# Introduction

The Arctic Ocean represents 34% of the world coastline (Lantuit et al. 2012), yet is among the least studied marine ecosystems in the world due to inclement weather and inaccessibility. Sea-ice coverage for most of the year necessitates marine sampling to be either limited in duration or requires ice-breaker capabilities. The shallow, broad coastal shelves in the Arctic comprise a much higher proportion than other oceans (Eakins and Sharman 2010), and are not accessible by deep-drafted, ocean-research vessels, causing nearshore Arctic regions to be under-studied. The nearshore regions of the Arctic support a robust fish community comprised of both marine, freshwater, and diadromous species of all life stages that subsist in the seasonally estuarine conditions. There are approximately 211 circumpolar marine fish species in 39 families (Mecklenburg et al. 2011), as well as approximately 99 freshwater or diadromous fish species in 17 families (Reist et al. 2006) that inhabit the Arctic waters, many of them found in the coastal Beaufort Sea along the northern Alaskan coast. Despite this diversity, there are few aquatic long-term studies in the Arctic (Kortsch et al. 2012), with most research focusing on either permafrost and resulting greenhouse gas emissions from thawing or high-trophic organisms (Fritz et al. 2017).

Fish populations are greatly affected by fluctuations in surrounding environmental conditions. As poikilotherms, fish have internal temperatures that are regulated by their environment, which causes surrounding water temperatures to greatly affect their rate dynamic parameters (Pauly 1980). As a result, fish exhibit behaviors to seek environmental conditions that optimize growth and survival (Cushing 1990; Monaghan 2008). Such parameters may vary by life stages, especially for diadromous fishes (Werner and Gilliam 1984). Conditions outside of this thermal range can be lethal, but it is often difficult to determine sub-optimal or sub-lethal effects (Coutant 1987). Within estuarine areas, fluctuations of salinity are another important environmental variable, as osmoregulation can incur a significant energetic cost (Bœuf and Payan 2001). Both marine and diadromous fishes (e.g., gadids and salmonids, respectively) living outside of their optimal salinity limits can experience substantial reductions in growth or higher natural mortality (Arnesen et al. 1993; Dutil et al. 1997). Unique to the Arctic Ocean is the persistent presence of sea ice and its effect upon the local ecosystem. Many ice-associated taxa (e.g., calanoid copepods and amphipods) exist at the sea ice edges (Bradstreet and Cross 1982), supporting fishes that prey upon such species such as Arctic Cod *Boreogadus saida* (Gradinger and Bluhm 2004). Thus, the intensity, duration, and variability of environmental factors plays a large role in determining species presence and abundance in a region, especially in the Arctic.

Climate models predict that the effects of climate change will be felt most acutely in the Arctic, with sea surface temperatures predicted to rise more than in temperate latitudes: mean annual temperatures are predicted to outpace global averages rising 3–10°C over the next 80 years (IPCC 2014). Expected changes are also much broader than just temperature; for example, observed mean annual sea-ice spatial extent has been decreasing 3.5–4.1% per decade and precipitation is expected to increase 30–50% (IPCC 2014). A reduced duration of shore-fast sea ice coverage also means that winter storms will likely erode shores more quickly, with coastlines in many locations along the Beaufort Sea expected to increase in erosion rates 2 m/year in many locations and up to 25 m/year, while barrier islands may erode completely (Jones et al. 2009; Lantuit et al. 2012; Gibbs and Richmond 2015). The loss of sea ice coverage was predicted to increase benthic light budgets (Clark et al. 2013), increasing primary productivity in polar regions. However, the reduction in sea ice in the Beaufort Sea has increased suspended sediment load (caused by an increase in coastal erosion rates), which decreases benthic and water column primary production (Bonsell and Dunton 2018). Such drastic changes in environmental conditions of the nearshore regions of the Arctic holds implications for the ecological responses of local fish species.

Nearshore areas are often important habitats that provide a wide diversity of trophic contributions, increased nursery production of juvenile fishes (Beck et al. 2001), and ontogenetic migration corridors (Sheaves et al. 2014). There are a variety of habitat types within nearshore habitats, which comprise a gradient of temperature and salinity conditions, helpful for fish species that prefer a specific niche. These environmental conditions can be reflected by the presence/absence and abundance of fish species because fish community composition can be a function of a temperature and other abiotic factors for both marine and freshwater species (Jackson et al. 2001; Collie et al. 2008). For example, the distribution of juveniles in estuarine conditions can be a function of turbidity (Blaber and Blaber 1980). Biotic factors can also inspire changes in fish community composition as a result of trophic interactions (e.g., intraspecific competition, commensalism, or mutualism) which change species assemblages and abundances (Fechhelm et al. 1995; Shurin and Allen 2001; Ruggerone et al. 2003). The variability of an ecological community assemblage structure is often thought to be indicative of increased stressors acting upon the populations (Warwick and Clarke 1993). Resilience of ecological communities to persist during changes to their habitat or environment is a characteristic of healthy communities with high biological diversity and wide response diversity of these species (Peterson et al. 1998; Elmqvist et al. 2003).

