
We accessed sampling lagoons located in Cape Krusenstern National Monument via base camps at the NPS Ranger Station at Anigaaq and the Killikmak Airstrip. We did not enter the ranger station, but tent

camped nearby, using the station as a windbreak. Golden Eagle Aviation of Kotzebue ferried personnel and equipment between Kotzebue and these base camps with wheel plane landings (Figure 3). Lagoons sampled in Cape Krusenstern included Krusenstern, Aukulak, and Kotlik. We did not visit Bering Land Bridge lagoons during the 2021 field season due to unresolved flight logistic challenges (lack of float plane available for work and inability of Golden Eagle Aviation to conduct beach landings).

Figure 3: WCS field technicians Thomas House and Michael Lunde getting picked up by Golden Eagle Aviation, after conducting fieldwork at Kotlik Lagoon in June 2021.

To reach Krusenstern Lagoon, we boated from Anigaaq up the Tukrok River and through the adjacent wetland, following GPS tracks of the stream channel generated from Google Earth. We utilized two navigable routes through the network of waterways, islands, shallows that made up the wetland. Both routes were accessible all season and were approximately equal in travel time; however, as the season proceeded, higher water levels made it more difficult to visually mark the channels. Sampling at the Tukrok River mouth was performed near our base at the ranger station. To reach Aukulak Lagoon, we boated from the ranger station to the mouth of the Tukrok River, then SE along the Chukchi Sea coast. Because Aukulak was not open to the Chukchi, we portaged the boat and gear across the marine edge berm into the lagoon. We accessed Kotlik Lagoon directly from the Killikmak Airstrip, and while visiting we set up camp and staged gear on the marine edge of the lagoon.

Throughout the 2021 field season, our team partnered with several individuals based in Kotzebue representing different organizations and agencies. Tahzay Jones and other National Park Service personnel provided vital advice and logistical support. We also relied on Alex Whiting of the Native Village of Kotzebue, who provided logistical assistance and insight into our study sites. Additionally, Bill Carter of the Selawik National Wildlife Refuge provided advice and knowledge on subsistence whitefish species included in our research.

FIELD NOTES FOR SAMPLED LAGOONS

Krusenstern

June 21st and 22nd

We sampled Krusenstern Lagoon for the first time in 2021 on June 21st. Snow patches remained in shaded areas and the vegetation was not yet green. We collected drinking water by boiling snow and by boating ~1 mile up the Situkuyok River from its confluence with the Tukrok River to fill carboys. We observed the Tukrok River/Krusenstern Lagoon outlet was open to the sea. With three personnel, a fyke net, gillnets, and extra fuel, travel was slow up the Tukrok River to the lagoon, taking approximately two hours to travel the ~14 km from Anigaaq base camp. While traveling to the lagoon we observed a herd of musk oxen, tundra swans, several jaegers, and a multitude of waterfowl and shorebirds. Upon arriving at the lagoon, the area that, in the past several field seasons has been the opening between the main body of the lagoon and the Tukrok River channel was blocked by a gravel berm, making boating straight into the lagoon impossible. We portaged the gear and boat over the berm and fished right inside what has historically been the mouth. As we prepared to unload gear, a young grizzly bear approached us multiple times along the narrow berm of the lagoon, likely attempting to reach the terrestrial edge. After deterring the bear by yelling, grouping together, and waving, it eventually caught our scent and ran off along the berm towards the marine edge of the lagoon. We set an onshore and offshore gillnet, and checked these two times each, every 30 minutes (to avoid fish mortality due to wave action and high volume catches). A fyke net was set for 4 hours and checked twice, and two beach seine pulls were performed. We boated back to Anigaaq that evening. The following day we returned to Krusenstern and proceeded to collect water quality data throughout the lagoon enroute to the marine edge and freshwater inlet fisheries monitoring sites. At each of these locations, we conducted three onshore and offshore gillnet sets for durations of 20 minutes-1 hour depending on catch rate and wave action. Two beach seines were also deployed at each site. At the end of the day, we boated across the lagoon (10 km from the freshwater inlet site to the outlet site) and back to camp at Anigaaq.

August 21st and 23rd

We revisited Krusenstern for the second round of sampling on August 21st. The Tukrok River/lagoon outlet was closed to the sea and water levels in the river and wetlands surrounding the lagoon were high. We boated up the Tukrok River to the typical Krusenstern Lagoon opening, which was breached during this visit. We observed a herd of muskoxen along the river channel, and a mother grizzly bear with three cubs along a high bank. Onshore and offshore gillnets were set near the open mouth of the lagoon and checked three times each, every 20 minutes and two beach seines were performed. Next, we attempted to cross the lagoon to the marine edge fisheries sampling site, but were turned back by large waves and water pooling in the boat. We returned to Anigaaq, and made another attempt to sample the lagoon two days later, under calmer conditions. On this second attempt, we conducted water quality measurements throughout the lagoon, and at the marine edge and freshwater inlet fisheries sampling sites set onshore and offshore gillnets (three checks each per site, 15-30-minute set times) and conducted 2-3 beach seines. We boated back across the lagoon and set a fyke net at the lagoon outflow site for 2 hours, but curtailed further sets due to high numbers of juvenile herring and stickleback captured (risk of mortality). We also attempted two 100-m Mysidae benthic tows from the boat, which yielded ample samples to be retained for sorting in the laboratory. Subsequently, we returned to Anigaaq.

Tukrok River Channel/Anigaaq

We sampled the Tukrok River mouth by the ranger station on June 23rd. A fyke net was set for four hours and checked twice, and three beach seines were attempted. The weather was warm and sunny and the sea was calm, with ice chunks floating some distance offshore. During the June and August sampling trips, fly fishing was attempted at the Tukrok River mouth for several hours without success (three humpback whitefish and flounder were foul-hooked and released).

Aukulak

June 24th

Sampling at Aukulak Lagoon was attempted on the morning of June 24th. We boated 1.6 km down the Tukrok River from Anigaaq through the open river mouth and 4 km down the coast to the typical breaching location of the lagoon, which was closed to the Chukchi Sea. We portaged the boat and gear over the lagoon berm and began sampling near the breaching location, within the lagoon. At the outlet site, we set onshore and offshore gillnets, each soaking for one hour a set and set twice apiece, and conducted two beach seine pulls. We set a fyke net for four hours, checking every two hours. Next, water quality data was collected throughout the lagoon and the freshwater inlet and marine edge fisheries sampling sites were visited. Hour-long onshore and offshore gillnets were set (twice each) and two beach seines were conducted at each fisheries sampling site, but no fish were caught. At the end of the day, we portaged the boat over the lagoon berm at the marine edge sampling site, then returned to Anigaaq.

Figure 4: Setting a fyke net near the Aukulak Lagoon outflow site in August 2021. Aukulak Lagoon did not open to the ocean in 2021 and thus held very few fish.

August 22nd

We traveled to Aukulak Lagoon on the 22nd of August, having to portage the boat across the closed mouth of the Tukrok River and the closed mouth of Aukulak Lagoon. We set a fyke net for 4 hours (Figure 4) and onshore and offshore gillnets (two hour-long sets each), and conducted two beach seines at the lagoon breaching site, but only caught one pond smelt. We observed several fat tire bicyclists break camp along the beach and begin to cycle southwards towards Kotzebue. We conducted two 100-m tows with a benthic Mysidae net, but only captured large numbers of freshwater zooplankton. Next, we boated throughout the lagoon to collect water quality data and access the freshwater inlet and marine edge sampling sites for fisheries work. Onshore and offshore gillnet sets and beach seines yielded no fish, though three Alaska blackfish were captured at the freshwater inlet site in the Mysidae tow net during three 50-m tows along shore. Two Mysidae tows were also conducted at the marine edge site, but only zooplankton were captured. One sample was retained for potential sorting in the laboratory. We portaged the boat over the berm by the marine edge site and boated back to the Tukrok River mouth, portaging again. Two subsistence practitioners were digging a traditional fish capture channel in the gravel berm, and we gave them lots of space to conduct their work without distraction. Schools of humpback whitefish were observed splashing near the closed river mouth as we returned to Anigaaq.

Kotlik

June 25th and 26th

We arrived at Kotlik on June 25, and noted the lagoon was open to the ocean. A large snowfield was present at the lagoon outlet area and jutted into the lagoon. First, we set a fyke net for six hours (checking it three times), three onshore gillnet sets, and conducted two beach seines at the lagoon outlet area. Notably, a large sheefish was captured. The next day, we boated throughout the lagoon conducting water quality measurements and fisheries sampling at the freshwater inlet and marine edge sites. Onshore and offshore gillnets were set at each site and checked every 15 min-1 hour (three sets each), and 2-3 beach seines were performed. Large-bodied fish were observed at the freshwater inlet site (Jade Creek), and fly fishing methods proved effective for capturing several of these fish, which were medium-sized sea-run Dolly Varden. We observed a solitary cow moose crossing Killikmak Creek when collecting freshwater on the second day. Drinking water was fond to be slightly salty, so we sourced a new carboy of it by boating several hundred yards up Jade Creek. Fly fishing was attempted by two crew members near the marine opening for two hours on the evening of the 25th, but only a saffron cod was caught.

August 24th- 26th

We arrived at Kotlik to sample for the second time on August 24th and the lagoon had closed to the ocean. Because poor weather was due to set in the following day, we boated throughout the lagoon to conduct water quality and fisheries sampling at the freshwater and marine edge sites. 2-3 onshore and offshore gillnet sets of 15 min-1 hour were set at each site, and two beach seines were performed. Additionally, 100-m Mysidae tows were conducted at each site, and yielded ample volume to be retained for sorting in the laboratory. The following day we set a fyke net for six hours, three hour-long gillnet sets, and conducted two beach seines at the lagoon outlet.

