



Coastal Lagoon Monitoring in Cape Krusenstern National Monument



Fieldwork Summary 2023-2024

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A report led by Wildlife Conservation Society, in partnership with US National Park Service and Native Village of Kotzebue, submitted to US National Park Service Arctic Network.

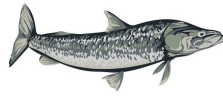
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EXECUTIVE SUMMARY	3
INTRODUCTION	5
<i>Coastal Lagoons in Northern Alaska</i>	6
<i>Prior Coastal Lagoon Research in ARCN National Park Units and Overall Picture of Lagoons</i>	8
2023-2024 FIELD EFFORTS	10
<i>Objectives</i>	10
<i>Study Design</i>	10
<i>Field Methodologies</i>	10
FIELD NOTES FOR SAMPLED LAGOONS	13
RESULTS AND DISCUSSION	18
<i>Water Quality</i>	18
<i>Primary Productivity</i>	19
<i>Fish Sampling</i>	20
FUTURE DIRECTIONS	26
ACKNOWLEDGEMENTS	26
LITERATURE CITED	27
ADDITIONAL TABLES	30

Title page photo: WCS Fisheries technician Max Auschwitz monitors a gillnet set in Atilagauraq Lagoon in June 2024.



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 2015-2022. Our 2023-2024 Vital Signs fieldwork sought to build upon the pre-existing database of in-depth temporal and spatial information on lagoon ecology, as well as to start developing a new Standard Operating Protocol (SOP) for basal food abundance (e.g., mysids).

We collected seasonal water quality and primary productivity data at three Cape Krusenstern lagoons including Kotlik, Krusenstern and Aukulak, which have been previously sampled in 2012 and 2015-2022. We also assessed lagoon fish assemblage diversity and abundance at these lagoons, as well as fish diversity at nearby Tasaychek, Imik/Rabbit Creek, and Atilagauraq lagoons. Two visits were made to the lagoons in June and August 2023, but only one in June 2024 due to budget constraints. 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.

During sampling periods in 2023-2024, all lagoons were open to the marine environment, which allows for passage of fish and two-way flow of water. Evaluation of water quality data indicated that physical water properties varied by lagoon and season. Seasonal salinity levels tracked those of previous years, though they were slightly higher than normal in 2023, as salinity is related to the duration of connection with the marine environment. Unlike in years before 2022, average salinity levels at all lagoons increased between the first and second sampling rounds in 2023, likely because of continued saltwater intrusion due to open marine connections. Because Krusenstern Lagoon is 14 km distant from the marine opening, it consistently exhibits low salinity. Similar to 2022 but in contrast to trends seen from 2015-2022, mean water temperatures at all three lagoons increased over the course of the field season in 2023, likely due to a late, colder spring that extended into June (there was still large amounts of jumbled ice along the coast and in the lagoons during our June field visit). Average temperatures in Krusenstern and Aukulak Lagoons in the early season of 2023 (3.21° and 6.63° C, respectively) were lower than any from 2012-2022, reflecting the colder-than-average June of 2022. Late season temperatures in 2023 and early season in 2024 were largely comparable to previous years. Dissolved oxygen saturation was higher than 96% at most times, indicating generally normoxic conditions, though Krusenstern Lagoon exhibited lower levels in 2023 (88%, but biased low due to missing some sampling locations because of weather and logistical challenges). Lagoon pH was not measured in 2023-2024 due to equipment malfunction. Sondes were sent in to the manufacturer for sensor calibration/refurbishment after the 2023 season, but this did not correct the problem with the pH sensor, as inaccurate readings continued in 2024.

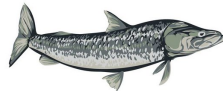
Turbidity of lagoons was moderate in both 2023 and 2024 (2-21 FNU) compared to previous years. Unlike in prior years, Krusenstern Lagoon did not exhibit the highest turbidity in 2023, with FNU levels in Kotlik (mean 10.72) higher than at other sites (5.79 and 8.86 FNU), but normal patterns returned in 2024. Turbidity is driven by wind and wave action stirring up lagoon sediments, and by freshwater runoff spates mobilizing terrestrial inputs. Indices of primary productivity were within ranges from previous years and are often influenced by periodic blue-green algae blooms, particularly in Krusenstern Lagoon.

We captured and processed 2,964 fish at the lagoons and the Tukrok River mouth in 2023, which represented similar overall abundance to previous years. Only 532 total fish were captured in 2024, due to sampling occurring only during the early season. 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 in 2023 and 15 in 2024, including the typical suite of key forage and important subsistence species. 2023 species diversity was similar to 2021-2022, but lower than the most speciose year in 2016 (25 species). Several species that had rarely been encountered in previous lagoons investigations were caught, including Alaska blackfish, broad whitefish, and chum salmon. Conversely, absent taxa included pond smelt, rainbow smelt, and threespine stickleback in 2024. Notable catches included an Alaska blackfish at the Krusenstern Lagoon freshwater inlet site (first time a blackfish has been caught here), a sheefish all the way north at Rabbit Creek (and the only sheefish of 2024), dozens of whitefish in Atilagauraq Lagoon, and a 31-inch Dolly Varden caught at Rabbit Creek (a particularly large specimen).

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 suggested efforts include evaluation of lagoon basal prey resource taxonomy and food web ecology and more work towards characterization of fish seasonal movements and life history chronology.

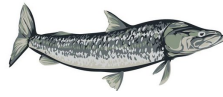


INTRODUCTION

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 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 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 2). 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 (von Biela et al. 2023). 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; Fraley et al. 2022b).

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 2). 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 km²) and Krusenstern Lagoon is the largest (56 km²). 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.

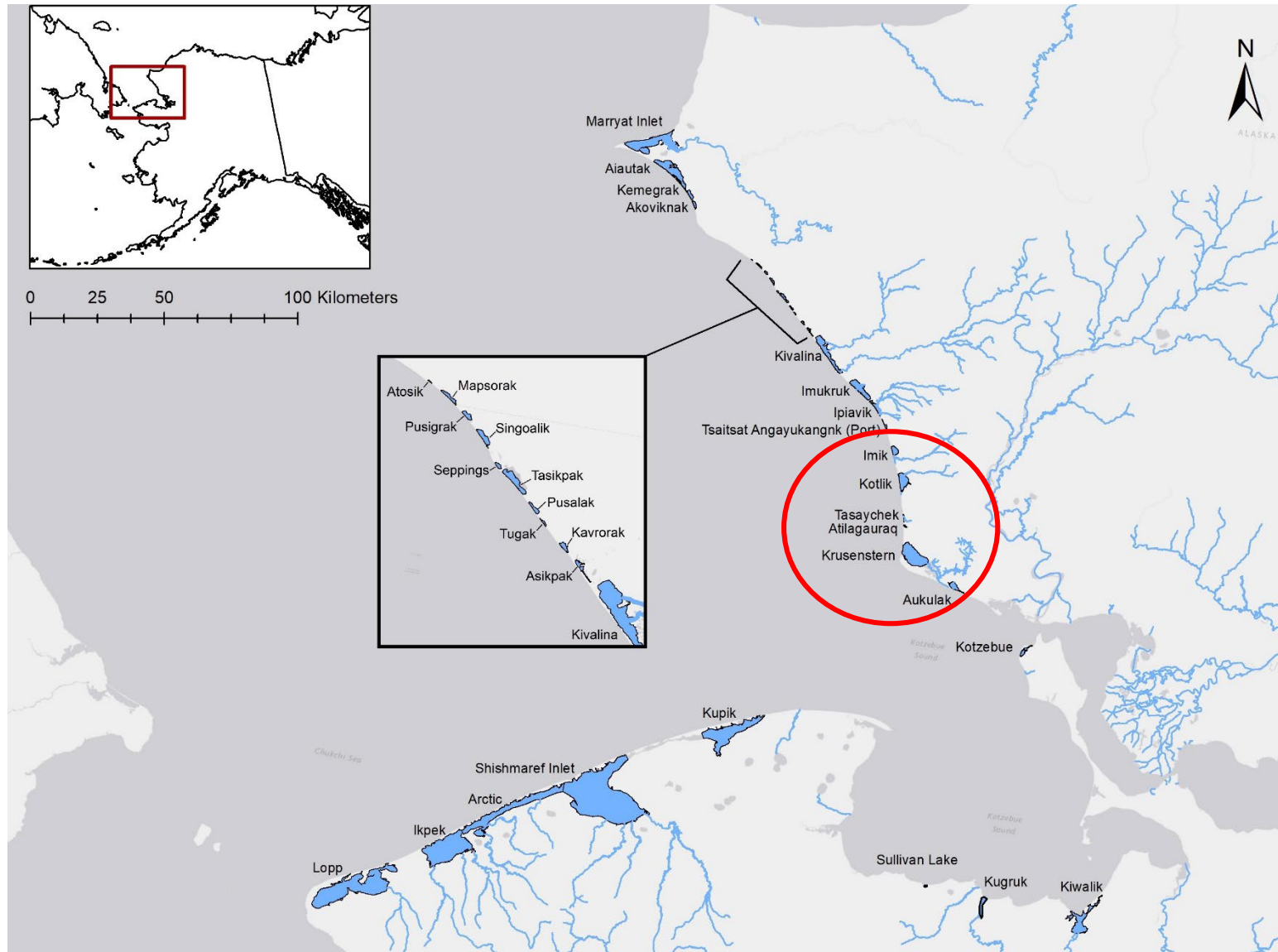
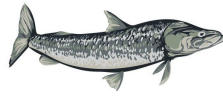


