Chapter 6. Conservation of Arctic Alaska's Marine Fish Resources

By Lyman K. Thorsteinson[1]

Abstract

Limitations in data and scientific uncertainties in our understanding of Arctic marine fish ecology are pronounced and indicative of the science that will be needed for effective resource management, environmental regulation, and conservation. The existing datasets are not conducive to quantitative evaluations of population dynamics or determinations of species abundance, and in most instances, it is not possible to estimate vital demographic parameters such as age and size structure, instantaneous growth rates, or mortality and survival rates. Cost and logistical constraints associated with Arctic research will likely focus future efforts on monitoring of trends in these key population parameters rather than actual changes in fish population sizes. Physiological data are lacking especially with respect to our understanding of key environmental effects on rates of growth, reproduction, and survival. Field and laboratory experiments will be needed to develop bioenergetics models to assess climate change effects or disturbances, such as possible Arctic oil spills. For now, in the absence of population understanding, information about species life history and ecological traits can be used to classify Arctic marine fish species into strategic groups based on the r-K theory to assist resource management and environmental decision-making including two previously undescribed groups we call Amphidromic and Cryophilic Strategists. Knowledge about the seasonal diets and food habits of dominant Arctic fishes are primarily known from stomach samples collected during ice-free months. Similarly, descriptions of predator-prey relationships and biological interactions tend to be limited to prominent species in food webs leading to apex predators. Integrated and interdisciplinary science approaches are priorities for long-term data collection that will be needed for the Arctic fishery-based ecosystem management recommended by the U.S. Department of Commerce. The information needs for 21 priority marine species identified in chapter 3 are considered in light of integrated research and monitoring in the Chukchi and Beaufort Seas.

[1]U.S. Geological Survey.

General Understanding of Marine Fish Life History

Much new biological information about marine Arctic fishes and their environmental relationships was acquired, reviewed, and synthesized in this study. It is an important synthesis because it expands the nature of information presented in the *Fishes of Alaska* (Mecklenburg and others, 2002) and along with biodiversity baseline presented in Mecklenburg and Steinke (2015) and Mecklenburg and others (2016) significantly updates the inventory represented for the Arctic in that monograph. The update of this information was timely because the user community is increasingly large and it requires accurate resource inventories and access to data and information. The need extends beyond a listing of species (Cook and Bundy, 2012) and, given the wide variety of uses for resource information, requires a consistent and reliable source of scientific information for each species (geographic distribution, abundance, and habitats). Although life history information is lacking for most species, it is generally true that, within a life cycle context, the most information is available for adult stages and much less is known about juvenile marine fish and younger stages (chapter 3). The ichthyoplankton sampling that has been done is an important source of information about the biodiversity of the region.

This synthesis is therefore timely for purposes of assessing potential climate effects and informing decision making about regional fisheries, offshore energy development, and other human uses (for example, increased marine shipping and tourism, and port developments). It is an encyclopedic effort with respect to content (biodiversity, life history, population ecology, and regional ecosystems), visualization of data, and scientific information presented and reviewed. The narratives, maps, and literature references provided in individual species accounts are meant to serve as trailheads or guides to more detailed information about the zoogeography, taxonomy, life histories, species niches, and life requirements in sectors of the Arctic marine ecosystem of the United States. We have attempted to present scientific information and concepts in language that will be understood and useful not only to professional scientists and resource managers but the broader swath of user communities involved in environmental research, community planning and development, and Arctic policy making.

Applications for Arctic Outer Continental Shelf Energy Development

The Chukchi and Beaufort Seas differ with respect to geographic setting, expanse of continental shelves, regional oceanography, and freshwater-marine interactions (rivers and streams). The differences (for example, topography of the shelf and slope habitats) affect patterns of species occurrence in Arctic marine habitats. The Chukchi Sea shelf is broad and generally less than 200 m deep. In contrast, the Beaufort Sea shelf is narrow and slope waters are deep (>1,000 m). The presence of sea ice is an important feature in both seas as it relates to environmental temperatures, light penetration, habitat for species such as the Arctic Cod (food, shelter, and potential nursery for early life stages), and processes affecting production cycles.

This report documents the confirmed occurrence of 109 species of known marine fishes in 24 families and 63 genera in the U.S. Chukchi and Beaufort Seas. The occurrences were based on published literature, specimens examined in museum collections, and species confirmed from expert identifications in ongoing field research. Of these, our review of Alaskan records indicates 97 species are found in the Chukchi Sea and 83 in the Beaufort Sea. Sixty-eight fishes are common to both seas. Since the latest publication covering all known Alaskan fishes (Mecklenburg and others, 2002), 18 new species to the region have been confirmed. In time, other species will be confirmed from this region. For example, at least three other species whose taxonomic identification is in progress are known, as well as several others marine fishes that are likely, but have not been observed in sampling. Given the intensity of sampling in nearshore areas, new species and range extensions are expected from these waters.