RESULTS AND DISCUSSION

Water Quality

Salinity

Physical and chemical properties varied between lagoons. Krusenstern and Kotlik Lagoons were open to the marine environment and Aukulak was closed during the first round of sampling in June, and all were closed during the second round of sampling in August. Average salinity levels at all lagoons dropped between the first and second sampling rounds (Table 4), likely because of the lack of saltwater intrusion thanks to closed marine openings and significant rainfall that preceded the final sampling excursion. Kotlik Lagoon exhibited the most dramatic decrease in mean salinity between seasons (From 11.03 to 7.56 ppt), undoubtedly because of the short-distance channel allowing significant saltwater inflow in June, which was absent in August. Because of the long channel to the ocean at Krusenstern preventing significant saltwater intrusion, and the lack of marine connection at Aukulak Lagoon, these sites remained relatively low in salinity throughout 2021 (2.7 - 4.0 mean ppt). Krusenstern has shown consistently low mean salinity from 2012-2021, always <6 ppt, because the main body of the lagoon is more than 14 km distant from its primary exchange with saline water from the ocean. However, in the past, when open to the marine environment, Aukulak has had relatively high mean salinity levels (e.g., 25.37 ppt in 2016 and 18.3 ppt in 2015), facilitated by its short marine channel. Mean salinity levels at Kotlik Lagoon in 2021 were comparable to historical values, which are highly variable and have ranged from 3.79 – 23.61 in the early summer season and 1.32 – 21.83 in the late season (Table 4). It is clear after almost a decade of investigations by WCS that the influences of lagoon connectivity to the ocean, distance of the lagoon from the ocean, and freshwater input from rivers and precipitation drive seasonal and annual salinity levels for Cape Krusenstern National Monument lagoons.

Temperature

Mean water temperature at all three lagoons decreased over the course of the 2021 season (Table 4), which mirrors trends seen in all lagoons from 2015—present. This is likely due to more solar warming and less precipitation occurring in the months of June-July, and increased cold freshwater input and cooler air temperatures in August-September due to storms and the onset of autumn. Average temperatures in Aukulak and Kotlik Lagoons in the early season (20.30 and 16.47 C, respectively) were higher than any from 2012-2018, perhaps indicating a warmer-than-average June in 2021. Mean temperatures for early and late-season Krusenstern and late-season Aukulak and Kotlik Lagoons fell within the range of those seen for those locations from 2015-2021 (5.11 – 16.28 C across lagoons and seasons; Table 4).

Dissolved Oxygen

Mean dissolved oxygen levels (DO) at all three lagoons across seasons were comparable to readings from 2012-2018 with average overall concentrations ranging between 100.9 and 115.98% saturation among lagoons (Table 5). Dissolved oxygen readings decreased from the early to late seasons across all lagoons, likely reflecting oxygen depletion from algal and other biotic processes later in the summer. Additionally, the lack of connection and water flow between lagoons and the marine environment in the late season that facilitates water cycling and mixing likely contributed to this decrease. However, DO levels across all lagoons and seasons indicate overall favorable, normoxic conditions for occupancy by fishes and other biota (>96% saturation; Davis 1975).

pH

Average pH was highest at Krusenstern Lagoon (7.80), which mirrors its ranking among lagoons in all previous seasons from 2012-2018 (Table 5). Similar to all seasons except 2012 and 2015, Aukulak Lagoon exhibited the lowest pH in 2021 (7.25), while Kotlik was in the middle (7.45). However, average pH for each lagoon in 2021, respectively, was lower (range 7.25 – 7.45) than during 2012-2018 (range 7.36 – 9.77). Additionally, pH decreased from the early (range 7.90 – 8.42) to late season (range 6.61 – 7.17) in 2021 across all lagoons. It is unclear why pH was lower in the late season, and lower compared to previous years. This indicates a shift towards greater acidity in 2021 (and in the 2021 late season), yet levels are comparable to Beaufort Sea estuarine environments near Prudhoe Bay (Khalsa et a. 2021) and remain well above a threshold that would result in stress or mortality among aquatic biota (threshold <6).

Turbidity

Turbidity was lowest at Kotlik Lagoon in 2021 (mean 2.51 FNU), and highest at Krusenstern (6.54 FNU) (Table 5). Between early and late sampling seasons, mean turbidity greatly increased from a range of -0.71 – 0.82 across lagoons to a range of 5.12 – 11.44 FNU. This is attributed to an uncommonly wind and rain-free June sampling window, resulting in very little wave-driven turbation of lagoon sediments and no freshwater runoff-driven suspended sediment. In contrast, during our August visit, heavy rain preceding sampling efforts and windstorms occurring throughout the duration of the field effort resulted in heavier loads of suspended sediment in most lagoons. In addition, stagnation of water due to lack of marine connectivity and increased abundance of suspended zooplankton in lagoons during the late season likely contributed to this result. Overall, when compared to previous years, the range of turbidities in lagoons in 2021 fell within those previously observed from 2012-2018 (-5.57 – 29.16 FNU), which were highly variable among lagoons and years. However, mean turbidity was always highest in Krusenstern Lagoon across years, undoubtedly reflecting the tendency for this lagoon to exhibit significant wave-driven turbation of sediment, due to its large surface area and fetch length.

Primary Productivity

As in most previous years from 2012-2018 (except 2015), primary productivity was highest at Krusenstern Lagoon in 2021, with a mean total chlorophyll level of 3.56 RFU and mean blue green algae (BGA) reading of 0.92 RFU (Table 5). Atypical in comparison to all previous years except 2015, Aukulak exhibited the lowest productivity with mean chlorophyll concentration of 1.01 RFU and BGA of 0.17 RFU. Chlorophyll concentrations increased in all lagoons from the early to late sampling season, and BGA levels mirrored this trend (except in Aukulak Lagoon). However, overall, indices of primary productivity were lower than in previous years (Table 5), likely due to poor algal growing conditions caused by an uncommonly stormy and rainy summer as reported by local residents (Jared Cummings, *personal communication*). Contrasting with prior years, we did not observe high concentrations of algae (visible blooms) at any of the lagoons during either sampling season, lending further support to this inference.

Mysidae Sampling
Benthic tows for Mysidae were performed at all lagoons, with 3-5 samples taken per lagoon, in lagoons where Mysidae were encountered. The custom-fabricated tow net was effective at capturing hundreds-thousands of Mysidae in varying habitats, whether deployed by wading or from the boat, with only minimal debris included in samples. Stickleback species, pond smelt, and Alaska blackfish had to be picked out of samples immediately after conducting tows to avoid fish mortality. Mysidae were not present in Aukulak Lagoon, due to a presumed overwinter die-off of most aquatic biota, a result of the lagoon being disconnected from the ocean since July 2020. Samples were frozen, are being held, and will be sent to University of Alaska facilities in Juneau to be analyzed for species composition, density, proximate composition, and stable isotope analysis. Additional Mysidae sampling in future field seasons will be attempted to collect data from lagoons that were neglected (Ikpek and Kupik) and to fill gaps in sampling sites (Krusenstern marine edge and inflow, Aukulak if connected to the ocean).

Fish Sampling
Overall assemblage composition, abundance, and length
Across all lagoons and seasons we performed thirty-eight beach seine pulls, 13 fyke net sets, 75 gill net sets, and five man-hours of angling (Figure 6) during 2021 fisheries sampling efforts. This amount of sampling effort was greater than in 2018 but not as extensive as in 2016 (Table 6-7), though largely comparable to previous years. 1,726 total fish were captured and processed, which was far fewer than all previous seasons (2015-2018 mean total catch = 22,184) except for 2012 (total catch = 114 fish), despite similar effort each year. This lower overall abundance is attributed to markedly lower numbers of small-bodied fishes such as stickleback, herring, and juvenile salmon; cessation of fishing efforts to avoid mortality when catch numbers were high; plus Aukulak Lagoon being nearly fishless throughout 2021.

Fish species richness and relative abundance in lagoons varied, with population composition and abundance differing between season, lagoon, and year (Figures 11-13). In 2021 we recorded a total of 20 different species including the typical forage and subsistence taxa seen in previous years such as stickleback, herring, pond smelt, whitefishes, flounders, and saffron cod (Table 8). However, several species that had rarely or never been encountered in previous lagoons investigations were caught, including broad whitefish, yellowfin sole, Arctic grayling, Alaska blackfish, and slimy sculpin. Conversely, notable absent taxa included Pacific salmon species, belligerent sculpin, capelin, and sand lance.

Lagoons in 2021 exhibited the same number of fish species as in 2018 (20), slightly higher than 2017 (19 species), but lower than in 2016 (25) and 2015 (23) (Table 8). Overall, diversity was highest at Kotlik Lagoon with 16 different species caught, and lowest in Aukulak Lagoon (2) because overwinter die-offs and lack of marine connectivity resulted in it being nearly barren of fish in 2021 (Figures 6-8). This represented a marked change from 2018 results, when Aukulak exhibited the highest diversity among lagoons. No trends were observed in species diversity and abundance across seasons, showing high variability between and within lagoons, across seasons (Figures 6-8).

Mean length (body size) of commonly-caught subsistence-harvested species has remained at overall consistent levels from 2012-2021, though much interannual variability is present (Figure 5). Fish mean length in Kotlik Lagoon decreased from early to late season in 2021, across all species that were found in both seasons (Table 12). This is likely due to large-bodied, mature migratory fish departing the lagoon and small-bodied young-of-the-year fishes that were too small to catch in the early season growing large enough to be captured in higher numbers by our gear. Previous sampling efforts have revealed a similar decrease in abundance of large-sized migratory species (e.g. sheefish, humpback whitefish) towards the end of the summer as they leave or attempt to leave the lagoons, likely in response to spawning cues or the imminent loss of connectivity to overwintering habitat during freeze-up. Of particular note, a 630-mm Dolly Varden and 359-mm Arctic grayling were caught in Kotlik Lagoon in June, representing by far the largest specimens of these species ever captured in the lagoons by WCS efforts from 2012-2021. Five Dolly Varden including this record-sized fish were caught via fly rod angling (Figure 6), highlighting the utility of this gear type for capturing larger-bodied, more elusive fishes.