Figure 1: Map of named Southern Chukchi Sea coastal lagoons. 2023-2024 study lagoons are denoted by the red circle.



Prior Coastal Lagoon Research in ARC National Park Units and Overall Picture of Lagoons

There have been a number of prior research efforts investigating the ARC 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; Blaylock 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 Krusenstern 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 2015-2022 seasons (Robards, 2014; Haynes et al., 2017; Tibbles, 2018; Tibbles and Robards, 2018; Tibbles et. al., 2018; Smith et al.,



2019 a-b; Fraley et al. 2022a). 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 et al. 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		2022		2023		2024	
		E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
<i>Alaska Maritime National Wildlife Refuge/ Cape Thompson</i>	Kemegrak									X									
	Akoviknak									X									
	Atosik									X	X								
	Mapsarak									X	X								
	Singoalik									X	X								
<i>Cape Krusenstern National Monument</i>	Kotlik	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Tasaychek					X										X		X	
	Atilagauraq					X												X	
	Krusenstern	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Tukrok River mouth/Anigaaq			X	X	X	X	X	X	X	X		X	X	X	X	X	X	
	Aukulak			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Imik/Rabbit Creek															X		X	
<i>Bering Land Bridge National Preserve</i>	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.

2023-2024 FIELD EFFORT

Objectives

The objectives of the Wildlife Conservation Society-led activities throughout the 2023 and 2024 field seasons 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 2015-2022 field seasons;
 - a. Streamline logistics and provide feedback on standardized sampling protocol;
 - b. Report findings from field seasons and incorporate data into comprehensive Arctic lagoons monitoring database;
2. Collect data from lagoon sites in Cape Krusenstern National Monument 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 2015-2022 implemented where appropriate. Two sampling efforts were undertaken for lagoons in 2023, one in June (termed “early season”) and one in August (“late season”). In 2024, due to funding constraints, only an early season visit was made.

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. Only Krusenstern, Kotlik, and Aukulak Lagoons were sampled for water quality.

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 2023-2024 seasons. 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.

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 2022 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 2022 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 (Figure 2).

We identified all fish to species and measured each individual to fork length. For a subset of Coregoninae, Dolly Varden, Arctic grayling, and Alaska blackfish 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. During the late season visit, we intended to attach pop up satellite archival tags to adult sheefish >600 mm fork length to characterize sheefish coastal movements and habitat use.



Figure 2: WCS Fisheries Technician Max Auschwitz with a Dolly Varden captured via rod and reel at Rabbit Creek/Imik Lagoon in June 2024.

Field logistics

We accessed lagoons located in Cape Krusenstern National Monument via base camps at the NPS Ranger Station at Anigaaq and the Kilikmak Airstrip. We primarily camped in tents nearby, using the ranger station at Anigaaq as a windbreak. Spike camps at Krusenstern and Aukulak Lagoons were used to optimize sampling (Figure 3). Golden Eagle Aviation of Kotzebue ferried personnel and equipment between Kotzebue and these base camps with wheel plane landings. Lagoons sampled included Krusenstern, Aukulak, Tasaychek, Atilagauraq, Rabbit Creek/Imik Lagoon, and Kotlik.



Figure 3: WCS field technician Michael Lunde preparing for net setting at a spike camp along Krusenstern Lagoon, in August 2023.



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. We accessed Kotlik Lagoon directly from the Kilikmak Airstrip, and while visiting we set up camp and staged gear on the marine edge of the lagoon.

Throughout the field seasons, 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

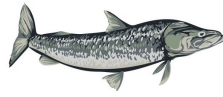
Aukulak

June 16th and August 24th, 2023

Sampling at Aukulak Lagoon occurred twice during the 2023 season. The lagoon was open to the ocean during both visits, though water levels were low and the channel was not flowing strongly in August. In June, a group of muskoxen were present near the outlet. Gillnet sets, beach seines, and fyke nets were deployed at the outlet site during both visits. Freshwater inlet and marine edge fisheries sampling sites were visited and beach seines and onshore and offshore gillnets were set. Standard water quality monitoring locations were sampled with EXO-2 sondes while transiting between fisheries sites. In June, a beaver was seen swimming in brackish water just inside the lagoon outlet, which was an uncommon sighting. In August, Mysidae shrimp benthic tows were conducted and sheefish satellite tagging was attempted, but sheefish large enough to tag were not caught.



Figure 4: Field gear arrayed along the shore of Aukulak Lagoon at the marine edge site in August 2023.



June 19-20th, 2024

Sampling at Aukulak Lagoon began on the morning of June 19th. We boated 1.6 km down the Tukrok River from Anigaaq through the open river mouth and 4 km down the coast to the breaching location of Aukulak Lagoon, which was open to the Chukchi Sea. We motored the boat into the lagoon, set up a spike camp, and began sampling at the outlet site. We set an offshore gillnet letting it soak for three one-hour sets, and conducted three beach seine pulls. We also set a fyke net for six hours, checking every two hours. Angling was conducted near the outlet channel for a total of four hours, without success. On June 20th, water quality data was collected throughout Aukulak Lagoon and the freshwater inlet and marine edge fisheries sampling sites were visited. At the marine edge, three half-hour onshore and offshore gillnets were set and three beach seines were conducted. When sampling the freshwater inlet four beach seines were conducted as well as three onshore and offshore gillnet sets, with a mix of half hour and hour long sets depending on the catch rate. At the end of the day we retrieved our camping gear and boated back along the coast to Anigaaq base camp.

Krusenstern

June 19th and 20th, 2023

A two-person WCS field crew boated up the Tukrok River from Anigaaq base camp and through the outlet area of Krusenstern Lagoon. Wind and wave conditions were calm, so we crossed the lagoon to sample water quality sites and the marine edge fisheries site. Offshore and onshore gillnets were set and checked three times each, every 10-30 minutes (to avoid fish mortality due to wave action and high volume catches). Wind picked up and the freshwater inlet site was inaccessible because it was still covered with ice covering approximately 2 km of the lagoon, so we returned to the outlet area to set up a spike camp for the night. The next day, at the outflow, we set an onshore and offshore gillnet, and checked these three times each, once every 25 minutes- an hour. A fyke net was set for 6 hours and checked three times, and three beach seine pulls were performed. After work was completed, we boated back to Anigaaq base camp.