The nearshore fish community of the Alaskan Arctic is comprised of marine, diadromous (both amphidromous and anadromous), and freshwater species. Typically, most of the Arctic nearshore fish community is comprised of various whitefishes species (Coregoninae), gadids, and species such as Arctic Flounder *Liopsetta glacialis*, Fourhorn Sculpin *Myoxocephalus quadricornis*, and Rainbow Smelt *Osmerus mordax* (George et al. 2009; Priest et al. 2018; C. Bonsell, Marine Science Institute, University of Texas at Austin, unpublished data). The dynamic nature of the Arctic means that resources are highly variable and patchy at both spatial and temporal scales (Power 1997). These conditions cause several Arctic fishes to adopt migratory life histories to utilize multiple habitats, leading to a higher chance of encountering favorable conditions (Craig 1984; Roux et al. 2016). Thus, interannual abundances of fish species can fluctuate greatly.

The Arctic marine ecosystem is dependent upon gadids, predominantly Arctic Cod, as a keystone species for upper trophic levels owing to the prevalence and high energetic content (Elliott and Gaston 2008; Harter et al. 2013) (Gradinger and Bluhm 2004; Majewski et al. 2016; Thorsteinson and Love 2016). Arctic Cod play a key linkage between abundant zooplankton such as calanoid copepods and amphipods and higher trophic organisms such as Black Guillemot *Cepphus grille*, ringed seals *Pusa hispida*, and beluga whales *Delphinapterus leucas* (Bradstreet and Cross 1982; Harter et al. 2013; Thorsteinson and Love 2016). Marine biological inventory projects in the Arctic often document Arctic Cod as are one of the most common Arctic marine fish species (Frost and Lowry 1983; Norcross et al. 2013).

Arctic fresh and nearshore waters are comprised of several species of whitefishes, including Broad Whitefish *Coregonus nasus*, Arctic Cisco *Coregonus autumnalis*, Least Cisco *Coregonus sardinella*, and Humpback Whitefish *Coregonus pidschian*. Arctic whitefish species are amphidromous and tolerant of moderate levels of salinity (Bond and Erickson 1985; de March 1989; Fechhelm et al. 1993). Arctic Cisco found in Alaskan waters are hatched in the Mackenzie River, Northwest Territories, Canada and transported east as juveniles through easterly winds pushing surface currents, returning to their natal waters within the Mackenzie River to spawn after spending 6–8 years rearing in Alaskan estuaries and rivers (von Biela et al. 2013; Zimmerman et al. 2013). Least Cisco, Broad Whitefish, and Humpback Whitefish are amphidromous species with spawning populations of this species in many of the rivers across northern Alaska (Craig 1989) (Craig 1984; Fechhelm et al. 1994). The juveniles of all four of these whitefish species spend summer months feeding in the estuaries and deltas found along the coastal Beaufort Sea and then overwinter in deep-water pools or areas of upwelling in local rivers, especially the Colville River (Craig et al. 1985; Fechhelm et al. 1999; Seigle and Gottschalk 2013).

Beginning with the first large-scale discovery of petroleum deposits in the late-1960s, northern Alaska has been developed for oil and natural gas interests, with further industrial expansion expected in the near future. Most extraction and production processing plants are within several miles of the coastline. To access further hydrocarbon reserves slightly offshore, several man-made production islands were created. Causeways extending several miles into the Beaufort Sea were made to access these islands, with bridges to allow water to pass from either side of the structure. Beginning in 1985, the sampling methodology was standardized to have daily sampling at four fixed stations with double-ended fyke nets, located across Prudhoe Bay, Alaska. Data from 1985–1998 are summarized in annual reports and, since 2001, daily abundance and length data (for select species of subsistence importance) have been recorded in an annual database.