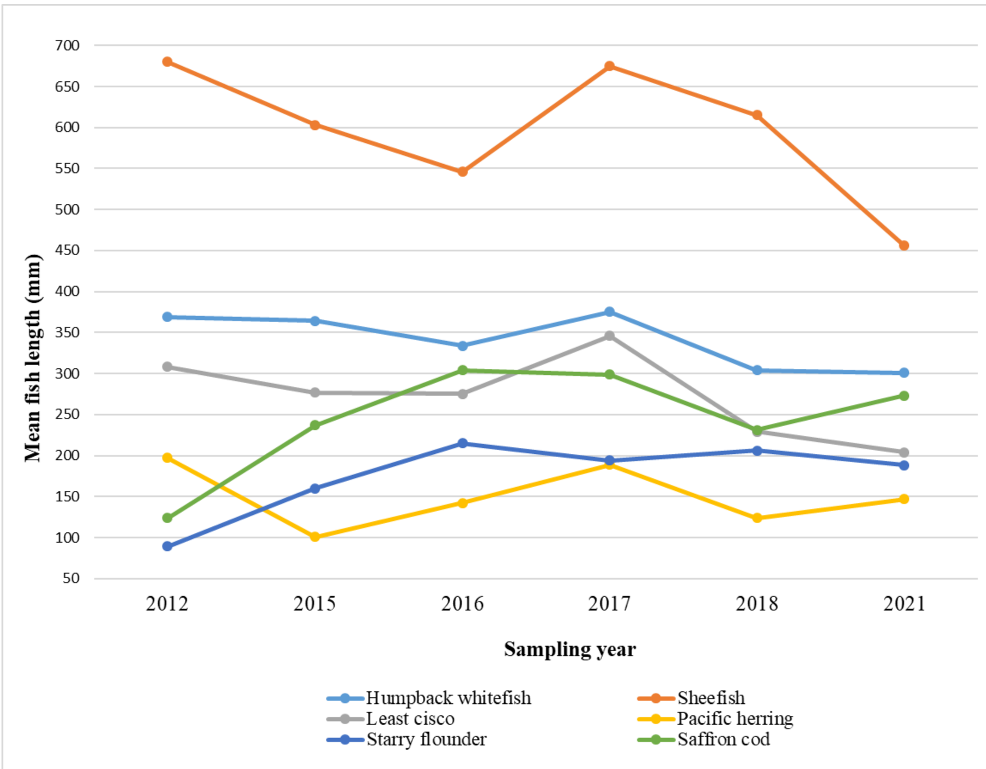

Figure 5: Mean lengths by year for Cape Krusenstern National Monument lagoon fish species of subsistence importance. Note that data is pooled across seasons and sites, and sample size by species is variable. Fork length is used for fishes with forked tails, and total length is used for all others.

The seasonal declining pattern in mean fish length seen at Kotlik was not as clear at Krusenstern Lagoon, where large-bodied broad whitefish, Bering cisco, and sheefish were indeed absent in the late season, but mean size for humpback whitefish and least cisco increased from the early to late period (Table 12). Large schools of humpback whitefish were observed attempting to enter the ocean at the closed Tukrok River mouth during the final sampling effort of the season, which mirrors observations from the 2017-2018 seasons and indicates large-bodied migratory fish had mostly departed Krusenstern Lagoon proper. Inferences about Aukulak Lagoon fish length and abundance dynamics were not possible, because no fish were captured in the early season and only 4 individuals were found during the late season. Fish lengths and weight were recorded for the June sampling effort at the Tukrok River mouth (Table 12), but because this site was not resampled in the late season, no evaluation of seasonal trends in fish size is possible.

Kotlik Lagoon

During the early sampling period in June, 130 fish comprising 10 species were caught (Table 10). The outflow and marine edge sites exhibited higher abundance of fish compared to the freshwater inlet site. At the outflow, because the lagoon marine connection was open, marine-oriented taxa such as saffron cod

(64% of the catch), Pacific herring (18%), and starry flounder (10%) dominated (Figure 7), with only one diadromous Coregoninae captured (a large sheefish). Ninespine and threespine stickleback were present, but in low numbers (3 individuals). At the marine edge site, only Pacific herring (93% of the catch) and starry flounder (7%) were present. A notably large starry flounder (420 mm) was captured, the largest of the species caught in 2021 and the largest WCS has encountered since 2017. The freshwater inflow site held fewer fish, but diadromous Dolly Varden (8%) and humpback whitefish (4%) were present, along with a single freshwater-oriented Arctic grayling (Figure 7).

Figure 6: WCS technician Michael Lunde with a Dolly Varden char caught via fly rod angling methods, measured, and sampled for contaminants analysis at the Kotlik Lagoon inlet site (Jade Creek) in June 2021.

The ubiquitous marine-oriented Pacific herring and starry flounder made up the majority of the catch (86%), and a single Bering cisco was also captured at the site. Despite catching only a small number of Dolly Varden and grayling, along the first 200 yards of Jade Creek we visually observed more than 50 medium-large Dolly Varden schooling in the clear water and at least a dozen grayling rising to the surface to eat winged insects. Beach seines and gillnets were not effective at capturing these elusive fishes, and angling was only moderately successful (Figure 6), thus the percentage of Dolly Varden and grayling is an underestimate. Grayling were not previously recorded at this lagoon, so encountering them during this sampling excursion was noteworthy. Interestingly, the largest grayling and Dolly Varden captured at the site represented the maximum size recorded (359 and 630 mm, respectively) for these species in all WCS lagoons sampling efforts from 2012-2021.

Fish assemblage composition changed drastically by the late season (August), shifting to more diadromous whitefishes and forage fishes and fewer marine taxa, undoubtedly because the lagoon was disconnected from the ocean. Overall abundance (278 individuals) and diversity (13 species) was higher than in the early season, and the outflow site exhibited the highest abundance. At the outflow site, threespine stickleback (52%), humpback whitefish (22%), and least cisco (18%) dominated the assemblage, with marine–oriented starry flounder and fourhorn sculpin comprising a modest 6% of the catch (Figure 7). One individual each of Bering cisco, sheefish, juvenile Dolly Varden, rainbow smelt, pond smelt were captured. Pacific herring and saffron cod were noticeably absent, indicating the seasonality of their lagoon occupancy and their reliance on ocean connectivity. The marine edge site of

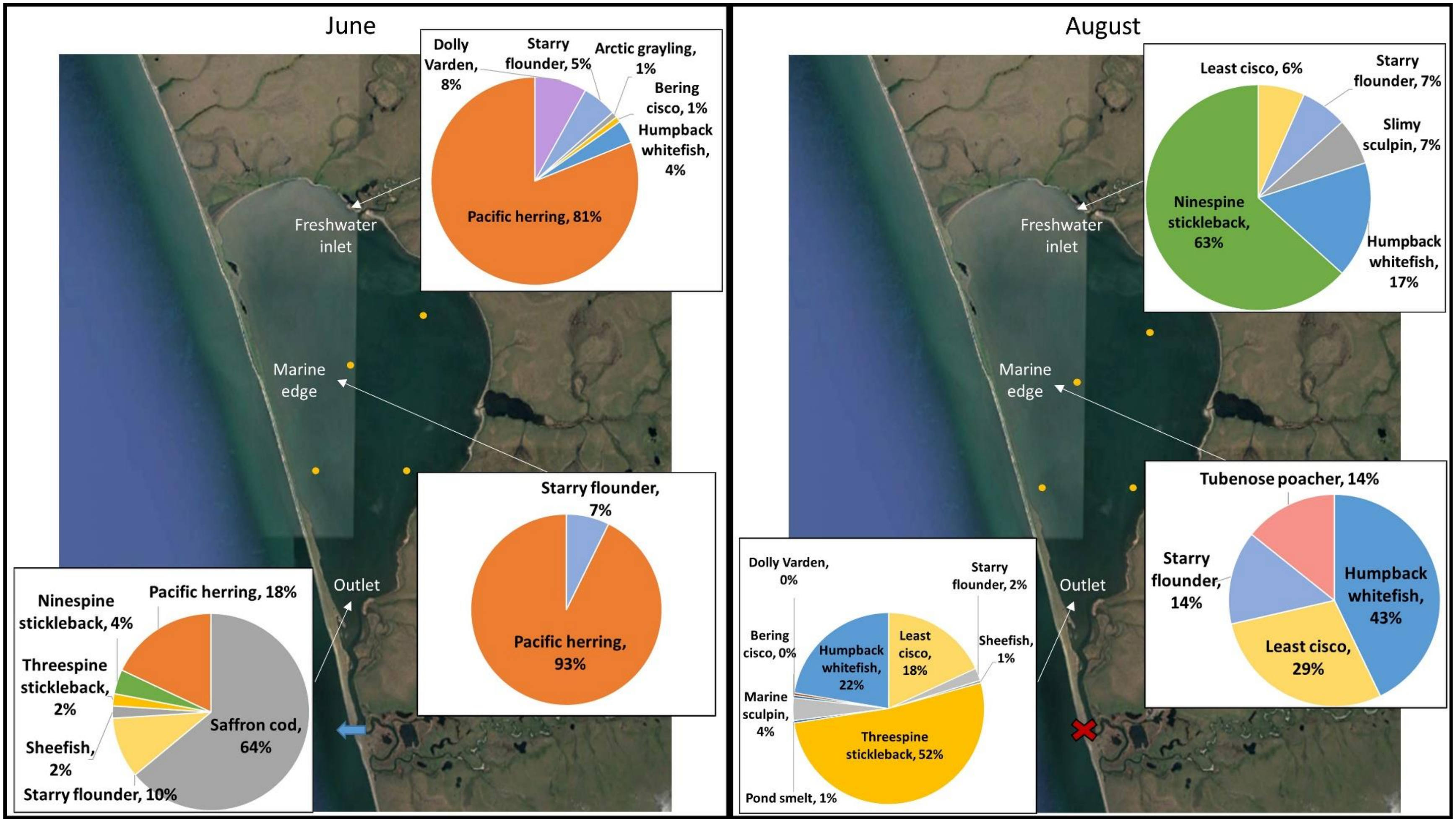

Figure 7: Fish assemblage composition for sampling locations in Kotlik Lagoon during June and August 2021 visits. A red "X" indicates the lagoon outlet was closed to the sea, while a blue arrow indicates the marine connection was open during time of sampling. Yellow dots indicate water quality sampling sites (fish sampling sites were also sampled for WQ).

the lagoon was quite depauperate, and only three humpback whitefish, two least cisco, one starry flounder, and one tubenose poacher were encountered. The freshwater inflow site boasted higher abundance and diversity, with many ninespine stickleback (63% of catch) caught in beach seines and mysid tows, a moderate number of diadromous whitefishes (23%), and a single representative each of starry flounder and freshwater slimy sculpin (Figure 7). Slimy sculpin had not been previously sampled in lagoons by WCS, although they are common in freshwaters in the region. The large pod of Dolly Varden seen during the early season was absent during this visit, although Arctic grayling were observed rising to eat insects ~100 m upstream in Jade Creek (but none were captured).