August 22-23rd, 2023

Unfortunately, the outboard motor that we brought to the field for the 2023 sampling trip did not work upon arrival, and we had to wait a couple days at Anigaaq base camp until an NPS crew visiting Anigaaq with their landing craft was kind enough to bring along a replacement motor. By the time our inflatable boat was mobile again, we only had two days to sample Krusenstern Lagoon in order to also successfully sample Aukulak Lagoon, before our air taxi to Kotlik Lagoon. We accessed and sampled the outlet site following a similar program to the effort in June, but due to bad weather on the second day causing poor wave conditions for boating, we were not able to cross the lagoon to collect water quality data or sample the marine edge and freshwater inlet fisheries sites and had to return to Anigaaq base camp.

June 21-22nd, 2024

We accessed Krusenstern Lagoon by boating up the Tukrok River to the lagoon, convoying with an NPS crew briefly (Figure 6), and taking approximately two hours to travel the ~14 km from Anigaaq base camp. While traveling to the lagoon we observed a multitude of waterfowl and shorebirds. Upon arriving at the lagoon outflow, we noticed that wind and wave conditions were suitable for boating across the lagoon. Therefore, we first boated km across the lagoon to the marine edge, collecting water quality data at standard sites enroute. We then set an onshore and offshore gill net and checked them three times each, every hour. Three beach seines were also conducted at the marine edge before boating to the freshwater inlet. There, three beach seines were conducted as well as an onshore and offshore gill net that were checked three times every thirty minutes. Water quality data was collected on the way back to the lagoon outlet area (Figure 3) where a spike camp was set up for the night. Upon waking up the next morning, heavy wind and weather conditions did not allow for sampling of the lagoon outlet. We waited six hours at the site with no weather change, and returned to Anigaaq without sampling fish at this site due to time constraints.



Kotlik

June 22nd – 23rd and August 26th– 27th, 2023

Kotlik Lagoon was open to the ocean during both visits in 2023, though water was barely flowing through the channel in August. Many ice chunks from the ocean were present, moving in and out of the lagoon with the tides during the June visit, which made netting challenging. During both visits, fyke nets were set at the outlet for six hours (checking it three times), three onshore gillnet sets were conducted, and three beach seine pulls. Aside from sampling the outlet, 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 3 beach seines were performed. Fly fishing methods were not effective for capturing Dolly Varden at the freshwater inflow site (Jade Creek), unlike in 2021. Drinking water was collected by boating several hundred yards up Jade Creek. Angling was conducted at the outlet area in June during the evenings after netting, which yielded catches of Dolly Varden and saffron cod.

June 24th and 27th, 2024

We arrived at Kotlik Lagoon and found that the outlet was open to the ocean. Ice chunks from the ocean were present and were moving in and out of the lagoon with the tides. We boated throughout the lagoon collecting water quality measurements, sampling the freshwater inlet and the marine edge. Onshore and offshore gillnets were used at both sites and checked every hour with three sets each, beach seines were also deployed three times at each site. Angling was attempted with success at the freshwater inlet site (Jade Creek) for capturing Dolly Varden and Arctic grayling. On June 27th the Kotlik outflow site was sampled by conducting three beach seines, a fyke net set for 6 hours, and 3-hour gill net sets. Angling was also conducted near the marine opening and numerous saffron cod and starry flounder were caught.



Figure 5: A gillnet set at Tasaychek Lagoon in June 2023. Tasaychek Lagoon had not been sampled by WCS since 2016.

Tasaychek and Atilagauraq Lagoons

Tasaychek Lagoon

On June 24th, 2023 and June 25th, 2024 we departed from Kotlik Lagoon for the 10-km boat ride along the Chukchi Sea coast to visit and sample Tasaychek Lagoon. Travel along the coast to this location is often difficult in our 10-horsepower inflatable boat, or by ATV (as historically used), due to waves, fast ocean current, and outboard motor fuel constraints. This is why the lagoon was not sampled by WCS between



2017-2023. During both visits, the lagoon outlet was open to the ocean and our inflatable boat could be walked through the channel into the lagoon. In 2023, the lagoon water levels were high and turbid, while in 2024 the water was low and clear.

In 2024, three beach seine pulls were performed as well as three hour-long gillnet sets at the Tasaychek Lagoon outlet. Travel through the lagoon to the inlet area was not attempted due to the low water levels, which rendered the outboard boat motor ineffective. We then traveled another 5 km down the ocean shore to Atilagauraq Lagoon where the water was extremely low and turbid, yet still connected to the ocean. Three beach seines were performed as well as one ten-minute gillnet set, which resulted in an abundance of whitefish. No additional gillnet sets were conducted, to avoid fish mortality due to high-volume catches.

Tukrok River Channel/Anigaaq

We sampled the Tukrok River and river mouth by the Anigaaq ranger cabin on June 21st and August 19th, 2023 and June 23, 2024. 2-3 beach seines were conducted and multiple gillnet sets were conducted during each visit. Rod-and-reel angling was attempted at the open Tukrok River mouth for several hours in both 2023 and 2024 with success capturing starry flounder, Arctic flounder, Saffron cod, Pacific herring, and a juvenile salmon. The river mouth was open to the Chukchi Sea during all visits. In June 2024, we rendezvoused with an NPS crew while they visited Anigaaq for maintenance tasks (Figure 6).



Figure 6: Working with NPS staff trialing transport of our fieldwork inflatable boat up the Tukrok River in June 2024. The large NPS craft could only go a couple km up the channel before the water became too shallow and the inflatable had to be offloaded.

Other Surveys

Rabbit Creek/Imik Lagoon

On June 25, 2023 and June 26th, 2024 we boated the 15 km from camp at Kotlik Lagoon for brief visits to the Rabbit Creek/Imik Lagoon coastal mouth to assess fish diversity and relative abundance. This system had not been previously visited by WCS, but was of interest for sampling due to its proximity to the Red Dog Mine Port and its popularity as a location for sport and subsistence anglers to catch anadromous Dolly Varden. Thirty-minute gillnet sets were conducted within the river mouth, but did not yield fish due to strong currents and wariness of fish in the clear water. Subsequently, several hours of angling were



conducted in both 2023 and 2024. Arctic grayling and anadromous Dolly Varden were captured in 2023, and these same species plus humpback whitefish and a lone sheefish were landed in 2024 (Figure 7). Upstream navigation was attempted with our inflatable boat, but we were only able to ascend the creek ~1.5 km before it became too shallow to run the outboard motor. On the return journey along the coast, we stopped to visit an NPS shelter cabin north of Kotlik Lagoon, which appeared to be very run-down but still a useable place to escape from poor weather.



Figure 7: A sheefish caught at the mouth of Rabbit Creek/Imik Lagoon in June 2024. This site had not been visited by WCS before 2023.

Situkuyok River

On August 21, 2023 and June 23rd, 2024 we boated up the Tukrok and Situkuyok Rivers from Anigaaq base camp to assess fish diversity and relative abundance in the freshwater-influenced portion of the Krusenstern Lagoon system, and to monitor new beaver activity in this area. We sampled fish at a site ~300 m downstream of the upstream limit of navigability for our inflatable boat (where the river channel changed from deep, slow moving to shallow, gravel riffles; 67.109642°, -163.347989°). Brief gillnet sets yielded no catches due to the wariness of fish in the clear water, so several hours of angling were conducted during each visit. We caught, measured, and released dozens of grayling, several anadromous Dolly Varden, and a few humpback whitefish during these efforts, though the Dolly Varden were only seen in 2024. We noticed new beaver cuttings and lodges near the sampling location that were not present in previous years (Figure 8).



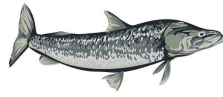
Figure 8: A new beaver lodge appeared along the lower Situkuyok River in June 2024. Beaver activity had not been previously noted this far downriver.

