# 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 (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, precipitation is expected to increase 30–50%, and mean annual temperatures are predicted to outpace global averages rising 3–10°C in the next 80 years (IPCC 2014). The loss of sea ice in the Arctic, and resulting change in albedo, elicit a positive feedback loop known as Arctic amplification to cause the Arctic to warm even more (Screen and Simmonds 2010). 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, recent work along the coastal Beaufort Sea indicates that the reduction in sea ice increases suspended sediment load (primarily 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, particularly at a specific location.

The Arctic marine ecosystem is dependent upon gadids, predominantly Arctic Cod, as a keystone species for upper trophic levels (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). Such species target Arctic Cod as a prey of choice because the lipid-rich fish offers a high energetic content (Elliott and Gaston 2008; Harter et al. 2013). Predators also consume Arctic Cod because of its abundance. For example, 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). Due to the limited scope and duration of sampling programs, little is known about the population dynamics of Arctic Cod, although the location of water masses appears to play a role in distribution (J. Marsh, UAF College of Fisheries and Ocean Sciences, unpublished data).

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). In northern Alaska, Least Cisco are amphidromous and predominately from the Colville River, and spawning populations are not found between the Colville River and the Mackenzie River (Craig 1984; Fechhelm et al. 1994). Broad Whitefish and Humpback Whitefish are amphidromous species common to Arctic and sub-Arctic regions of North American and Eurasia, with spawning populations of this species in many of the rivers across northern Alaska (Craig 1989). In northern Alaska, Broad Whitefish appear to be more widely distributed while Humpback Whitefish populations seem to be more concentrated in larger rivers such as the Colville River. 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).

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.

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. As development around Prudhoe Bay began to increase, a plan was developed to monitor fish populations in the region, with a particular focus on fishes important to local communities. The monitoring program began in the early 1980s to quantify effects of the West Dock causeway upon fish passage and was expanded a decade later to include the effects of a second causeway (Endicott Island causeway). 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.

This proposed project intends to use the 2001–2018 time series from the four sampling sites near Prudhoe Bay, Alaska, to determine how individual whitefish species and the overall fish species assemblage structure has changed, then to quantify causative abiotic and biotic factors responsible for such changes. Previous studies from this project have been limited to identifying how specific environmental variables affect a single species, for example, modeling the effects of salinity and temperature upon Arctic Cisco (Fechhelm et al. 1993) and Broad Whitefish (Fechhelm et al. 1992), theorized about inferred trophic competition between Broad Whitefish and Least Cisco (Fechhelm et al. 1995), or documented the effects of offshore seismic surveys (Streever et al. 2016). My project will take a more integrated approach and will be the first long-term study in the Alaskan Arctic to quantify how fish assemblage structure responds to external stimuli. Shifts in environmental conditions due to climate change in the Arctic mean that even basic species responses would need to be updated as the reaction norm would not necessarily be expected to be the same.

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.

Climate change within the Arctic is often difficult to pinpoint and harder to predict, and this study aims to quantify how the important fish resources of Prudhoe Bay will respond to such changes.

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.

# Literature Cited

Arnesen, A. M., E. H. Jørgensen, and M. Jobling. 1993. Feed intake, growth and osmoregulation in Arctic charr, Salvelinus alpinus (L.), following abrupt transfer from freshwater to more saline water. Aquaculture 114:327–338.

Bai, J., and P. Perron. 2003. Computation and analysis of multiple structural change models. Journal of Applied Econometrics 18(1):1–22.

Barry, R. G., R. E. Moritz, and J. C. Rogers. 1979. The fast ice regimes of the Beaufort and Chukchi Sea coasts, Alaska. Cold Regions Science and Technology 1(2):129–152.

Beck, M. W., K. L. Heck, K. W. Able, D. L. Childers, D. B. Eggleston, B. M. Gillanders, B. Halpern, C. G. Hays, K. Hoshino, T. J. Minello, R. J. Orth, P. F. Sheridan, and M. P. Weinstein. 2001. The Identification, Conservation, and Management of Estuarine and Marine Nurseries for Fish and Invertebrates. BioScience 51(8):633–641.

Belchansky, G. I., D. C. Douglas, and N. G. Platonov. 2004. Duration of the Arctic sea ice melt season: Regional and interannual variability, 1979-2001. Journal of Climate 17(1):67–80.

von Biela, V. R., C. E. Zimmerman, B. R. Cohn, and J. M. Welker. 2013. Terrestrial and marine trophic pathways support young-of-year growth in a nearshore Arctic fish. Polar Biology 36(1):137–146.