Krusenstern Lagoon and Tukrok River mouth
During the early sampling season, 370 fish representing 10 species were captured. Highest abundance was observed at the outflow site, while the freshwater inlet and marine edge sampling locations held relatively few fish (32 and 18 individuals, respectively). Humpback whitefish and pond smelt largely dominated the assemblages across sites. Despite the Tukrok River being open to the ocean, the only marine-oriented species encountered was Pacific herring. This is similar to findings from previous years, where marine taxa are uncommon in the lagoon proper due to the 14 km channel they would have to transit to reach it from the ocean (Table 11). At the outflow, pond smelt were most numerous (43% of catch), followed by ninespine stickleback (25%) and humpback whitefish (15%) (Figure 8). Other diadromous whitefishes made up a combined 4%, and Pacific herring were also present (11%). A single Arctic grayling was also encountered, which was notable because grayling had not been caught at this site since 2015. Bering cisco and broad whitefish captured at this site were of particular interest, because they did not appear during the late season and broad whitefish had not been recorded by WCS in Cape Krusenstern lagoons previously. A notably large herring (295 mm) was caught at the outlet site, the largest captured in 2021 and the exact same size as the largest herring from across-lagoon 2018 efforts. The marine edge site exhibited little diversity, with only humpback whitefish and Pacific herring present (83 and 17% of the catch, respectively). Humpback whitefish were again the dominant taxa at the freshwater inlet site (41%), closely followed by pond smelt (31%). Pacific herring were present, as well as two freshwater-oriented Arctic grayling, a broad whitefish, a sheefish, and a ninespine stickleback (Figure 8). Interestingly, grayling had not been captured by WCS at this site previously, despite the creek inflow habitat appearing highly suitable for them.

In the late season, 560 fish of 4 species were caught throughout Krusenstern Lagoon. The outflow site held the highest number (301 individuals), while the freshwater inlet was much less populated (4 individuals). It is unclear why several species of diadromous whitefish and the freshwater Arctic grayling that were present in the early season were not encountered in the late season. Possibly, diadromous whitefishes had left the lagoon proper or ascended tributaries in preparation for spawning during this time. Pacific herring and ninespine stickleback dominated the assemblages at most sites within the lagoon. At the outlet, Pacific herring comprised the majority of the catch (59%), with ninespine stickleback (33%), humpback whitefish (7%), and least cisco (1%) making up the rest of the assemblage (Figure 8). Similarly, at the marine edge site, herring made up 57% of the catch while ninespine stickleback (40%), humpback whitefish (2%), and least cisco (1%) comprised the rest. The freshwater inflow site was particularly depauperate, yielding only three humpback whitefish and one Pacific herring.

The mouth of the Tukrok River, sampled only in June 2021, yielded a catch of 241 fish of 8 species. Arctic flounder made up the majority of the catch (54%), while other marine taxa such as starry flounder (20%), Pacific herring (1%), and yellowfin sole (<1%) comprised much of the remainder (Figure 8). Diadromous fishes including threespine stickleback (12%), humpback whitefish (9%), least cisco (3%), and ninespine stickleback (1%) were also present. The dominance of marine species at this sampling location is unsurprising, given the proximity and direct connection to the marine environment.

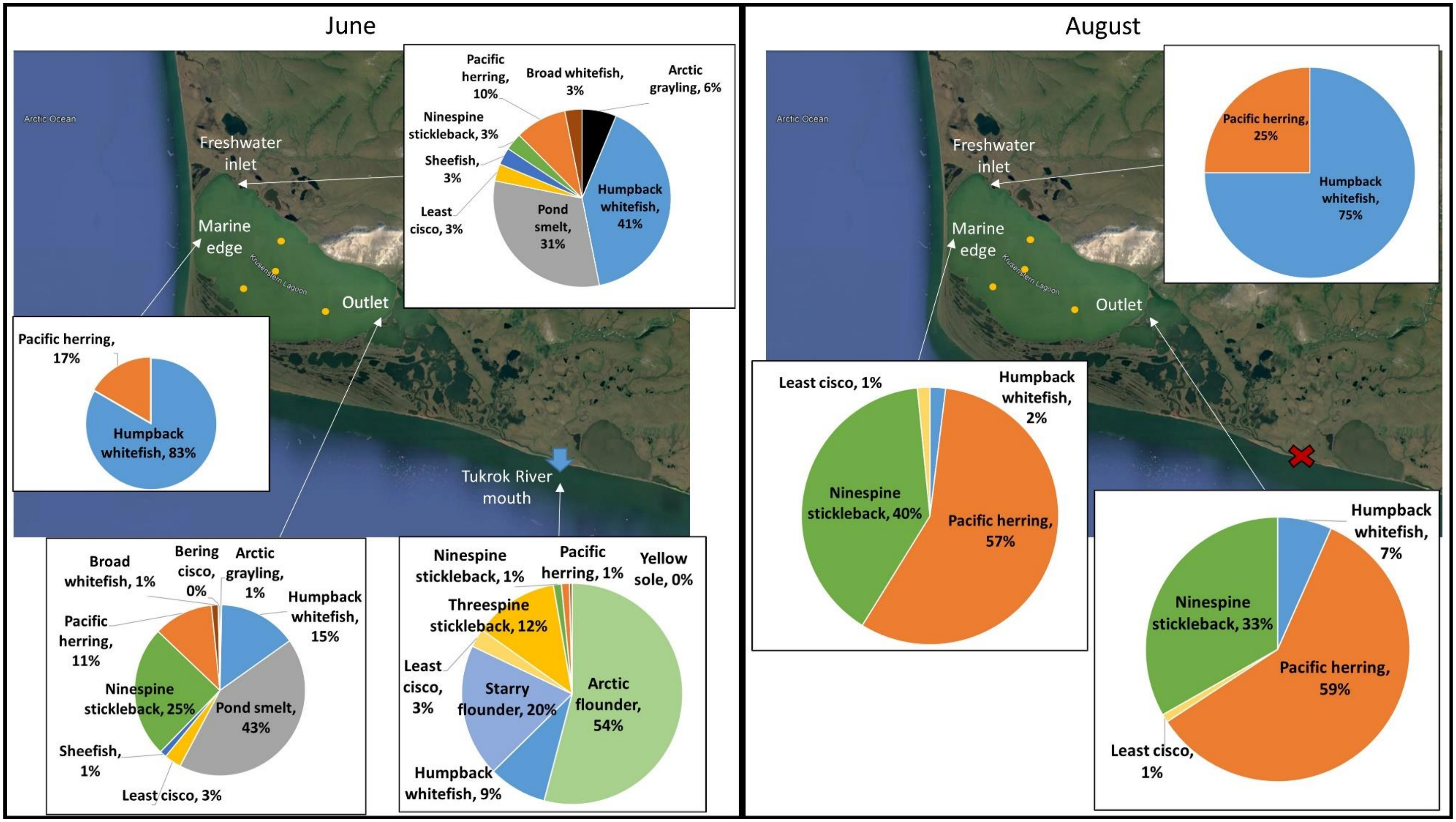

Figure 8: Fish assemblage composition for sampling locations in Krusenstern Lagoon during June and August 2021 visits. A red "X" indicates the lagoon outlet was closed to the sea, while a blue arrow indicates the marine connection was open during time of sampling. Yellow dots indicate water quality sampling sites (fish sampling sites were also sampled for WQ). Note: The Tukrok River mouth site was not sampled in August.

Aukulak Lagoon

No fish were captured in Aukulak Lagoon during the early sampling period in June (Figure 9). Based on similar happenstance in a previous season (2017; Table 9), and by reviewing daily-weekly Sentinel-2 satellite imagery from 2020 and 2021, we inferred that this was due to fish overwintering die-offs and lack of recolonization from the ocean, because the lagoon had not connected to the marine environment since July 4, 2020. During the late sampling period in August, the lagoon had remained closed, but a single pond smelt was captured in a fyke net at the outlet site (Figure 9). Additionally, three Alaska blackfish, a species that had not previously been captured at this lagoon by WCS, were caught in Mysidae tows at the freshwater inlet site. These fish likely represent the few, hardy individuals that were able to overwinter in scant freshwater habitats that did not freeze to the lagoon bottom during the winter of 2020-2021 (Tibbles et al. 2018). These findings are a stark contrast to previous years in which Aukulak boasted the highest species diversity among the lagoons, and highlight the importance of marine connectivity and freshwater overwintering refugia for the occupancy and survival of diadromous subsistence species in Southern Chukchi Sea lagoons.

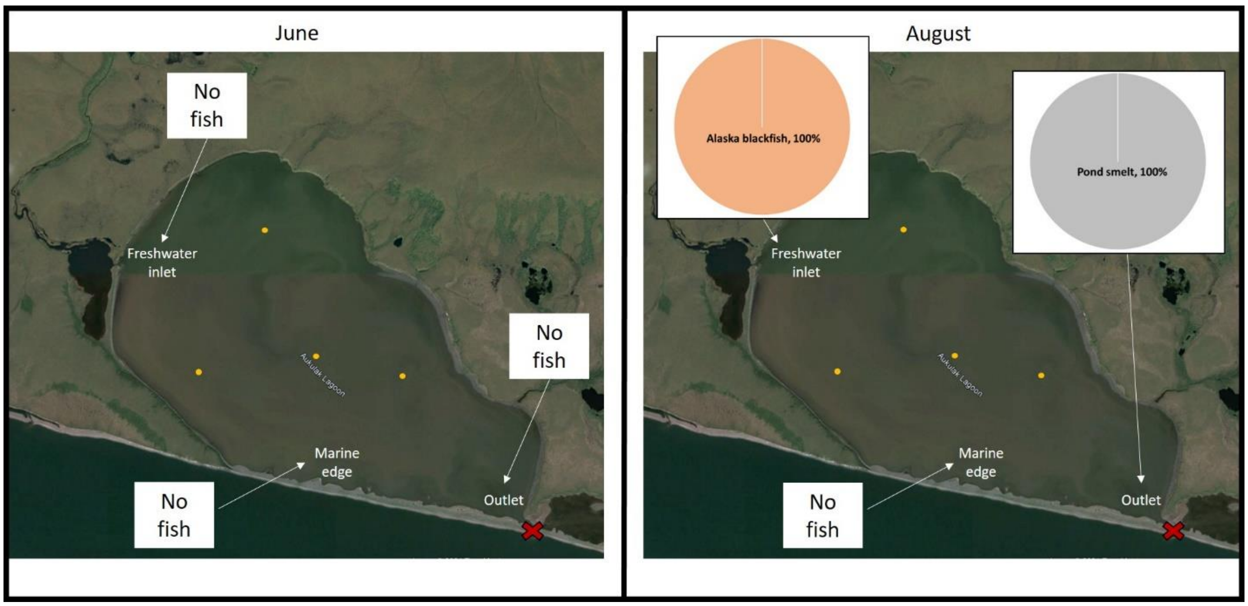

Figure 9: Fish assemblage composition for sampling locations at Aukulak Lagoon during June and August 2021 visits. A red "X" indicates the lagoon outlet was closed to the sea. Yellow dots indicate water quality sampling sites (fish sampling sites were also sampled for WQ). A single pond smelt was captured at the outlet site and three Alaska blackfish at the inflow site during the August visit.