RESULTS AND DISCUSSION

Water Quality (Krusenstern, Kotlik, and Aukulak Lagoons only)

Salinity

Physical and chemical properties varied between lagoons and across years (2023-2024). All lagoons were open to the marine environment during sampling, which is uncommon. Typically, Aukulak, Krusenstern, and Kotlik Lagoons close to the ocean during the August “late” season as water levels drop and wave action allows gravel to accumulate at the mouths of the channels connecting to the ocean. This resulted in relatively high salinity in lagoons when compared to low-water years where lagoons were closed to the ocean for lengthy periods, or in the case of Aukulak Lagoon in 2018 and 2021, never opened to the sea. Average salinity levels at all lagoons increased between the first and second sampling rounds of 2023 (Table 3), likely because of continued saltwater intrusion thanks to open marine connections and diminishing freshwater runoff amounts. Aukulak and Kotlik Lagoons exhibited the most dramatic increase in mean salinity between seasons, undoubtedly because of declining freshwater runoff into the lagoons throughout the summer (these lagoons have relatively small feeder streams) and tidal saltwater intrusions. Because of the long channel to the ocean at Krusenstern preventing significant saltwater intrusion, this lagoon remained relatively low in salinity throughout 2023-2024 (2.18 – 7.12 mean ppt). Krusenstern has shown consistently low mean salinity from 2012-2022, always <7.5 ppt, because the main body of the lagoon is more than 14 km distant from its primary exchange with saline water from the ocean. Mean salinity levels at all lagoons in 2023-2024 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 3). It is clear that the influences of lagoon connectivity to the ocean and volume of 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 increased over the course of the 2023 season (Table 3), which is in reverse of trends seen in all lagoons from 2015-2021, but matches what was seen in 2022. This is likely due to a late, colder spring that extended into June (there was still large amounts of jumbled ice along the coast and in the lagoons during our June field visit). Average temperatures in Krusenstern and Aukulak Lagoons in the 2023 early season (3.21 and 6.63 C, respectively) were lower than any from 2012-2022, and average temperatures in Kotlik Lagoon (9.91 C) were lower than any year except 2022, reflecting the colder-than-average June of 2023. Mean temperatures for lagoons during the late season of 2023, and the early season of 2024 (8.67 – 12.58 C across lagoons and seasons) fell within the range of those seen for those locations from 2012-2022 (Table 3).

Dissolved Oxygen

Mean dissolved oxygen levels (DO) at all three lagoons across seasons in 2023 were slightly lower than readings from 2012-2021, but similar to 2022, with average overall concentrations ranging between 88% and 105% saturation among lagoons (Table 4). DO in Krusenstern Lagoon in 2023 (88.61%) was lower than any previous year, however it should be noted that not all water quality sites were able to be accessed during both seasons due to weather and logistical challenges, so the levels may not be representative of the overall lagoon. DO levels were higher and back within typical ranges seen from 2012-2021 at all lagoons in 2024, but only the early season was measured. Overall, DO levels across lagoons and years indicate generally favorable, normoxic conditions for occupancy by fishes and other biota (>96% saturation; Davis 1975), except for at Krusenstern Lagoon in 2023.

pH

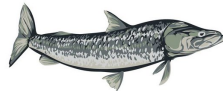
Unfortunately, the pH sensors on our Exo-2 Sondes were giving unreliable readings throughout 2023-2024. Sondes were sent in to the manufacturer for sensor calibration/refurbishment after the 2023 season, but this did not correct the problem as inaccurate readings continued in 2024. Therefore, pH was not recorded during these field seasons.

Turbidity

In contrast to previous years, turbidity was highest at Kotlik Lagoon in 2023 (mean 10.72 FNU) when compared to other lagoons (means 5.79 and 8.86). Typically, turbidity in Krusenstern Lagoon is highest due to persistent wind and wave action stirring the sediment here. However, the pattern seen in 2023 reversed back to normal in 2024 (2.37 FNU in Kotlik compared to 14.12 and 20.98 in other lagoons) (Table 4). The difference in 2023 is attributed to rain events causing mobilization of sediment into Kotlik Lagoon during both visits. Overall, when compared to previous years, the range of turbidities in lagoons in 2023-2024 fell within those previously observed from 2012-2022 (-5.57 – 29.16 FNU), which were highly variable among lagoons and years. Turbidity is driven by freshwater runoff events and wind and wave action in the lagoons.

Primary Productivity (Krusenstern, Kotlik, and Aukulak Lagoons only)

Unlike most previous years from 2012-2022 (except 2015), primary productivity was not the highest at Krusenstern Lagoon in 2023, but was highest in Aukulak Lagoon. Aukulak Lagoon exhibited a mean total chlorophyll level of 1.41 RFU and mean blue green algae (BGA) reading of 0.67 RFU (Table 4). Additionally, in a difference from patterns of all previous years except 2015 and 2022, Kotlik Lagoon did not exhibit the lowest productivity. This time, Krusenstern was the lowest, with mean chlorophyll concentration of 0.88 RFU and BGA of 0.49 RFU. This change in typical patterns may be due to patchy sampling occurring at Krusenstern Lagoon in 2023, when several sites were not sampled due to weather and logistical challenges. However, in 2024, the typical pattern between lagoons returned, With Krusenstern showing the highest and Kotlik the lowest (Table 4). Overall, indices of primary productivity were in line with previous years.



Fish Sampling

Overall assemblage composition, abundance, and length

In 2023, across all lagoons and seasons we performed fifty-one beach seine pulls (Figure 9), 18 fyke net sets, 95 gill net sets, and ten man-hours of angling during fisheries sampling efforts at Kotlik, Krusenstern, Aukulak, Tasaychek, and Imik/Rabbit Creek lagoons. This amount of sampling effort was similar to what was performed in 2022, but greater than in most other years (Tables 5). In 2024, Kotlik, Krusenstern, Aukulak, Tasaychek, Imik/Rabbit Creek, and Atilagauraq lagoons were visited. However, sampling was only conducted during the early season in 2024, and thus sampling effort was diminished compared to previous years (approximately half the typical number of net sets and beach seine pulls; Table 5).

In 2023, 2,964 total fish were captured and processed, which was slightly higher than in 2022 but fewer than previous seasons (2015-2018 mean total catch = 22,184), except for 2012 (total catch = 114 fish) and 2021 (total catch = 1,726). This lower overall abundance is attributed to markedly lower catches of small-bodied fishes such as stickleback, herring, and juvenile salmon in recent years, and our efforts to curtail fishing efforts to avoid mortality when catch numbers were high. In 2024, because sampling was conducted only during the early season, catches were lower (532 total fish).



Figure 9: WCS technician Michael Lunde prepares a beach seine at the Kotlik Lagoon outlet site in June 2023.

Fish species richness and relative abundance in lagoons varied, with population composition and abundance differing between season, lagoon, and year (Figures 11-13). In 2023 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 6), and in 2024 we caught 15 species. Several species that had rarely been encountered in previous lagoons investigations were caught, including broad whitefish and Alaska blackfish in 2023. Conversely, notable absent taxa included pond smelt, rainbow smelt, and threespine stickleback in 2024. The absence of those species in 2024 is



likely due to a curtailed sampling effort, with only one visit to the lagoons occurring in the early season due to budget constraints.

Lagoons in 2023 exhibited one more fish species than in 2022 and 2017 (19), the same number as during 2018 and 2021 (20), but lower than in 2016 (25) and 2015 (23) (Table 6). The number of species seen in 2024 (15) was low due to the curtailed sampling effort. Overall, diversity was highest at Kotlik and Aukulak Lagoons, and lowest in Krusenstern Lagoon, likely because the lengthy channel from the ocean discourages marine-oriented taxa from occupying Krusenstern. This is different from 2021 and 2018 results, when Aukulak exhibited the lowest diversity among lagoons because it was closed to the ocean the entire summer season. No trends were observed in species diversity and abundance across seasons, showing high variability between and within lagoons, across seasons.