Blaber, S. J. M., and T. G. Blaber. 1980. Factors affecting the distribution of juvenile estuarine and inshore fish. Journal of Fish Biology 17(2):143–162.

Bœuf, G., and P. Payan. 2001. How should salinity influence fish growth? Comparative Biochemistry and Physiology - Part C Toxicology and Pharmacology 130(4):411–423.

Bond, W. A., and R. N. Erickson. 1985. Life History Studies of Anadromous Coregonid Fishes in Two Freshwater Lake Systems on the Tuktoyaktuk Peninsula, Northwest Territories Canadian Technical Report of Fisheries and Aquatic Sciences. Canadian Technical Report of Fisheries and Aquatic Sciences 1336.

Bonsell, C., and K. H. Dunton. 2018. Long-term patterns of benthic irradiance and kelp production in the central Beaufort Sea reveal implications of warming for Arctic inner shelves. Progress in Oceanography 162:160–170.

Bradstreet, M. S. W., and W. E. Cross. 1982. Trophic Relationships at High Arctic Ice Edges. Arctic 35(1):1–12.

Britch, R. P., R. C. Miller, J. Downing, T. Petrillo, and M. Veit. 1983. 1982 Environmental Summer Studies for the Endicott Development Volume II. B. J. Gallaway and R. P. Britch, editors Environmental Summer Studies (1982) for the Endicott Development.

Clark, G. F., J. S. Stark, E. L. Johnston, J. W. Runcie, P. M. Goldsworthy, B. Raymond, and M. J. Riddle. 2013. Light-driven tipping points in polar ecosystems. Global Change Biology 19(12):3749–3761.

Collie, J. S., A. D. Wood, and H. P. Jeffries. 2008. Long-term shifts in the species composition of a coastal fish community. Canadian Journal of Fisheries and Aquatic Sciences 65(7):1352–1365.

Coutant, C. C. 1987. Thermal preference: when does an asset become a liability? Environmental Biology of Fishes 18(3):161–172.

Craig, P. C. 1984. Fish use of coastal waters of the Alaska Beaufort Sea: a review. Transactions of the American Fisheries Society 113(3):265–282.

Craig, P. C. 1987. Subsistence Fisheries at Coastal Villages in the Alaskan Arctic, 1970-1986. Springfield, Virginia.

Craig, P. C. 1989. An introduction to anadromous fishes in the Alaskan Arctic. Biological Papers of the University of Alaska (24):27–54.

Craig, P. C., W. B. Griffiths, L. Haldorson, and H. McElderry. 1985. Distributional Patterns of Fishes in an Alaskan Arctic Lagoon. Polar Biology 4:9–18.

Cushing, D. H. 1990. Plankton production and year-class strength in fish populations: An update of the match/mismatch hypothesis. Advances in Marine Biology 26:249–293.

Dutil, J.-D., Y. Lambert, and E. Boucher. 1997. Does higher growth rate in Atlantic cod (Gadus morhua) at low salinity result from lower standard metabolic rate or increased protein digestibility? Canadian Journal of Fisheries and Aquatic Sciences 54:99–103.

Eakins, B. W., and G. F. Sharman. 2010. Volumes of the World’s Oceans from ETOPO1. NOAA National Geophysical Data Center, Boulder, CO.

Elliott, K. H., and A. J. Gaston. 2008. Mass-length relationships and energy content of fishes and invertebrates delivered to nestling Thick-billed Murres Uria lomvia in the Canadian Arctic, 1981-2007. Marine Ornithology 36(1):25–34.

Elmqvist, T., C. Folke, M. Nystrom, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change, and resilience RID C-1309-2008 RID F-2386-2011. Frontiers in Ecology and the Environment 1(9):488–494.

Fechhelm, R. G., J. D. Bryan, W. B. Griffiths, W. J. Wilson, and B. J. Gallaway. 1994. Effect of Coastal Winds on the Summer Dispersal of Young Least Cisco (Coregonus-Sardinella) from the Colville River to Prudhoe Bay, Alaska - a Simulation-Model. Canadian Journal of Fisheries and Aquatic Sciences 51(4):890–899.

Fechhelm, R. G., R. E. Dillinger Jr., B. J. Gallaway, and W. B. Griffiths. 1992. Modeling of in Situ Temperature and Growth Relationships for Yearling Broad Whitefish in Prudhoe Bay, Alaska. Transactions of the American Fisheries Society 121(1):1–12.