Supported by these ecological resources, northern Alaska is home to several human communities along the Beaufort Sea coast. These primarily Iñupiat communities each depend upon seasonal subsistence harvest of fishes, typically targeting Arctic Cisco or Broad Whitefish (Craig 1987; Fechhelm et al. 2007). Subsistence activities take place near population centers or traditional harvest areas such as Utqiaġvik (Barrow), Colville River Delta / Nuiqsut, and Kaktovik (Moulton et al. 2010; Moerlein and Carothers 2012). The federal Fishery Management Plan (FMP) for the Arctic currently does not allow for any commercial harvest of any fish species in federal waters (NPFMC 2009). Within state of Alaska waters, there was historically a small-scale commercial fishery at the mouth of the Colville River targeting Arctic Cisco and Least Cisco, but fishing effort has declined substantially in recent years, transitioning to a predominately subsistence fishery (Fechhelm et al. 2007; Moulton et al. 2010; Seigle and Gottschalk 2013). The growth of subsistence and commercial fisheries have occurred while the human population in the region has increased, concomitant with local economic growth in the oil and natural gas industry.

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As one of the few long-term studies in the region, we can use this dataset to appropriately determine and contextualize any changes in Arctic fish communities. Long-term ecological studies are necessary to determine changes that are subtle, especially when the phenomena are slow and/or complex or when interannual variability is large compared to the magnitude of the effect (Strayer et al. 1986). In particular, long-term ecological studies are valuable to help quantify how ecosystems react to changes or disturbance (Lindenmayer et al. 2012). We anticipate that as the Arctic warms (IPCC 2014), this would be reflected within subtle shifts in Arctic fish species composition. The existing 17-year dataset would be more likely to allow detection of significant changes occurring in the ecosystem.

Several species of fish common in the study area, particularly Arctic cod, are keystone species of the Arctic ecosystem, serving as the main forage prey base for higher-trophic animals (Majewski et al. 2016; Thorsteinson and Love 2016). The amphidromous whitefish species also provide key linkages between marine and freshwater ecosystems. Changes to these stocks could have widespread effects upon several Arctic aquatic ecosystems. As a result, finding evidence of the influence of global forcing factors upon local fish stocks could be beneficial to understanding how to mitigate effects upon the entire ecosystem. Further, changes within lower trophic levels can manifest as bottom-up trophic cascades with dynamic effects felt throughout the species community ecological web (Ware and Thomson 2005). Local indigenous communities directly depend upon the fish species investigated and also upon the higher trophic levels of the marine ecosystem for which the fish provide a forage base (Moerlein and Carothers 2012). Subsistence fisheries take place yearlong but are especially important during winter months when alternative food sources are difficult to obtain. It is important for local Iñupiat cultures to maintain a subsistence lifestyle in order to preserve local traditions and communities. Understanding how fish assemblages shift given environmental changes assist natural resource managers and subsistence users to plan and adapt accordingly. Predictions of how fish assemblage structure responds to environmental shifts would allow for powerful advance awareness of the coming changes to the ecosystem.

Quantifying species assemblage responses to abiotic shifts would allow for increased predictive abilities in an increasingly dynamic ecosystem. Detectable changes in community indices are likely indicative of broader, regional trends, possibly global in scale. Wind patterns are known to be the largest drivers of cisco abundance in the study area (Fechhelm and Fissel 1988; Fechhelm et al. 1994, 1999). Therefore, many of the changes within the Prudhoe Bay estuarine ecosystem are likely attributable to changes in environmental conditions. Understanding the relative importance of such environmental variables can allow for the identification of future habitats that will increase in ecological value as the underlying system changes. Future environmental scenarios planning has identified likely outcomes from changes in climate but is typically limited to abiotic predictions (SNAP 2012). Modeling how the current fish assemblage structure responds to environmental factors would allow for insight into how this assemblage structure might be expected to respond.

The Beaufort Sea is a peripheral sea to the Arctic Ocean along the northern coast of Alaska and Canada. Coastlines along the Alaskan Beaufort Sea are typically salt marshes and slumping tundra, and coastal erosion rates appear to be increasing at many locations (Gibbs and Richmond 2015). Much of the coastal Beaufort Sea is shallow; for example, the 2-m isobath is 1 to 8 km from shore (Britch et al. 1983; Ross 1988). Barrier islands occur along much of the Alaskan Beaufort Sea coast, differentiating outside marine waters from the coastal waters. There are several large sources of freshwater inputs into the Beaufort Sea, including the Colville River (9.0 km3/year; USGS 2018a), the Sagavanirktok River (1.5 km3/year; USGS 2018b), and the Mackenzie River (325 km3/year; Yang et al. 2015).

Wind patterns along the Alaskan Beaufort Sea coast are typically east-west during summer months (Priest et al. 2018). Such wind patterns have the effect of increasing or decreasing water levels up to 1.5 m in areas behind barrier islands (Britch et al. 1983; Ross 1988). East winds lower nearshore water levels by pushing surface waters offshore, while west winds raise nearshore water levels by driving surface waters onshore (Britch et al. 1983). Because much of the coastal areas of the Alaskan Beaufort Sea are shallow, vast regions of shoreline become dewatered by changes in wind direction or intensity.