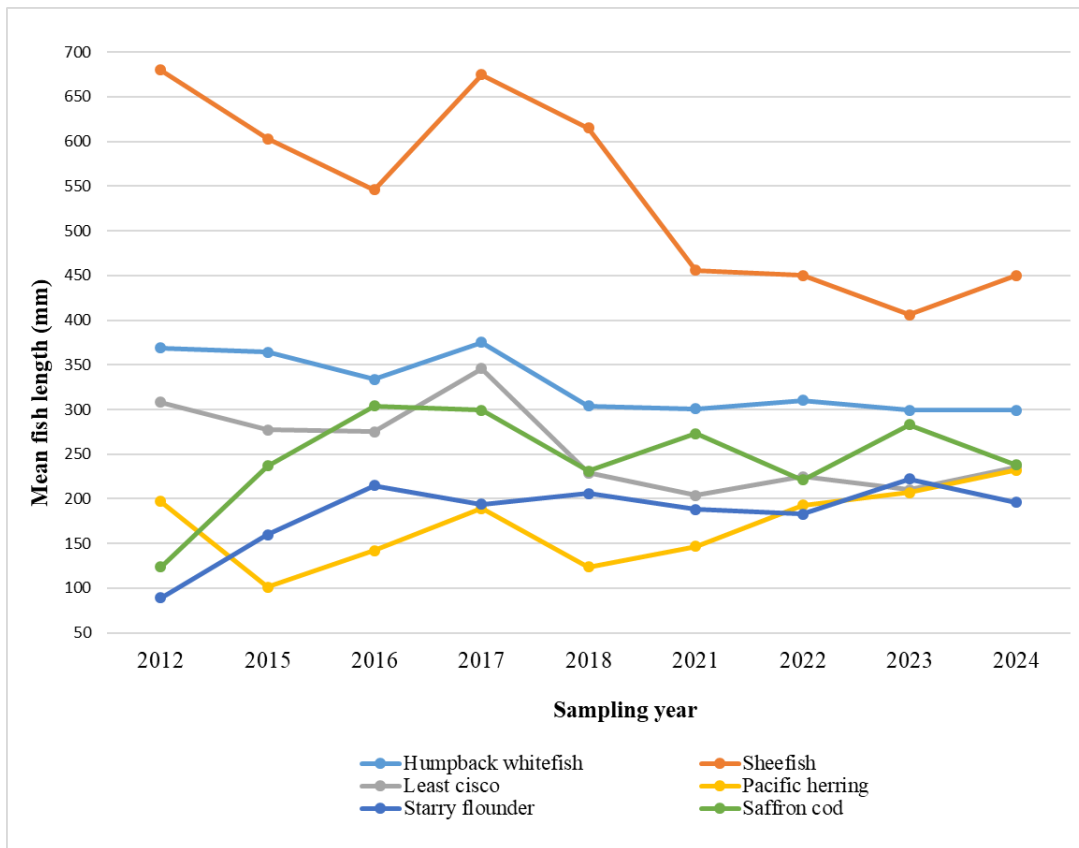


Figure 10: Mean lengths by year for Cape Krusenstern National Monument lagoon fish species of subsistence importance. Note that data is pooled across seasons and sites, and sample size by species is variable. Fork length is used for fishes with forked tails, and total length is used for all others.

Mean length (body size) of commonly-caught subsistence-harvested species has remained at overall consistent levels from 2012-2024, though much interannual variability is present (Figure 10). Previous sampling efforts revealed a 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. A slight downward trend in the size of sheefish found at lagoons was observed, though the number of sheefish caught in 2024 ($n=1$) was low and thus may not be a good representation. Similar to 2022, adult pink and chum salmon were captured or seen in lagoons in August 2023, undoubtedly because lagoon marine connectivity was maintained throughout the summer.



In June 2023, no sheefish were caught at any lagoons, which was atypical, but likely due to the late season slowing their movements along the coast to populate these habitats. However, anadromous Dolly Varden were caught in greater numbers than normal. Tasaychek Lagoon was sampled for the first time since 2016 and held moderate numbers of whitefishes, flounders, Dolly Varden, and saffron cod. In August 2023, abundance of larger-bodied Coregoninae was low across the lagoons, though we caught more Bering Cisco than usual. Herring were largely absent, as were saffron cod and Arctic flounder. Starry flounder were consistently present. Interesting catches in 2023 included a small broad whitefish in Kotlik Lagoon (the first time this species has been caught in this lagoon, and the first time during Cape Krusenstern lagoons sampling since 2021) and a grayling in the Tukrok River near the mouth (salinity 4.2). Sheefish were scarce in August 2023, and too small-bodied to place the remainder of our pop-up satellite archival tags on. The tags were deployed on sheefish a month later on the upper Kobuk River instead.

In June 2024, fish abundance was low overall compared to previous years, largely due to the lack of typically high catches of forage fish like pond smelt and ninespine stickleback. However, some notable catches included an Alaska blackfish at the Krusenstern Lagoon freshwater inlet site (first time a blackfish has been caught here), a sheefish all the way north at Rabbit Creek (and the only sheefish of the trip), and a 31-inch Dolly Varden caught at Rabbit Creek (a particularly large specimen). Certain species were more prevalent than normal, including Bering Cisco at Kotlik Lagoon, saffron cod and starry flounder in Aukulak and Kotlik Lagoons. Atilagauraq Lagoon was sampled for the first time since 2016 and surprisingly held a high abundance of humpback whitefish. The Tasaychek Lagoon fish assemblage had completely changed from the previous year, with flounders dominating and only one whitefish caught besides that.

Fin clips were opportunistically collected from ~ 12 chum and pink salmon from lagoons and their tributaries during August 2023, to be furnished to the Alaska Department of Fish and Game's Salmon Genetics Laboratory, for salmon stock identification analyses. Additionally, fin clips were collected from approximately 60 Coregoninae, Arctic grayling, Alaska blackfish, and Dolly Varden to be furnished to Professor Andres Lopez at the University of Alaska Museum of the North for genetic analyses.