Fechhelm, R. G., and D. B. Fissel. 1988. Recruitment of Canadian Arctic Cisco (Coregonus autumnalis) into Alaskan Waters. Canadian Journal of Fisheries and Aquatic Sciences 45:906–910.

Fechhelm, R. G., P. S. Fitzgerald, J. D. Bryan, and B. J. Gallaway. 1993. Effect of salinity and temperature on the growth of yearling Arctic cisco (Coregonus autumnalis) of the Alaskan Beaufort Sea.

Fechhelm, R. G., W. B. Griffiths, J. D. Bryan, B. J. Gallaway, and W. J. Wilson. 1995. Application of an in Situ Growth Model: Inferred Instance of Interspecific Trophic Competition between Anadromous Fishes of Prudhoe Bay, Alaska. Transactions of the American Fisheries Society 124(1):55–69.

Fechhelm, R. G., L. R. Martin, B. J. Gallaway, W. J. Wilson, and W. B. Griffiths. 1999. Prudhoe Bay causeways and the summer coastal movements of Arctic Cisco and Least Cisco. Arctic 52(2):139–151.

Fechhelm, R. G., B. Streever, and B. J. Gallaway. 2007. The Arctic cisco (Coregonus autumnalis) subsistence and commercial fisheries, Colville River, Alaska: A conceptual model. Arctic 60(4):421–429.

Fetterer, F., K. Knowles, W. Meier, M. Savoie, and A. K. Windnagel. 2018. Sea Ice Index, Version 3. 2001 - 2017. Boulder, Colorado.

Fritz, M., J. E. Vonk, and H. Lantuit. 2017. Collapsing Arctic coastlines. Nature Climate Change 7(1):6–7.

Frost, K. J., and L. F. Lowry. 1983. Demersal Fishes and Invertebrates Trawled in the Northeastern Chukchi and Western Beaufort Seas, 1976-77.

George, C., L. L. Moulton, and M. Johnson. 2009. A field guide to the common fishes of the North Slope of Alaska.

Gibbs, A. E., and B. M. Richmond. 2015. National Assessment of Shoreline Change — Historical Shoreline Change Along the North Coast of Alaska , U.S.-Canadian Border to Icy Cape. U.S. Geological Survey Open File Report 2015 - 1048.

Gradinger, R. R., and B. A. Bluhm. 2004. In-situ observations on the distribution and behavior of amphipods and Arctic cod (Boreogadus saida) under the sea ice of the High Arctic Canada Basin. Polar Biology 27(10):595–603.

Guisan, A., T. C. Edwards, and T. Hastie. 2002. Generalized linear and generalized additive models in studies of species distributions: setting the scene. Ecological Modelling 157:89–100.

Harter, B. B., K. H. Elliott, G. J. Divoky, and G. K. Davoren. 2013. Arctic Cod (Boreogadus saida) as Prey: Fish Length-Energetics Relationships in the Beaufort Sea and Hudson Bay. Arctic 66(2):191–196.

IPCC. 2014. Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, *in* C. W. Team, R. K. Pachauri, and L. Meyer, editors. IPCC. Geneva, Switzerland.

Jackson, D. A., P. R. Peres-Neto, and J. D. Olden. 2001. What controls who is where in freshwater fish communities – the roles of biotic, abiotic, and spatial factors. Canadian Journal of Fisheries and Aquatic Sciences 58(1):157–170.

Johnson, M., and H. Eicken. 2016. Estimating Arctic sea-ice freeze-up and break-up from the satellite record: A comparison of different approaches in the Chukchi and Beaufort Seas. Elementa: Science of the Anthropocene 4(124).

Jones, B. M., C. D. Arp, M. T. Jorgenson, K. M. Hinkel, J. A. Schmutz, and P. L. Flint. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophysical Research Letters 36(3):1–5.

Kortsch, S., R. Primicerio, F. Beuchel, P. E. Renaud, J. Rodrigues, O. J. Lonne, and B. Gulliksen. 2012. Climate-driven regime shifts in Arctic marine benthos. Proceedings of the National Academy of Sciences 109(35):14052–14057.

Lantuit, H., P. P. Overduin, N. Couture, S. Wetterich, F. Aré, D. Atkinson, J. Brown, G. Cherkashov, D. Drozdov, L. Donald Forbes, A. Graves-Gaylord, M. Grigoriev, H. W. Hubberten, J. Jordan, T. Jorgenson, R. S. Ødegård, S. Ogorodov, W. H. Pollard, V. Rachold, S. Sedenko, S. Solomon, F. Steenhuisen, I. Streletskaya, and A. Vasiliev. 2012. The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines. Estuaries and Coasts 35(2):383–400.