The NEPA process requires that BOEM analysts use the best resource information available in their assessments of environmental effects associated with offshore oil and gas development in Arctic OCS Planning Areas. Through review and synthesis, our summaries provide current information about which fishes are present, when and where they are present, and the physical and biological processes that affect their distribution and abundance. This information is valuable because in reporting what is known about the Arctic marine fish fauna and its traditional, cultural, and economic values, this study also indicates where further study is needed. The immediate applications of this work extend beyond the BOEM's purposes and are of immediate value to other Federal and state research and management agencies to Alaska Native and other Arctic residents interested in Arctic marine ecosystems, potential Arctic fisheries, and the conservation of Arctic marine fishery resources. At the same time, the format and information presented, especially in the species accounts, are intended to be useful to a public audience.

Theoretical Applications to Resource Management

Information about species-specific and interspecific life history and ecological traits informs not only theoretical ecology (such as r-K adaptations), but has implications for resource management (Hardie, 2003). The relationship between multiple traits is addressed in the fast-slow continuum hypothesis, which "*explains life history traits as reflecting the causal influence of mortality patterns in interaction with trade-offs among traits, particularly more reproductive effort at a cost of shorter lives*" (Paemelaere and Dobson, 2011). Bjørkvoll and others (2012) recently examined this hypothesis with respect to the population dynamics of nine species of marine fishes from the Barents Sea. A major finding was that mean natural mortality rates, annual recruitment, and population growth rates were lower in long-lived species (slow end of the continuum) than in short-lived species (fast end). Interspecific characteristics also were associated with ecological traits where it was determined that species at the fast end were mainly pelagic with short generation times and high natural mortality, annual recruitment, population growth rates, and high temporal variability in these demographic traits. In contrast, species at the slow end of the continuum were long-lived, demersal species with low rates and reduced temporal variability in the same demographic traits.

Life History and Ecological Traits

The relations between basic life history characteristics and population dynamics have implications for managing marine fish resources where population data are limited or non-existent, like the Arctic. To illustrate, in a conceptually similar analysis, Winemiller (2005) used a triangular model (Kawasaki, 1980: Winemiller and Rose, 1992) to classify the life history traits of mature individuals of marine fishes into life history strategist groups (based on position within the fast-slow continuum) to investigate their predictive capacity and management applications. King and McFarlane (2003) completed a much larger analysis (n = 42 species) and identified 5 strategist groups represented by species common to pelagic, benthic, and nearshore habitats in the western Gulf of Alaska. Two of the strategic groups had been previously described by Winemiller and Rose (1992) including opportunistic and periodic strategists. Three additional distinct groupings, equilibrium strategists, salmonic strategists, and intermediate strategists were described by King and McFarland (2003). King and McFarlane (2003) described each group as:

Opportunistic Strategists.—Opportunistic strategists are short-lived with a small body size at maturation, low fecundity, high growth rates, and small eggs. They are surface and midwater pelagic species that exhibit little if any parental investment and are planktivores or lower-order carnivores. They occupy habitats that have a high degree of environmental variability but potentially large resources of energy. As such, their population responses tend to be large in amplitude and species in this group display highly variable, fluctuating population patterns. Species include clupeids (for example, Pacific Sardine, Pacific Herring), smelts (for example, Eulachons), and other forage fishes (for example, Northern Lampfish and Arctic Sand Lance). Because abundance is dynamic and survival rates are variable, the opportunistic strategists are susceptible to rapid depletion augmented by fisheries.

Periodic Strategists.—Periodic strategists are long-lived and slow growing with a high fecundity, but are medium in size, have a midrange for size at maturity, and have medium sized-eggs. These fishes are higher-order carnivores that inhabit shelf or slope benthic habitat and exhibit some parental investment. In the eastern Pacific, rockfishes and flatfishes are good examples of periodic strategists. These species were classified as having a steady-state population pattern. The period between strong year classes can be relatively long (as much as several decades), and these species can exhibit decadal scale patterns in recruitment coincident with climate–ocean regimes. Annual recruitment is only a fraction of the spawning stock biomass, and maintaining an appropriate age-structure in the spawning stock biomass should be a paramount management goal for these relatively long-lived, late maturing species.