Laboratory Analyses

Mysidae samples taken during the 2021 field season will be evaluated for taxonomy, abundance, stable isotope ratios, and proximate composition. Fish samples were assessed for Per- and polyfluoroalkyl substances (PFAS) contamination (Figure 10; Table 2) and will be evaluated for mercury levels and life history chronology via otolith microchemistry. Stickleback samples from Krusenstern and Kotlik Lagoons are being held for proximate composition and stable isotope analysis. Using results from these analyses we hope to answer several questions including:

- Do subsistence-harvested fishes pose a risk to consumers based on mercury and PFAS loads in muscle tissue?
- What life history patterns are evident in different fish species that occupy coastal lagoons?
- What is the assemblage structure and abundance of Mysidae in Cape Krusenstern lagoons?
- What is the trophic structure and relative energy value of the basal lagoon food web (Mysidae and stickleback)?

Figure 10: American Fisheries Society-WCS Hutton Scholar Kerra Witte and WCS technician Michael Lunde conduct muscle tissue extraction from fishes collected at Cape Krusenstern National Monument lagoons, to be run for PFAS and mercury contaminants analyses.

Preliminary results from laboratory analyses showed that lagoon fish species of subsistence importance contained very little-no amounts of PFAS in their muscle tissues (Table 2), which is excellent news for subsistence and sport fishers who harvest and consume these taxa. However, the sample size is low and composite analyses were employed, where tissue from multiple individuals was homogenized together and analyzed as a single sample to reduce costs. The next step will be to evaluate mercury loads in these fish, the analyses to facilitate this are in-progress.

Fin clips were collected from 50 individual Krusenstern Lagoon Coregoninae during the June sampling visit, and an additional 38 were collected from Kotlik Lagoon Coregoninae in August. These samples were delivered to Professor Andres Lopez at the UAF Museum of the North, for future genomics investigations. Additionally, fin clips and lagoon sediment samples from humpback whitefish, least cisco, and sheefish were collected at the request of Tahzay Jones and delivered to the University of California, Santa Cruz for future eDNA calibration and analyses.

Table 2. Preliminary results from fish PFAS contaminant analyses (ppb). Each species was run as a composite sample (tissue from multiple fish per sample; n=) due to high cost of each sample. "ND" = no detections, "J" = result is less than the reporting limit but greater than or equal to the method detection limit and the concentration is an approximate value, and "B" = compound was found in the blank and sample.

Contaminant	**Dolly Varden** *n*= 2	**Sheefish** *n*= 3	**Humpback whitefish** *n*= 3	**Broad whitefish** *n*= 2	**Least cisco** *n*= 3	**Saffron cod** *n*= 3	**Arctic flounder** *n*= 3
Perfluoroheptanoic acid (PFHpA)	ND	ND	0.69 J	0.52 J	ND	ND	ND
Perfluorooctanoic acid (PFOA)	ND	ND	0.45 J	0.29 J	ND	ND	ND
Perfluorononanoic acid (PFNA)	ND	0.20 J	0.56 J	0.38 J	0.18 J	0.21 J	ND
Perfluorodecanoic acid (PFDA)	ND	ND	ND	ND	ND	ND	0.12 J B

Outputs

Media Outputs/Outreach

Kotzebue Sound Whitefish Ecology handout distributed to the Native Village of Kotzebue: https://drive.google.com/file/d/1tKOPbwysli06b0q8AyePsc8a2r97bEXG/view?usp=sharing

Presentation on lagoon ecology and fish overwintering behavior given to Fairbanks K-12 students as part of the University of Alaska Fairbanks "Fresh Eyes on Ice" program field day. January 15, 2022.

Scientific Outputs

Fraley, K.M., Robards, M.D., Rogers, M.C., Vollenweider, J., Smith, B., Whiting, A., and Jones, T. 2021. Freshwater input and ocean connectivity affect habitats and trophic ecology of fishes in Arctic coastal lagoons. *Polar Biology* 44: 1401-1414.

Fraley, K.M., Robards, M.D., Vollenweider, J., Whiting, A., Jones, T., and Rogers, M.C. 2021b. Energy Condition of Subsistence-Harvested Fishes in Arctic Coastal Lagoons. *Marine and Coastal Fisheries* 13(6): 665-672.

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Fraley, K.M., Robards, M.D., Vollenweider, J., Whiting, A., Jones, T., and Rogers, M.C . 2021. Trophic ecology and proximate composition of marine and diadromous fishes in Chukchi Sea coastal lagoons. Presentation given at the Alaska Chapter American Fisheries Society Annual Virtual Meeting. March 25, 2021.

Future Directions

Data compiled throughout the 2021 field season builds upon baseline information compiled from previous field seasons. While our research encompasses many aspects of lagoon ecology and provides valuable insight into the complexity of these systems, there remain important knowledge gaps that we hope to address in future field efforts.

1. To continue to develop knowledge of basal prey resources that exist in these lagoons, it is important to further expand our understanding of Mysidae diversity and abundance at our study sites. We plan to collect additional Mysidae tow and stickleback samples at sites neglected in 2021, including Aukulak Lagoon and lagoons at Bering Land Bridge National Preserve;

2. In the future we will work to establish a better understanding of movement of species between marine, freshwater, and lagoon environments. This may include otolith microchemistry analyses and satellite and radio telemetry tracking studies;

3. Recent prevalence of blue-green algae blooms in the Chukchi Sea and regional fish and marine mammal die-offs require investigation of fishes as accumulators of toxins and as intermediary vectors causing accumulation of toxins in marine mammals. Are blue-green algae blooms threats to fish and marine mammal populations, or the subsistence harvesters that consume them?

4. While some brochures have been produced and outreach activities conducted describing lagoon ecology work, a comprehensive public database of outputs is needed. Additionally, a video project summarizing ecology work to date, research activities and practices, and subsistence fishermen activities around coastal lagoons is needed, to spread knowledge and increase the awareness of NPS and WCS monitoring and research operations.

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Additional Figures and Tables

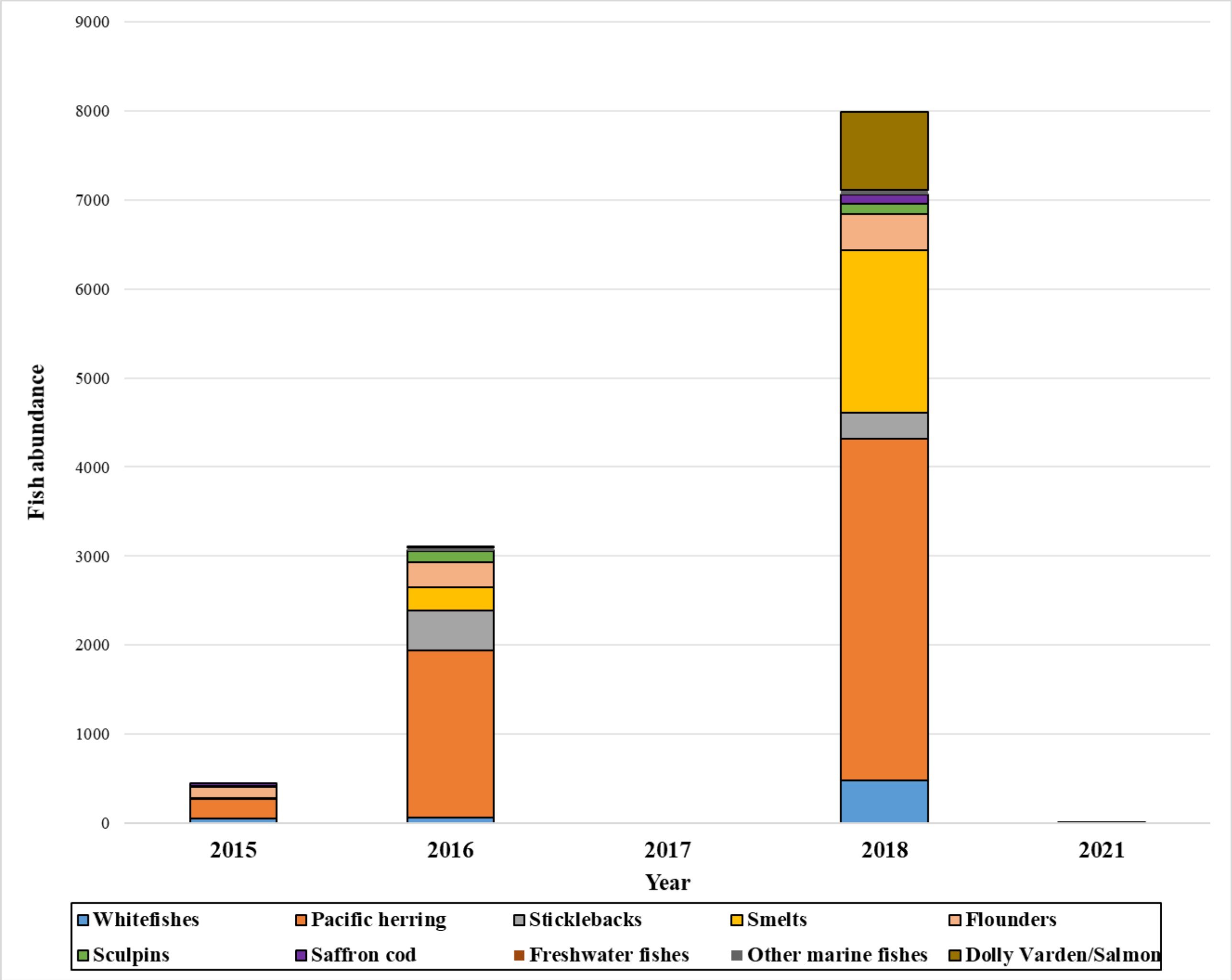

Figure 11: Abundance of fish taxonomic groups in Aukulak Lagoon by year. Note zero and low abundance of all fishes in 2017 and 2021, years when the lagoon did not open to the ocean.