Lindegren, M., V. Dakos, J. P. Gröger, A. Gårdmark, G. Kornilovs, S. A. Otto, and C. Möllmann. 2012. Early detection of ecosystem regime shifts: A multiple method evaluation for management application. PLoS ONE 7(7).

Lindenmayer, D. B., G. E. Likens, A. Andersen, D. Bowman, C. M. Bull, E. Burns, C. R. Dickman, A. A. Hoffmann, D. A. Keith, M. J. Liddell, A. J. Lowe, D. J. Metcalfe, S. R. Phinn, J. Russell-Smith, N. Thurgate, and G. M. Wardle. 2012. Value of long-term ecological studies. Austral Ecology 37(7):745–757.

Majewski, A. R., W. Walkusz, B. R. Lynn, S. Atchison, J. Eert, and J. D. Reist. 2016. Distribution and diet of demersal Arctic Cod, Boreogadus saida, in relation to habitat characteristics in the Canadian Beaufort Sea. Polar Biology 39(6):1087–1098.

de March, B. G. E. 1989. Salinity tolerance of larval and juvenile broad whitefish (Coregonus nasus). Canadian Journal of Zoology 67:2392–2397.

McDowall, R. M. 1992. Particular problems for the conservation of diadromous fish. Aquatic Conservation: Marine and Freshwater Ecosystems 2(4):351–355.

Mecklenburg, C. W., T. A. Mecklenburg, and L. K. Thorsteinson. 2002. Fishes of Alaska. American Fisheries Society. Bethesda, Maryland.

Mecklenburg, C. W., P. R. Møller, and D. Steinke. 2011. Biodiversity of arctic marine fishes: Taxonomy and zoogeography. Marine Biodiversity 41(1):109–140.

Moerlein, K. J., and C. Carothers. 2012. Total Environment of Change: Impacts of Climate Change and Social Transitions on Subsistence Fisheries in Northwest Alaska. Ecology and Society 17(1):10.

Monaghan, P. 2008. Early growth conditions, phenotypic development and environmental change. Philosophical Transactions of the Royal Society B: Biological Sciences 363(1497):1635–1645.

Moulton, L. L., B. Seavey, and J. Pausanna. 2010. History of an Under-Ice Subsistence Fishery for Arctic Cisco and Least Cisco in the Colville River, Alaska. Arctic 63(4):381–390.

Norcross, B. L., S. W. Raborn, B. A. Holladay, B. J. Gallaway, S. T. Crawford, J. T. Priest, L. E. Edenfield, and R. Meyer. 2013. Northeastern Chukchi Sea demersal fishes and associated environmental characteristics, 2009-2010. Continental Shelf Research 67:77–95.

NPFMC. 2009. Fishery Management Plan for Fish Resources of the Arctic Management Area.

Oksanen, J., F. G. Blanchet, R. Kindt, P. Legendre, P. R. Minchin, R. B. O’hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, H. Wagner, and M. J. Oksanen. 2018. Vegan: community ecology package. CRAN.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. ICES Journal of Marine Science 39(2):175–192.

Peterson, G., C. R. Allen, and C. S. Holling. 1998. Ecological Resilience, Biodiversity, and Scale. Ecosystems 1:6–18.

Poos, M. S., and D. A. Jackson. 2012. Addressing the removal of rare species in multivariate bioassessments: The impact of methodological choices. Ecological Indicators 18:82–90.

Power, G. 1997. A Review of Fish Ecology in Arctic North America. Pages 13–39 *in* J. B. Reynolds, editor.Fish Ecology in Arctic North America. American Fisheries Society, Bethesda, Maryland.

Priest, J. T., D. G. Green, B. M. Fletcher, and T. M. Sutton. 2018. Beaufort Sea Nearshore Fish Monitoring Study: 2017 Annual Report. University of Alaska Fairbanks, College of Fisheries and Ocean Sciences. Fairbanks, Alaska.

Reist, J. D., F. J. Wrona, T. D. Prowse, M. Power, J. B. Dempson, R. J. Beamish, J. R. King, T. J. Carmichael, and C. D. Sawatzky. 2006. General effects of climate change on Arctic fishes and fish populations. Ambio 35(7):370–380.

Ross, B. D. 1988. Causeways in the Alaskan Beaufort Sea. United States Environmental Protection Agency. Anchorage, Alaska.

Roux, M. J., L. A. Harwood, X. Zhu, and P. Sparling. 2016. Early summer near-shore fish assemblage and environmental correlates in an Arctic estuary. Journal of Great Lakes Research 42(2):256–266.