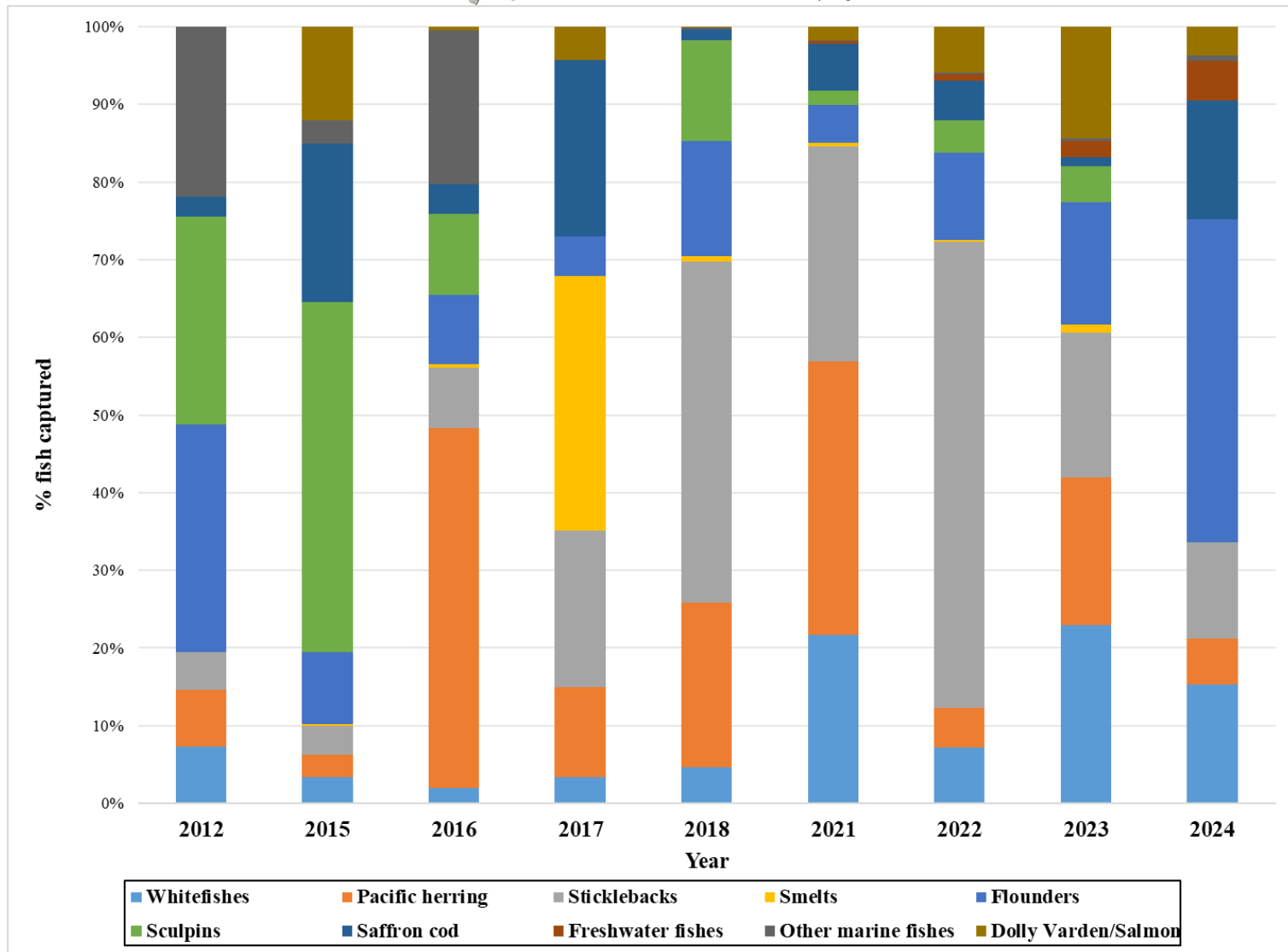


Figure 11: Relative abundance of fish taxonomic groups in Kotlik Lagoon by year.



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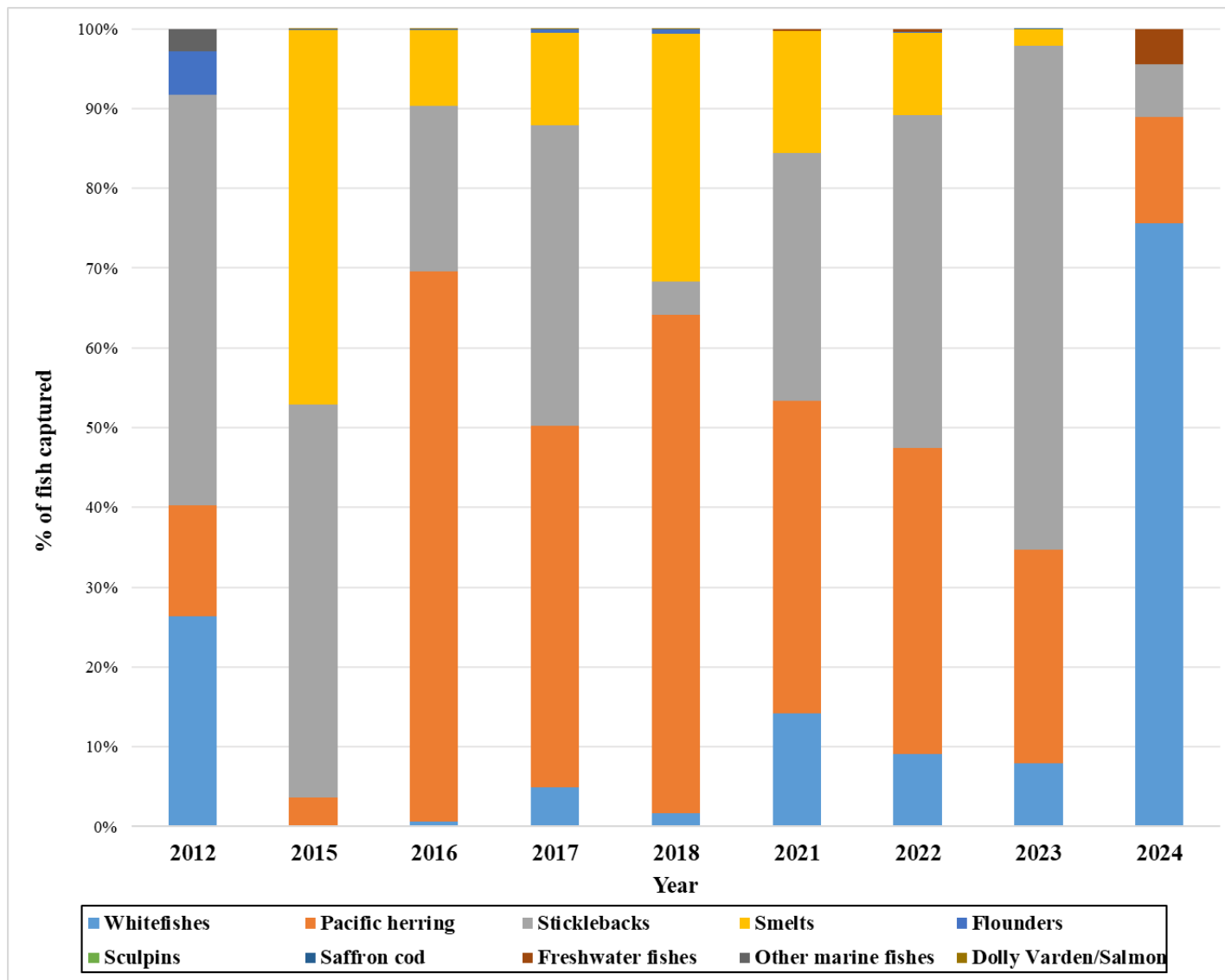


Figure 12: Relative abundance of fish taxonomic groups in Krusenstern Lagoon by year.

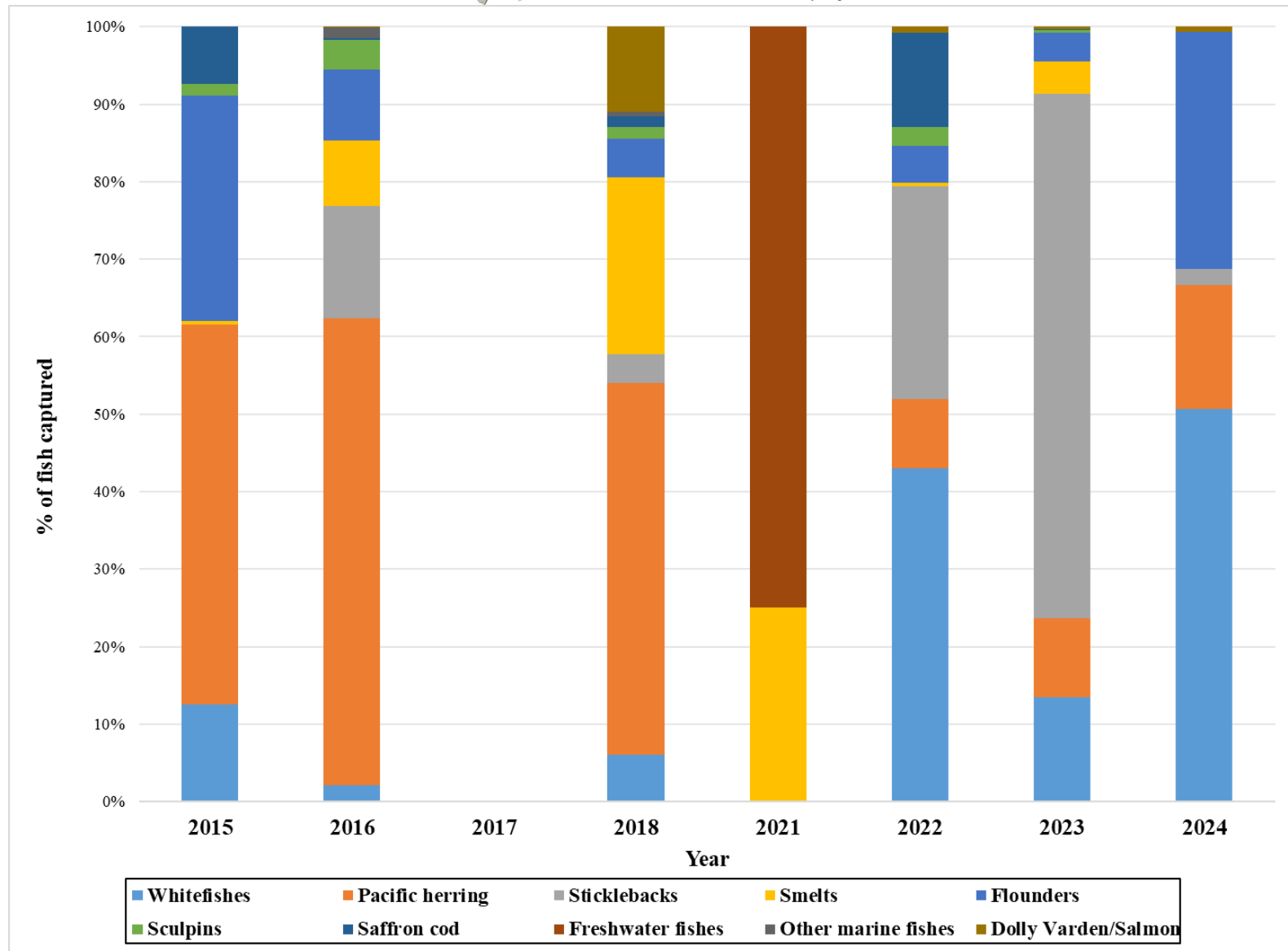
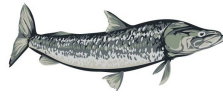