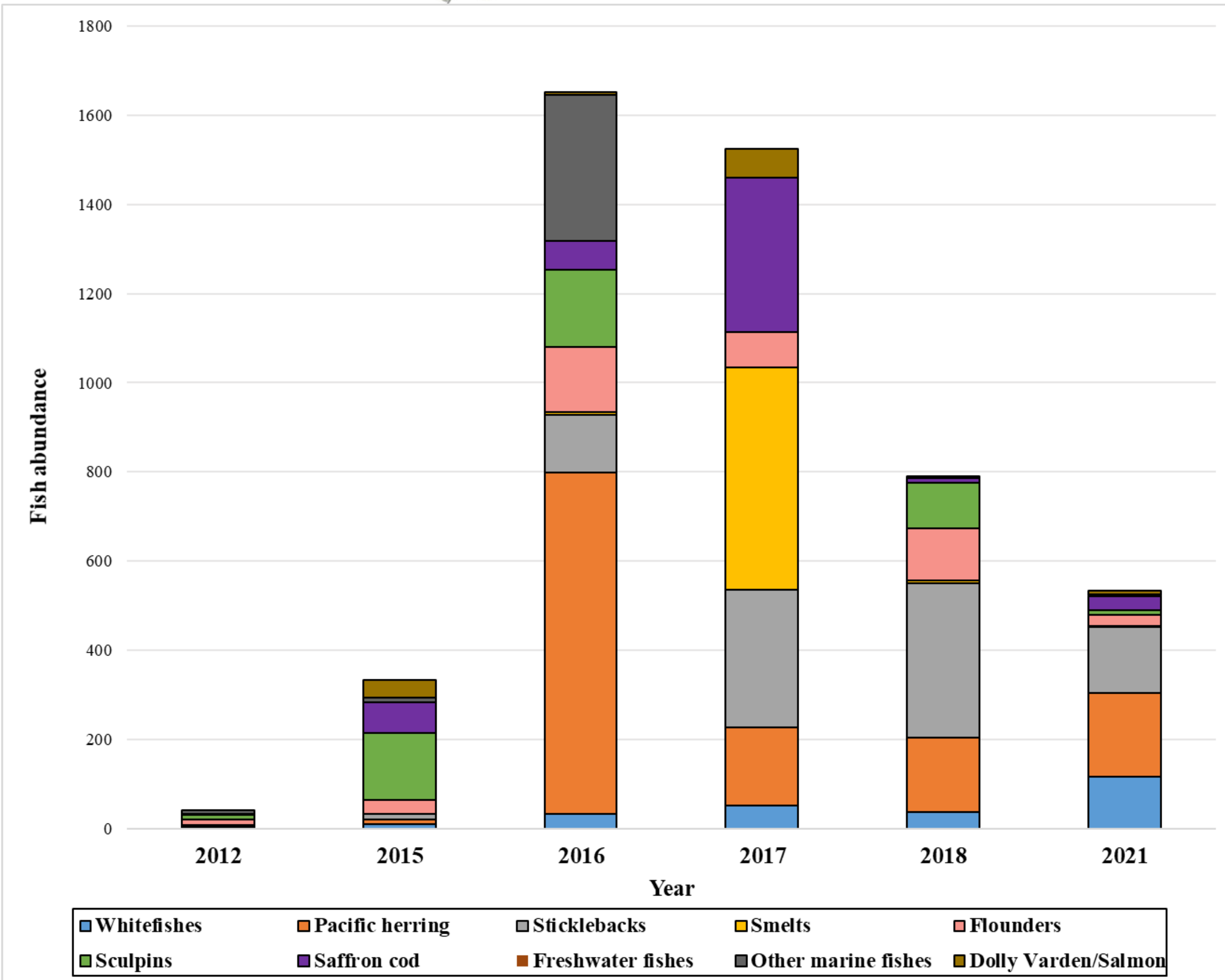

Figure 12: Abundance of fish taxonomic groups in Kotlik Lagoon by year. Note the lower abundance scale compared to Fig. 10.

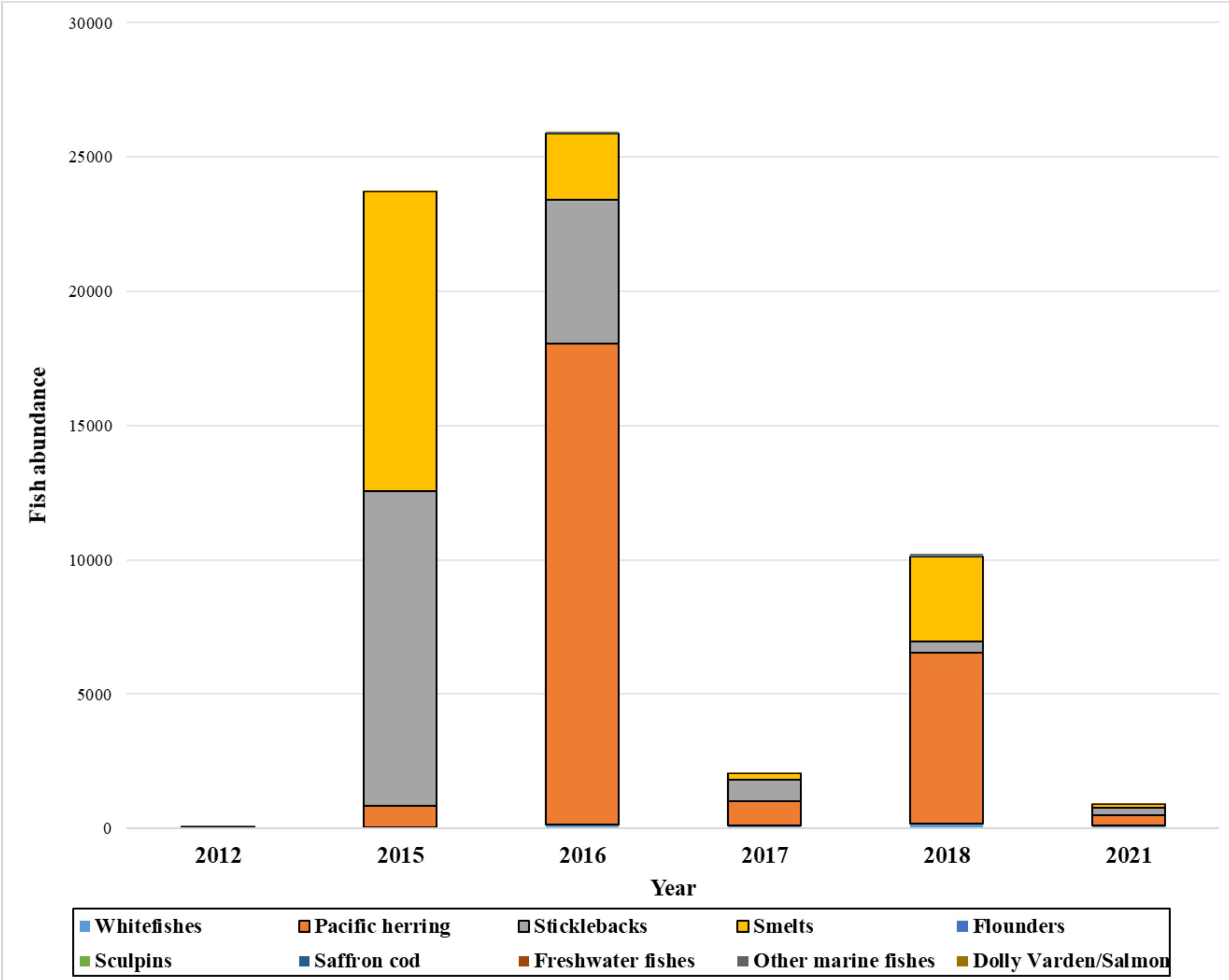

Figure 13: Abundance of fish taxonomic groups in Krusenstern Lagoon by year. Note the higher abundance scale compared to Fig. 10-11.

Table 3. Named lagoons along the Alaska coast of the southern Chukchi Sea ordered from north to south. Lagoon type is listed if known: I = closed to the sea, II = intermittently connected, III = stable-channel connection, and IV = open to the sea with barrier island. Mean physical data are included for lagoons with data available. "U" denotes unknown lagoon type. Fieldwork conducted: FCA stands for Fish Community and Abundance, FC for Fish Contaminants, FSI for Fish Stable Isotopes, FD for Fish Diet, PP for primary productivity, WC for water quality, AV for Avian Surveys, SC for secondary consumers, ST for Seasonal Trends, Z for zooplankton. Asterisk in AWC column indicates a designated anadromous water flows into the lagoon in question. Other lagoons exist in the southern Chukchi Sea region, but are not included here unless named/studied. Sisualik and Espenberg, while lagoons in name, were deemed to not fit the definition of lagoons and thus are not included.

Lagoon	Type	Mean depth (m)	Mean salinity (ppt)	Study	Conservation unit/land management	AWC*	Closest community (distance km)	Field Work Conducted
Marryat Inlet	III	--	--	Tibbles et al. 2020	Alaska Native (Tigara Corp)	Y*	0	FCA, WC
Aiautak	U	< 2.5	0.53	Wilimovsky and Wolfe 1966	Alaska Native (Tigara Corp)	N	11	WC
Kemegrak	I	1.3-3	1.2	Robards and Pinchuk 2020	Alaska Native (Tigara Corp)	N	28	FCA, Z, PP, WC
Akoviknak	I	1.3-3	1.9	Robards and Pinchuk 2020	Alaska Native (Tigara Corp)	N	32	FCA, Z, PP, WC, FSI, FC
Atosik	I	1.3-3	1.6	Robards and Pinchuk 2020	FWS (AMNWR)	N	51	FCA, Z, PP, WC
Mapsorak	II	1.3-3	0.7	Robards and Pinchuk 2020	FWS (AMNWR)	N	47	FCA, Z, PP, WC
Pusigrak	U	1.3-3	1	Dames and Moore 1983	FWS (AMNWR)	N	44	FCA, SC, WC
Singoalik	II	1.3-3	9.3	Robards and Pinchuk 2020	State/BLM	N	40	FCA, Z, PP, WC
Seppings	U	1.3-3	0.8	Johnson 1966	State	N	35	Z, WC
Tasikpak	U	1.3-3	0.7	Johnson 1966	State/BLM	N	30	Z, WC
Pusalak	I	1.3-3	3.6	Johnson 1966	BLM	N	27	Z, WC
Tugak	II	--	--	--	BLM	N	24	--
Kavrorak	U	--	--	--	Alaska Native (NANA)	N	20	--
Asikpak	II	--	--	--	Alaska Native (Kivalina Sinuakmuet)	N	15	--
Kivalina	III	--	--	--	Alaska Native (Kivalina Sinuakmuet)	Y*	0	--