Historically, shore-bound sea ice persists in the southern Beaufort Sea until late June or early July and reaches a minimum extent in September (Barry et al. 1979; Belchansky et al. 2004; Wendler et al. 2010). Freeze up typically begins in September or October (Belchansky et al. 2004). However, icebergs occasionally can persist throughout the year depending upon annual temperatures and oceanic currents (Johnson and Eicken 2016). The duration of the ice-free season has expanded in recent years as the freeze up date has moved later and the melt date has become earlier, with the central Beaufort Sea serving as an example of the most dramatic changes due to this environmental shift (Stroeve et al. 2014; Johnson and Eicken 2016). The completion of break-up is arriving earlier by 10–12 days per decade, with freeze up occurring approximately one week later (Johnson and Eicken 2016).

Prudhoe Bay is a semi-estuarine bay of the Beaufort Sea formed near the mouth of the Sagavanirktok River delta. The immediate surrounding coastal waters are shallow, with the 6-m water depth contour less than 5 km from most parts of natural, unaltered shore and several barrier islands are within 15 km of shore (Ross 1988). Much of the terrestrial environment around Prudhoe Bay has developed infrastructure for the extraction and processing of oil, with many permanent structures inland from the coast. In addition, several oil extraction and processing facilities have been constructed on man-made islands that are connected to shore with gravel causeways and bridge breaches (Ross 1988). The majority of the shoreline remains as natural tundra banks, although the rate of erosion has increased at many locations (Gibbs and Richmond 2015). A reduction in the duration of shore-fast sea ice has meant that shorelines are exposed for longer periods to waves caused by summer storms, which has contributed to the increased rate of erosion.

# Methods

Since 1981, daily fish monitoring has occurred annually along the coast near Prudhoe Bay, Alaska for approximately 8–10 weeks each summer during July and August, with the exception of the 1999 and 2000 field seasons. Beginning in 2001, a complete dataset and standardized methodology have been implemented at four fixed stations with double-ended fyke nets. The sample locations are aligned roughly east-west, spaced approximately 27 km apart (Figure 1). From west to east, these sites are identified as Site 220 (approximately 1 km west from the base of the West Dock causeway; sampled 2001–2018), Site 218 (on the west side of Prudhoe Bay at the West Beach drilling pad; sampled 2001–2018), Site 214 (at the Niakuk drilling pad on the tip of Heald Point; sampled 2002–2018), and Site 230 (on the eastern side of the Endicott Causeway, south of the middle of three causeway breaches; sampled 2001–2018). In 2001, Site 231 was fished on the western side of the Endicott causeway to follow historical sampling locations, but due to changing bathymetry the site was replaced the following year with the current sampling location of Site 214.

At each of the four sampling locations, two fyke nets with an opening of 1.8 m by 1.7 m were set side-by-side, opening towards the coastline, with a 60-m blocker net leading to shore. A 15-m blocker wing was attached to the outer edge of each cod end. Using this bi-directional sampling method, the fyke nets could intercept and catch fish moving along the shoreline in either direction. All blocker lead nets and wings were constructed from 2.5-cm stretch mesh, while the fyke net mesh consisted of 1.27-cm stretch mesh. Three consecutive throats were located behind each 1.7-m frame opening, with the outermost throat having a functional width of 11.4 cm. Net specifications were consistently used throughout the duration of the study, with the exception of a modification in 2009 to add a vertical metal bar to the fyke net funnel to prevent incidental seal catches. Sampling sites were operated from approximately July 1 through September 1 each year, with the precise dates of installation and removal for each site varying each year. The latest date of first sampling was July 6 (2018) and the earliest date of last sampling was August 25.

Each net was checked daily and all fish were identified to species and enumerated. After species identification, enumeration, and measurements of a subsample of select species, fish were released away and offshore from the cod-end openings to minimize recapture. All fish were identified using Mecklenburg et al. (2002), George et al. (2009), and Thorsteinson and Love (2016). Field sampling protocols were essentially unchanged from 2001 to 2018, except for the addition in 2017 of length measurements from new fish species.

During all years, salinity (ppt) and water temperature (°C) data were also collected daily during each sampling event at each site using a calibrated handheld YSI 30 salinity / conductivity / temperature meter (YSI Inc., Yellow Springs, Ohio) at the bottom, mid-water column, and just below the surface. All water temperature and salinity measurements were collected near the cod ends of the fyke nets.

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