Figure 13: Relative abundance of fish taxonomic groups in Aukulak Lagoon by year. There were zero, and low abundance of all fishes in 2017 and 2021, years when the lagoon did not open to the ocean.



FUTURE DIRECTIONS

Data compiled throughout the 2023-2024 field seasons builds upon baseline information from previous efforts. 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 work on laboratory and taxonomic analyses of previously-collected samples with UAF Professor Alexei Pinchuk. Tracking of Mysidae abundance and diversity in the future may provide an additional metric to assess any long-term change;
2. In the future we hope to establish a better understanding of movement of species between marine, freshwater, and lagoon environments. This could include otolith microchemistry analyses and satellite and radio telemetry tracking studies;
3. Fish overwintering habitat conditions, and overwintering behaviors and locations in lagoons and their tributaries, particularly for resident Arctic grayling, are largely unknown and require investigation.

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ADDITIONAL TABLES

Table 2. 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	--



Lagoon	Type	Mean depth (m)	Mean salinity (ppt)	Study	Conservation unit/land management	AWC*	Closest community (distance km)	Field Work Conducted
Asikpak	II	--	--	--	Alaska Native (Kivalina Sinuakmuet)	N	15	--
Kivalina	III	--	--	--	Alaska Native (Kivalina Sinuakmuet)	Y*	0	--
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
Tsitsat 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
Akulak	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



Lagoon	Type	Mean depth (m)	Mean salinity (ppt)	Study	Conservation unit/land management	AWC*	Closest community (distance km)	Field Work Conducted
Shishmaref Inlet	IV	--	--	--	NANA/NPS (Bering Land Bridge)	N*	0	--
Arctic	IV	--	--	--	NANA/NPS (Bering Land Bridge)	N*	10	--
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 3. Mean (standard deviation) for salinity and temperature at three Cape Krusenstern lagoons over the 2012-2022 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
2024	Krusenstern	2.18	0.18	10.81	0.48		--	--	--	--
	Aukulak	6.61	4.69	10.98	2.92		--	--	--	--
	Kotlik	7.78	1.91	12.58	1.22		--	--	--	--
2023	Krusenstern	2.60	0.25	3.21	0.69		7.12	0.02	8.67	0.06
	Aukulak	1.63	0.33	6.63	0.89		9.48	0.60	9.82	0.35
	Kotlik	3.55	0.35	9.91	0.42		10.98	0.26	10.20	0.16
2022	Krusenstern	2.33	0.14	9.63	1.15		2.94	0.18	12.36	0.36
	Aukulak	2.60	0.60	13.00	3.06		12.83	0.74	14.20	1.08
	Kotlik	5.78	0.79	8.29	0.74		12.60	0.42	9.20	0.36
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 4. Mean water quality parameters at three Cape Krusenstern lagoons from 2012-2022. *denotes turbidity measurements recorded in units of NTU, ** denotes measurements made in units of RFU rather than $\mu\text{g/L}$ or mg/L , and ^ indicates measurements were in units of mg/L rather than %. Measurements were averaged across seasons. ^a denotes lagoons that were only partially sampled during these years. Persistent issues with the pH sensor on the EXO-2 sondes, despite sensor refurbishment by the manufacturer after the 2023 season, prevented collection of accurate readings.

Year	Lagoon	Depth (m)	ODO %	Specific conductivity ($\mu\text{S/cm}$)	pH	Chlorophyll mg/L	BGA $\mu\text{g/L}$	Turbidity (FNU)
2024	Kotlik	1.5	103.75	13409.95	--	0.26**	0.16**	2.37
	Krusenstern ^a	1.7	112.19	4093.94	--	5.11**	1.20**	20.98
	Aukulak	1	103.40	12933.62	--	1.03**	0.36**	14.12
2023	Kotlik	2.1	104.22	12462.33	--	1.23**	0.44*	10.72
	Krusenstern ^a	2.2	88.61	5977.58	--	0.88*	0.49**	5.79
	Aukulak	1	96.35	16184.62	--	1.41**	0.67**	8.86
2022	Kotlik	1.5	94.89	13615.06	--	0.98**	0.36**	13.08
	Krusenstern	1	105.95	4888.5	--	3.79**	1.00**	13.91
	Aukulak	0.75	98.04	1311.60	--	2.24**	0.55**	45.82
2021	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	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	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	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	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	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*

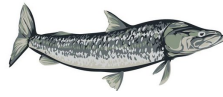


Table 5. Number of gear sets or hours fished for angling at Cape Krusenstern National Monument lagoons by type for each year sampled. ^a some sites were not sampled at Krusenstern Lagoon during this year due to logistical and weather issues. ^b Only early season (June) sampling occurred in 2024.

Gear Type	Year							
	2015	2016	2017	2018	2021	2022	2023 ^a	2024 ^b
Number of Sets/Hours Angling								
Beach Seine	40	41	39	7	38	39	51	28
Fyke Net	8	7	3	4	13	18	18	6
Gill Net	68	110	50	40	75	96	95	41
Dip Net	0	1	0	0	0	0	0	0
Angling	0	9	0	0	5	6	10	12
Minnow Trap	25	0	0	0	0	0	0	0



Table 6. 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	2022	2023	2024
Ammodytidae	<i>Ammodytes hexapterus</i>	Pacific sand lance								
Agonidae	<i>Pallasina barbata</i>	Tube-nose poacher		x						
	<i>Occella dodecaedron</i>	Bering poacher		x						
Clupeidae	<i>Clupea pallasii</i>	Pacific herring	x	x		x		x		x
Esocidae	<i>Dallia pectoralis</i>	Alaska blackfish					x			
Osmeridae	<i>Mallotus villosus</i>	Capelin		x						
	<i>Osmerus mordax</i>	Rainbow smelt		x		x		x	x	
	<i>Hypomesus olidus</i>	Pond smelt	x	x		x	x	x	x	
Salmonidae	<i>Coregonus laurettae</i>	Bering cisco		x		x		x	x	x
	<i>C. pidschian</i>	Humpback whitefish		x		x		x	x	x
	<i>C. sardinella</i>	Least cisco	x	x		x		x		x
	<i>Stenodus leucichthys</i>	Sheefish	x			x		x	x	
	<i>Oncorhynchus gorbuscha</i>	Pink salmon		x		x		x		
	<i>O. keta</i>	Chum salmon						x	x	x
	<i>O. kisutch</i>	Coho salmon				x				
	<i>S. malma</i>	Dolly Varden	x					x	x	
		Unidentified whitefish	x	x						
	<i>Thymallus arcticus</i>	Arctic grayling								
Gadidae	<i>Eleginus gracilis</i>	Saffron cod		x		x		x	x	
Gasterosteidae	<i>Gasterosteus aculeatus</i>	Threespine stickleback		x		x		x	x	
	<i>Pungitius pungitius</i>	Ninespine stickleback				x		x	x	x