Lagoon	Type	Mean depth (m)	Mean salinity (ppt)	Study	Conservation unit/land management	AWC*	Closest community (distance km)	Field Work Conducted
Imukruk	U	--	1.1	Dames and Moore 1983	Alaska Native (Kivalina Sinuakmuet)/BLM	Y*	6	FCA, SC, WC
Ipiavik	II	--	6.2	Dames and Moore 1983	NANA/NPS (Cape Krusenstern)	Y*	16	FCA, SC, WC
Tsaitsat Angayukangnk (Port)	II	--	1.4	Dames and Moore 1983	NANA/Private	N	26	FCA, SC, WC
Imik	II	0.9	2.5	Reynolds 2012	NPS (Cape Krusenstern)	Y	35	FCA,WC, Z
Kotlik	II	2.1	15.1	Smith et al. 2019 a,b	NPS (Cape Krusenstern)	Y*	46	FCA, FC, FSI, FD, PP, Z, SC, ST, Z
Tasaychek	II	--	7.5	Smith et al. 2019 a,b	NPS (Cape Krusenstern)	Y*	61	FCA, FSI, WC
Atilagauraq	II	--	20	Smith et al. 2019 a,b	NPS (Cape Krusenstern)	N	64	FCA, WC
Krusenstern	II	2.4	3	Smith et al. 2019 a,b	NPS (Cape Krusenstern)	Y*	48	FCA, FC, FSI, FD, PP, Z, SC, ST, Z
Aukulak	II	1.4	15.7	Smith et al. 2019 a,b	NPS (Cape Krusenstern)	Y	32	FCA, FC, FSI, FD, PP, Z, SC, ST, Z
Kotzebue Lagoon	III	--	--	--	State	N	0	--
Kiwalik	IV	--	--	--	State	N*	29	--
Kugruk	III	--	--	--	State	Y*	6	--
Sullivan Lake	U	--	--	--	State	N	18	--
Kupik	IV	--	20.5	Smith et al. 2019a	NANA/NPS (Bering Land Bridge)	N	40	FCA, WC
Shishmaref Inlet	IV	--	--	--	NANA/NPS (Bering Land Bridge)	N*	0	--
Arctic	IV	--	--	--	NANA/NPS (Bering Land Bridge)	N*	10	--

Lagoon	Type	Mean depth (m)	Mean salinity (ppt)	Study	Conservation unit/land management	AWC*	Closest community (distance km)	Field Work Conducted
Ikpek	IV	--	23	Smith et al. 2019a	NANA/NPS (Bering Land Bridge)	N*	48	FCA, WC
Lopp	IV	--	--	--	NANA/NPS (Bering Land Bridge)	N*	3	--

Table 4. Mean (standard deviation) for salinity and temperature at three Cape Krusenstern lagoons over the 2012-2021 field seasons. Early = June-July sample effort and Late = August-September sampling effort.

Year	Lagoon	Early				Late			
		Salinity (ppt)		Temperature (°C)		Salinity (ppt)		Temperature (°C)	
		AVG	SD	AVG	SD	AVG	SD	AVG	SD
2021	Krusenstern	3.94	0.13	15.64	0.75	3.39	0.25	9.69	0.50
	Aukulak	3.95	0.05	20.30	0.12	2.70	0.03	10.00	0.09
	Kotlik	11.03	1.67	16.47	2.23	7.56	0.58	9.68	0.14
2018	Krusenstern	3.65	0.22	16.28	0.19	4.30	0.09	13.45	0.64
	Aukulak	11.86	0.30	15.53	0.42	12.48	0.11	14.36	0.13
	Kotlik	20.83	1.29	14.55	0.46	16.83	1.96	11.25	0.45
2017	Krusenstern	3.28	3.77	15.19	1.83	0.21	0.01	9.64	0.20
	Aukulak	4.63	4.40	14.31	2.97	0.37	0.001	11.75	0.09
	Kotlik	3.79	3.46	15.44	0.37	1.32	0.47	9.60	0.55
2016	Krusenstern	4.01	1.67	15.31	1.07	5.43	0.58	8.85	3.97
	Aukulak	24.69	3.07	16.27	0.48	24.99	1.72	13.26	0.32
	Kotlik	23.61	1.19	15.08	0.92	21.83	3.31	11.20	0.35
2015	Krusenstern	1.32	0.55	15.27	1.30	2.16	0.23	8.07	3.37
	Aukulak	15.12	4.76	18.35	0.94	14.88	0.75	5.11	0.92
	Kotlik	11.82	1.48	15.57	0.54	16.77	5.42	9.39	6.57
2012	Krusenstern	4.03	0.19	12.58	0.10	--	--	--	--
	Aukulak	4.03	1.19	12.29	0.28	--	--	--	--
	Kotlik	17.61	2.50	12.39	0.15	--	--	--	--

Table 5. Mean water quality parameters at three Cape Krusenstern lagoons from 2012-2021. *denotes turbidity measurements recorded in units of NTU, ** denotes measurements made in units of RFU rather than µg/L or mg/L, and ^ indicates measurements were in units of mg/L rather than %. 2021 measurements were pooled across seasons (“Both”) and calculated for each season (“Early” or “Late”), while other years were not split by season for sake of brevity.

Year	Season	Lagoon	Depth (m)	ODO %	Specific conductivity (µS/cm)	pH	Chlorophyll mg/L	BGA µg/L	Turbidity (FNU)
2021	Early	Kotlik	0.9	105.03	18527.98	8.15	0.51**	0.09**	0.27
		Krusenstern	1.27	124.38	7122.08	8.42	1.56**	0.30**	0.82
		Aukulak	0.67	102.22	7168.48	7.90	0.95**	0.07**	-0.71
	Late	Kotlik	0.95	98.81	13060.22	6.63	3.17**	0.91**	5.12
		Krusenstern	1.12	107.59	6191.48	7.17	5.27**	1.45**	11.44
		Aukulak	1.13	99.58	5012.48	6.61	1.07**	0.28**	5.90
	Both	Kotlik	0.94	102.16	16004.4	7.45	1.74**	0.47**	2.51
		Krusenstern	1.17	115.98	6656.78	7.80	3.56**	0.92**	6.54
		Aukulak	1.01	100.9	6090.48	7.25	1.01**	0.17**	2.60
2018	Both	Kotlik	1.36	102.98	27615.36	8.38	1.64	17.88	1.89
		Krusenstern	2.13	108.57	7109.08	9.15	27.12	181.76	15.64
		Aukulak	1.07	102.10	20417.58	8.05	8.41	84.80	10.40
2017	Both	Kotlik	2.14	104.66	5499.04	7.70	2.91	0.49	-5.57
		Krusenstern	2.38	112.73	3601.84	8.79	13.82	2.22	29.16
		Aukulak	1.47	100.82	13282.78	7.36	3.66	0.74**	3.07
2016	Both	Kotlik	1.58	117.67	35916.41	8.28	2.77	0.38	27.45
		Krusenstern	2.04	119.94	11644.39	8.6	29.30	1.50	28.89
		Aukulak	1.13	122.13	39794.61	8.1	3.64	0.48	11.61
2015	Both	Kotlik	1.76	11.87^	28558	7.89	2.21**	-0.59**	9.43*
		Krusenstern	2.1	11.83^	3505	8.02	2.14**	-0.67**	9.73*
		Aukulak	1.14	11.76^	26728	7.97	1.78**	-0.75**	7.25*
2012	Both	Kotlik	1.01	114.09	28500	8.84	2.89	--	41.89*
		Krusenstern	1.10	122.44	7290	9.77	84.27	--	56.90*
		Aukulak	0.86	111.01	7990	8.87	4.64	--	35.90*

Table 6. Number of gear sets at Cape Krusenstern National Monument lagoons by type for each year sampled.

Gear Type	Year 2015	Year 2016	Year 2017	Year 2018	Year 2021
	Number of Sets				
Beach Seine	40	41	39	7	38
Fyke Net	8	7	3	4	13
Gill Net	68	110	50	40	75
Dip Net	0	1	0	0	0
Angling	0	9	0	0	5
Minnow Trap	25	0	0	0	0

Table 7. Number of gear sets by lagoon for 2018 and 2021 sampling seasons.

Year	2018			2021		
	Gear Type			Gear Type		
Lagoon	**Beach Seine**	**Gillnet**	**Fyke Net**	**Beach Seine**	**Gillnet**	**Fyke Net**
Krusenstern	1	14	2	13	3	34
Aukulak	4	7	1	12	4	24
Kotlik	2	19	1	13	6	17

Table 8. Total number of individuals per species caught by field season.[1]

Family	Latin Name	Common Name	2015	2016	2017	2018	2021
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance	109	31	4	1	0
Agonidae	*Pallasina barbata*	Tubenose poacher	14	152	0	48	1
	Ocella dodecaedron	Bering poacher	0	32	0	0	0
Clupeidae	*Clupea pallasii*	Pacific herring	1041	21248	1438	10362	556
Esocidae	*Dallia pectoralis*	Alaska blackfish	0	0	0	0	3
Osmerideae	*Mallotus villosus*	Capelin	1	77	0	0	0
	Osmerus mordax	Rainbow smelt	30	82	2	310	1
	Hypomesus olidus	Pond smelt	11350	2699	751	4700	144
Salmonidae	*Coregonus laurettae*	Bering cisco	7	29	15	3	3
	C. pidschian	Humpback whitefish	84	317	507	264	189
	C. sardinella	Least cisco	16	54	37	403	72
	Stenodus leucichthys	Sheefish	21	13	34	24	7
	Coregonus nasus	Broad whitefish	0	0	0	0	5
	Oncorhynchus gorbuscha	Pink salmon	38	115	82	2	0
	O. keta	Chum salmon	0	3	4	6	0
	O. kisutch	Coho salmon	0	0	0	875	0
	S. malma	Dolly Varden	7	39	6	0	10
		Unidentified whitefish	1	1	0	0	0
	Thymallus arcticus	Arctic grayling	3	0	0	0	4
Gadidae	*Eleginus gracilis*	Saffron cod	118	157	425	118	32
Gasterosteidae	*Gasterosteus aculeatus*	Threespine stickleback	6	30	141	70	169
	Pungitius pungitius	Ninespine stickleback	11962	6027	1060	994	303
		Unidentified stickleback	0	0	10202	0	0
Cottidae	*Chitonotus pugetensis*	Roughback sculpin	17	0	0	0	0
	Enophrys bison	Buffalo sculpin	0	17	0	0	0
	Megalocottus platycephalus	Belligerent sculpin	0	76	8	26	0

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
	Myoxocephalus quadricornis	Fourhorn sculpin	58	220	15	7	10
	Myoxocephalus polycanthocephalus	Great sculpin	56	0	0	0	0
	Gymnocanthus tricuspis	Arctic Staghorn sculpin	0	14	0	0	0
	Cottus cognatus	Slimy sculpin	0	0	0	0	1
		Unidentified sculpin	73	144	0	194	0
Pleuronectidae	*Limanda proboscidea*	Long head dab	1	4	0	0	0
	Platichthys stellatus	Starry flounder	154	419	118	239	76
	Pleuronectes glacialis	Arctic flounder	177	178	20	206	139
	Limanda aspera	Yellowfin sole	0	0	0	0	1
		Unidentified flatfish	8	170	43	119	10
Stichaeidae	*Acantholumpenus mackai*	Blackline prickleback	1	1	0	0	0

[1] Unidentified classification includes juvenile individuals who could not be identified to species.