Ruggerone, G. T., M. Zimmermann, K. W. Myers, J. L. Nielsen, and D. E. Rogers. 2003. Competition between Asian pink salmon (Oncorhynchus gorbuscha) and Alaskan sockeye salmon (O-nerka) in the North Pacific Ocean. Fisheries Oceanography 12(3):209–219.

Screen, J. A., and I. Simmonds. 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. Nature 464(7293):1334–1337.

Seigle, J. C., and J. M. Gottschalk. 2013. Fall 2012 subsistence fishery monitoring on the Colville River. ABR, Inc. – Environmental Research & Services. Fairbanks, Alaska.

Sheaves, M., R. Baker, I. Nagelkerken, and R. M. Connolly. 2014. True Value of Estuarine and Coastal Nurseries for Fish: Incorporating Complexity and Dynamics. Estuaries and Coasts 38(2):401–414.

Shurin, J. B., and E. G. Allen. 2001. Effects of Competition, Predation, and Dispersal on Species Richness at Local and Regional Scales. The American Naturalist 158(6):624–637.

SNAP. 2012. Predicting Future Potential Climate-Biomes for the Yukon, Northwest Territories, and Alaska. Scenarios Network for Arctic Planning and the EWHALE lab, University of Alaska Fairbanks. Fairbanks, Alaska.

Strayer, D., J. S. Glitezenstein, C. G. Jones, J. Kolasa, G. E. Likens, M. J. McDonnell, G. G. Parker, and S. T. A. Pickett. 1986. Long-Term Ecological Studies: An Illustrated Account Of their Design, Operation, and Importance To Ecology.

Streever, B., S. W. Raborn, K. H. Kim, A. D. Hawkins, and A. N. Popper. 2016. Changes in fish catch rates in the presence of air gun sounds in Prudhoe Bay, Alaska. Arctic 69(4):346–358.

Stroeve, J. C., T. Markus, L. Boisvert, J. Miller, and A. Barret. 2014. Changes in Arctic melt season and implications for sea ice loss. Geophysical Research Letters 41(4):1216–1225.

Thorsteinson, L. K., and M. S. Love. 2016. Alaska Arctic Marine Fish Ecology Catalog. U.S. Geological Survey Scientific Investigations Report 2016-5038 (OCS Study, BOEM 2016-048), 768 p.

USGS. 2018a. USGS National Water Information System - Colville River at Umiat, AK. https://waterdata.usgs.gov/ak/nwis/uv/?site\_no=15875000&PARAmeter\_cd=00065,00060.

USGS. 2018b. USGS National Water Information System - Sagavanirktok River near Pump Station 3, Alaska. https://waterdata.usgs.gov/ak/nwis/uv?site\_no=15908000.

Ware, D. M., and R. E. Thomson. 2005. Ecology: Bottom-up ecosystem trophic dynamics determine fish production in the northeast pacific. Science 308(5726):1280–1284.

Warwick, R. M., and K. R. Clarke. 1993. Increased variability as a symptom of stress in marine communities. Journal of Experimental Marine Biology and Ecology 172(1–2):215–226.

Wendler, G., M. Shulski, and B. Moore. 2010. Changes in the climate of the Alaskan North Slope and the ice concentration of the adjacent Beaufort Sea. Theoretical and Applied Climatology 99:67–74.

Werner, E. E., and J. F. Gilliam. 1984. The Ontogenetic Niche and Species Interactions in Size-Structured Populations. Annual Review of Ecology and Systematics 15:393–425.

Yang, D., X. Shi, and P. Marsh. 2015. Variability and extreme of Mackenzie River daily discharge during 1973-2011. Quaternary International 380–381:159–168.

Young, D., T. Benaglia, D. Chauveau, D. Hunter, R. Elmore, T. Hettmansperger, H. Thomas, and F. Xuan. 2017. R Package mixtools - Tools for Analyzing Finite Mixture Models. CRAN.

Zeileis, A., F. Leisch, K. Hornik, C. Kleiber, B. Hansen, and E. C. Merkle. 2015. R package strucchange - Testing, Monitoring, and Dating Structural Changes Description. Version 1.5-1. CRAN.

Zimmerman, C. E., A. M. Ramey, S. M. Turner, F. J. Mueter, S. M. Murphy, and J. L. Nielsen. 2013. Genetics, recruitment, and migration patterns of Arctic cisco (Coregonus autumnalis) in the Colville River, Alaska, and Mackenzie River, Canada. Polar Biology 36(11):1543–1555.