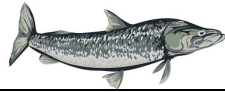


Family	Latin Name	Common Name	2015	2016	2017	2018	2021	2022	2023	2024
Cottidae	<i>Chitonotus pugetensis</i>	Roughback sculpin	x							
	<i>Enophrys bison</i>	Buffalo sculpin		x						
	<i>Megalocottus platycephalus</i>	Belligerent sculpin		x						
	<i>Myoxocephalus quadricornis</i>	Fourhorn sculpin		x		x		x	x	
	<i>Myoxocephalus polycanthocephalus</i>	Great sculpin	x							
	<i>Gymnocanthus tricuspis</i>	Arctic Staghorn sculpin		x						
		Unidentified sculpin		x		x				
Pleuronectidae	<i>Limanda proboscidea</i>	Long head dab		x						
	<i>Platichthys stellatus</i>	Starry flounder		x		x		x	x	x
	<i>Pleuronectes glacialis</i>	Arctic flounder	x	x		x		x	x	x
		Unidentified flatfish		x		x			x	
Stichaeidae	<i>Acantholumpenus mackai</i>	Blackline prickleback								



Table 7. 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	2022	2023	2024
Ammodytidae	<i>Ammodytes hexapterus</i>	Pacific sand lance	x	x		x				x
Agonidae	<i>Pallasina barbata</i>	Tube-nose poacher	x	x		x	x	x		
	<i>Occella dodecaedron</i>	Bering poacher		x						
Clupeidae	<i>Clupea pallasii</i>	Pacific herring	x	x	x	x	x	x	x	x
Umbridae	<i>Dallia pectoralis</i>	Alaska blackfish								
Osmeridae	<i>Mallotus villosus</i>	Capelin		x						
	<i>Osmerus mordax</i>	Rainbow smelt	x	x			x	x	x	
	<i>Hypomesus olidus</i>	Pond smelt		x	x	x	x		x	
Salmonidae	<i>Coregonus laurettae</i>	Bering cisco	x	x	x		x	x	x	x
	<i>C. pidschian</i>	Humpback whitefish	x	x	x	x	x	x	x	x
	<i>C. sardinella</i>	Least cisco	x	x	x	x	x	x	x	
	<i>Stenodus leucichthys</i>	Sheefish	x				x		x	
	<i>Oncorhynchus gorbuscha</i>	Pink salmon	x	x	x			x		
	<i>O. keta</i>	Chum salmon				x		x	x	
	<i>S. malma</i>	Dolly Varden	x	x			x	x	x	x
	<i>C. nasus</i>	Broad whitefish							x	
	<i>Thymallus arcticus</i>	Arctic grayling					x	x	x	x
	<i>Eleginus gracilis</i>	Saffron cod	x	x	x	x	x	x	x	x
Gasterosteidae	<i>Gasterosteus aculeatus</i>	Threespine stickleback	x	x	x	x	x	x	x	
	<i>Pungitius pungitius</i>	Ninespine stickleback	x		x	x	x	x	x	x
		Unidentified stickleback			x					
Cottidae	<i>Chitonotus pugetensis</i>	Roughback sculpin	x							
	<i>Enophrys bison</i>	Buffalo sculpin								
	<i>Megalocottus platycephalus</i>	Belligerent sculpin		x		x				



Family	Latin Name	Common Name	2015	2016	2017	2018	2021	2022	2023	2024
	<i>Myoxocephalus quadricornis</i>	Fourhorn sculpin	x	x			x	x	x	
	<i>Myoxocephalus polycanthocephalus</i>	Great sculpin	x							
	<i>Gymnocanthus tricuspis</i>	Arctic Staghorn sculpin		x						
	<i>Cottus cognatus</i>	Slimy sculpin					x			
		Unidentified sculpin	x			x				
Pleuronectidae	<i>Limanda proboscidea</i>	Long head dab								
	<i>Platichthys stellatus</i>	Starry flounder	x	x	x	x	x	x	x	x
	<i>Pleuronectes glacialis</i>	Arctic flounder	x	x	x	x		x	x	
		Unidentified flatfish		x	x	x			x	x
Stichaeidae	<i>Acantholumpenus mackai</i>	Blackline prickleback		x					x	



Table 8. Species richness in Krusenstern Lagoon by field season. X indicates species was sampled in the lagoon during the corresponding field season. Some sites were not sampled at Krusenstern Lagoon during this year due to logistical and weather issues^a

Family	Latin Name	Common Name	2015	2016	2017	2018	2021	2022	2023 ^a	2024
Ammodytidae	<i>Ammodytes hexapterus</i>	Pacific sand lance								
Agonidae	<i>Pallasina barbata</i>	Tubenose poacher								
	<i>Ocella dodecaedron</i>	Bering poacher								
Clupeidae	<i>Clupea pallasii</i>	Pacific herring	x	x	x	x	x	x	x	x
Umbridae	<i>Dallia pectoralis</i>	Alaska blackfish						x		x
Osmeridae	<i>Mallotus villosus</i>	Capelin								
	<i>Osmerus mordax</i>	Rainbow smelt				x				
	<i>Hypomesus olidus</i>	Pond smelt	x	x	x	x	x	x		
Salmonidae	<i>Coregonus laurettae</i>	Bering cisco	x	x	x	x	x			
	<i>C. pidschian</i>	Humpback whitefish	x	x	x	x	x	x	x	x
	<i>C. sardinella</i>	Least cisco	x	x	x	x	x	x	x	x
	<i>Stenodus leucichthys</i>	Sheefish	x		x	x	x	x		
	<i>Coregonus nasus</i>	Broad whitefish					x			
	<i>Oncorhynchus gorbuscha</i>	Pink salmon	x	x	x	x				
	<i>O. keta</i>	Chum salmon		x						
	<i>S. malma</i>	Dolly Varden	x	x						
		Unidentified whitefish		x						
	<i>Thymallus arcticus</i>	Arctic grayling	x				x	x		x
Gadidae	<i>Eleginus gracilis</i>	Saffron cod	x			x		x	x	
Gasterosteidae	<i>Gasterosteus aculeatus</i>	Threespine stickleback	x	x	x	x	x	x	x	
	<i>Pungitius pungitius</i>	Ninespine stickleback	x	x	x	x	x	x	x	x
		Unidentified stickleback								
Cottidae	<i>Chitonotus pugetensis</i>	Roughback sculpin								
	<i>Enophrys bison</i>	Buffalo sculpin								
	<i>Megalocottus platycephalus</i>	Belligerent sculpin								



Family	Latin Name	Common Name	2015	2016	2017	2018	2021	2022	2023	2024
	<i>Myoxocephalus quadricornis</i>	Fourhorn sculpin	x							
	<i>Myoxocephalus polycanthocephalus</i>	Great sculpin								
	<i>Gymnocanthus tricuspis</i>	Arctic Staghorn sculpin								
		Unidentified sculpin				x				
Pleuronectidae	<i>Limanda proboscidea</i>	Long head dab								
	<i>Platichthys stellatus</i>	Starry flounder	x	x	x	x		x		
	<i>Pleuronectes glacialis</i>	Arctic flounder		x	x	x				
		Unidentified flatfish		x		x				
Stichaeidae	<i>Acantholumpenus mackai</i>	Blackline prickleback								