Table 9. Species richness in Aukulak Lagoon by field season. X indicates species was sampled in the lagoon during the corresponding field season.

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance					
Agonidae	*Pallasina barbata*	Tubenose poacher		x			
	Occella dodecaedron	Bering poacher		x			
Clupeidae	*Clupea pallasii*	Pacific herring	x	x		x	
Esocidae	*Dallia pectoralis*	Alaska blackfish					x
Osmerideae	*Mallotus villosus*	Capelin		x			
	Osmerus mordax	Rainbow smelt		x		x	
	Hypomesus olidus	Pond smelt	x	x		x	x
Salmonidae	*Coregonus laurettae*	Bering cisco		x		x	
	C. pidschian	Humpback whitefish		x		x	
	C. sardinella	Least cisco	x	x		x	
	Stenodus leucichthys	Sheefish	x			x	
	Oncorhynchus gorbuscha	Pink salmon		x		x	
	O. keta	Chum salmon					
	O. kisutch	Coho salmon				x	
	S. malma	Dolly Varden	x				
		Unidentified whitefish	x	x			
	Thymallus arcticus	Arctic grayling					
Gadidae	*Eleginus gracilis*	Saffron cod		x		x	
Gasterosteidae	*Gasterosteus aculeatus*	Threespine stickleback		x		x	
	Pungitius pungitius	Ninespine stickleback				x	
		Unidentified stickleback					
Cottidae	*Chitonotus pugetensis*	Roughback sculpin	x				
	Enophrys bison	Buffalo sculpin		x			
	Megalocottus platycephalus	Belligerent sculpin		x			

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
	Myoxocephalus quadricornis	Fourhorn sculpin		x		x	
	Myoxocephalus polycanthocephalus	Great sculpin	x				
	Gymnocanthus tricuspis	Arctic Staghorn sculpin		x			
		Unidentified sculpin		x		x	
Pleuronectidae	*Limanda proboscidea*	Long head dab		x			
	Platichthys stellatus	Starry flounder		x		x	
	Pleuronectes glacialis	Arctic flounder	x	x		x	
		Unidentified flatfish		x		x	
Stichaeidae	*Acantholumpenus mackai*	Blackline prickleback					

Table 10. Species richness in Kotlik Lagoon by field season. X indicates species was sampled in the lagoon during the corresponding field season.

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance	x	x		x	
Agonidae	*Pallasina barbata*	Tubenose poacher	x	x		x	x
	Occella dodecaedron	Bering poacher		x			
Clupeidae	*Clupea pallasii*	Pacific herring	x	x	x	x	x
Umbridae	*Dallia pectoralis*	Alaska blackfish					
Osmerideae	*Mallotus villosus*	Capelin		x			
	Osmerus mordax	Rainbow smelt	x	x			x
	Hypomesus olidus	Pond smelt		x	x	x	x
Salmonidae	*Coregonus laurettae*	Bering cisco	x	x	x		x
	C. pidschian	Humpback whitefish	x	x	x	x	x
	C. sardinella	Least cisco	x	x	x	x	x
	Stenodus leucichthys	Sheefish	x				x
	Oncorhynchus gorbuscha	Pink salmon	x	x	x		
	O. keta	Chum salmon				x	
	S. malma	Dolly Varden	x	x			x
		Unidentified whitefish					
	Thymallus arcticus	Arctic grayling					x
Gadidae	*Eleginus gracilis*	Saffron cod	x	x	x	x	x
Gasterosteidae	*Gasterosteus aculeatus*	Threespine stickleback	x	x	x	x	x
	Pungitius pungitius	Ninespine stickleback	x		x	x	x
		Unidentified stickleback			x		
Cottidae	*Chitonotus pugetensis*	Roughback sculpin	x				
	Enophrys bison	Buffalo sculpin					
	Megalocottus platycephalus	Belligerent sculpin		x		x	

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
	Myoxocephalus quadricornis	Fourhorn sculpin	x	x			x
	Myoxocephalus polycanthocephalus	Great sculpin	x				
	Gymnocanthus tricuspis	Arctic Staghorn sculpin		x			
	Cottus cognatus	Slimy sculpin					x
		Unidentified sculpin	x			x	
Pleuronectidae	*Limanda proboscidea*	Long head dab					
	Platichthys stellatus	Starry flounder	x	x	x	x	x
	Pleuronectes glacialis	Arctic flounder	x	x	x	x	
		Unidentified flatfish		x	x	x	
Stichaeidae	*Acantholumpenus mackai*	Blackline prickleback		x			

Table 11. Species richness in Krusenstern Lagoon by field season. X indicates species was sampled in the lagoon during the corresponding field season.

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
Ammodytidae	*Ammodytes hexapterus*	Pacific sand lance					
Agonidae	*Pallasina barbata*	Tubenose poacher					
	Occella dodecaedron	Bering poacher					
Clupeidae	*Clupea pallasii*	Pacific herring	x	x	x	x	x
Umbridae	*Dallia pectoralis*	Alaska blackfish					
Osmerideae	*Mallotus villosus*	Capelin					
	Osmerus mordax	Rainbow smelt				x	
	Hypomesus olidus	Pond smelt	x	x	x	x	x
Salmonidae	*Coregonus laurettae*	Bering cisco	x	x	x	x	x
	C. pidschian	Humpback whitefish	x	x	x	x	x
	C. sardinella	Least cisco	x	x	x	x	x
	Stenodus leucichthys	Sheefish	x		x	x	x
	Coregonus nasus	Broad whitefish					x
	Oncorhynchus gorbuscha	Pink salmon	x	x	x	x	
	O. keta	Chum salmon		x			
	S. malma	Dolly Varden	x	x			
		Unidentified whitefish		x			
	Thymallus arcticus	Arctic grayling	x				x
Gadidae	*Eleginus gracilis*	Saffron cod	x			x	
Gasterosteidae	*Gasterosteus aculeatus*	Threespine stickleback	x	x	x	x	x
	Pungitius pungitius	Ninespine stickleback	x	x	x	x	x
		Unidentified stickleback					
Cottidae	*Chitonotus pugetensis*	Roughback sculpin					
	Enophrys bison	Buffalo sculpin					
	Megalocottus platycephalus	Belligerent sculpin					

Family	*Latin Name*	Common Name	2015	2016	2017	2018	2021
	Myoxocephalus quadricornis	Fourhorn sculpin	x				
	Myoxocephalus polycanthocephalus	Great sculpin					
	Gymnocanthus tricuspis	Arctic Staghorn sculpin					
		Unidentified sculpin				x	
Pleuronectidae	*Limanda proboscidea*	Long head dab					
	Platichthys stellatus	Starry flounder	x	x	x	x	
	Pleuronectes glacialis	Arctic flounder		x	x	x	
		Unidentified flatfish		x		x	
Stichaeidae	*Acantholumpenus mackai*	Blackline prickleback					

Table 12. Abundance (N=), mean length (mm), length range (mm), and mean weight (g; if measured) for fishes caught in Cape Krusenstern National Monument lagoons. Lengths were recorded in fork length, unless the species does not have a forked tail, in which case they were recorded as total length.

		Early Season				*Late Season*			
Lagoon	**Species**	**N=**	**Mean length (mm)**	**Length range (mm)**	**Mean weight (g)**	**N=**	**Mean length (mm)**	**Length range (mm)**	**Mean weight (g)**
Kotlik	Arctic grayling	1	359	NA	--	0	--	--	--
	Bering cisco	1	372	NA	--	1	325	NA	--
	Dolly Varden	9	550	477-630	--	1	104	NA	--
	Fourhorn sculpin	0	--	--	--	11	66	41-75	--
	Humpback whitefish	4	315	254-362	--	61	277	161-445	--
	Least cisco	0	--	--	--	47	188	93-295	--
	Ninespine stickleback	2	42	NA	0.38	19	36	26-52	--
	Pacific herring	188	205	183-280	70.86	0	--	--	--
	Pond smelt	0	--	--	--	1	103	NA	--
	Rainbow smelt	0	--	--	--	1	149	NA	--
	Saffron cod	32	273	230-355	--	0	--	--	--
	Sheefish	1	890	NA	--	1	400	NA	--
	Slimy sculpin	0	--	--	--	1	60	NA	--
	Starry flounder	18	229	155-420	108.54	8	222	161-270	--
	Threespine stickleback	1	85	NA	--	126	82	72-91	--
	Tubenose poacher	0	--	--	--	1	54	NA	--
Krusenstern	Arctic grayling	3	226	191-251	--	0	--	--	--
	Bering cisco	1	196	NA	80.90	0	--	--	--
	Broad whitefish	5	317	290-350	--	0	--	--	--
	Humpback whitefish	74	314	226-421	--	28	342	255-393	--
	Least cisco	11	243	219-280	--	7	253	238-277	--
	Ninespine stickleback	78	55	39-68	--	201	40	NA	--
	Pacific herring	41	146	55-295	46.43	324	121	39-235	--
	Pond smelt	142	67	39-96	1.91	0	--	--	--
	Sheefish	5	381	303-510	--	0	--	--	--
	Threespine stickleback	10	93	NA	--	0	--	--	--
Tukrok River mouth	Arctic flounder	139	192	70-247	76.19	--	--	--	--
	Humpback whitefish	22	269	201-365	--	--	--	--	--
	Least cisco	7	202	87-300	--	--	--	--	--
	Ninespine stickleback	3	41	40-41	--	--	--	--	--
	Pacific herring	3	82	61-104	11.15	--	--	--	--

	Species	Early Season N=	Early Season Mean length (mm)	Early Season Length range (mm)	Early Season Mean weight (g)	Late Season N=	Late Season Mean length (mm)	Late Season Length range (mm)	Late Season Mean weight (g)
Tukrok River mouth	Starry flounder	50	168	110-240	55.12	--	--	--	--
	Threespine stickleback	32	85	80-93	5.54	--	--	--	--
	Yellowfin sole	1	205	NA	--	--	--	--	--
Aukulak	Alaska blackfish	--	--	--	--	3	62	56-68	--
	Pond smelt	--	--	--	--	1	48	NA	--