Equilibrium Strategists.—Equilibrium strategists are dominated by elasmobranchs (skates and sharks), which are slow growing, have low fecundity, are large in size, and have large eggs (K selection traits). These species exhibit modest to great degrees of parental investment, are higher order carnivores and piscivores, and inhabit a range of habitats. Equilibrium strategists have a low fecundity and late maturation, and therefore, not able to recover as quickly as other fishes after population reduction.

Salmonic Strategists.—Salmonic strategists, *Oncorhynchus spp.,* are relatively short-lived, but fast growing and large sized. Compared with other marine species, they are not extremely fecund, but have large eggs. The life history traits of the Pacific salmon differ from opportunistic strategists with their semelparous nature and the higher degree of parental investment. Large-scale changes in ocean condition affect salmon productivity. Ocean survival, notably during the first marine summer conditions, may be especially critical in the salmon strategist population dynamics. Improved estimation of freshwater (egg-smolt production) and marine (smolt-adult production) survival in population models will aid management forecasts.

Intermediate Strategists.—Intermediate strategists, cods and scombrids, have life history traits that are mid-range when compared to opportunistic and periodic strategists. They have a longer life span than the opportunistic strategists, with maximum ages typically 10–20 years, but exhibit the same population dynamics as this group. Gadids are considered typical groundfish species (that is, benthic or bathypelagic), but are different from the other groundfish species (for example, rockfish, flatfish, and sablefish) grouped with periodic strategists. For example, gadids are not as long-lived and scombrids are highly migratory surface pelagics, but differ from the other surface pelagics because of their larger size and longevity. Populations of intermediate strategists can withstand periods of unfavorable environmental conditions for recruitment better than the opportunistic strategists, but they do not exhibit the more stable populations as in periodic strategists. Their shorter generation time makes them more vulnerable to fluctuations in biomass through fluctuations in recruitment. Intermediate strategists are large-sized, highly migratory pelagic species that are able to move from areas of poor conditions to areas of better conditions as reflected in large distributional changes.

The study by King and McFarlane (2003) included species from the Gulf of Alaska where fish life histories and population dynamics and trends are relatively well known from long-term research. The species accounts demonstrate that, although in many instances, life history and ecological trait information is not available from United States waters, the general information that is available is of sufficient quality to identify the relative positions of certain species on the fast-slow continuum. Additionally, the similarities between Arctic and subarctic traits allow an initial classification of Arctic marine fishes using the strategist grouping of King and McFarlane (2003) as an initial screen.

The assignments are a first-order projection and, as such, are preliminary in nature; however, as noted by King and McFarlane (2003), in the absence of information on absolute or relative biomass (Arctic case) this conceptual framework can guide management options. Although a comprehensive analysis of the entire fauna is not feasible, initial decisions about (1) what species to include were based on abundance (that is, selected species were common in both Chukchi and Beaufort Seas), and (2) assignment to strategic groupings were based on life history knowledge including resiliency (that is, estimates of population doubling time). The Arctic marine fish strategic groupings for selected dominant species are shown in table 6.1 following criteria described by King and McFarland (2003).

Table 6.1. Life history strategy groupings of common Arctic marine fishes in the Chukchi and Beaufort Seas.

[**Resiliency:** Based on estimates of population doubling time: low (4.5–15 years); medium (1.4–4.4 years); and high (<15 months) turnover. **Life history:** Information is based on King and McFarland (2003). <, less than]

Taxonomic family	Resiliency	Life history strategic grouping				
		Opportunistic	Periodic	Equilibrium	Salmonic	Intermediate
		Common fish species				
Petromyzontidae	Low				Arctic Lamprey	
Squalidae	Low			Spotted Spiny Dogfish		
Rajidae	Low			Arctic Skate		
Clupeidae	Medium	Pacific Herring				
Osmeridae	Medium	Arctic Smelt, Capelin				
Salmonidae	High				Chum Salmon	
Myctophidae[1]						
Gadidae	Medium					Walleye Pollock, Saffron Cod
Gasterosteidae	Medium	Ninespine Stickleback				
Cottidae	Low to high					Hamecon, Fourhorn Sculpin, Shorthorn Sculpin
Agonidae	Medium					Alligatorfish, Arctic Alligatorfish, Veteran Poacher
Liparidae	Medium					Gelatinous Snailfish, Kelp Snailfish
Zoarcidae	Low to medium					Fish Doctor, Marbled Eelpout, Polar Eelpout
Stichaeidae	Low to medium					Fourline Snakeblenny, Slender Eelbenny, Arctic Shanny
Ammodytidae	Medium		Arctic Sand Lance			
Pleuronectidae	Low to medium					Bering Flounder, Arctic Flounder

[1]Not commonly found in Chukchi or Beaufort Seas.

Two additional strategic groupings are described to capture other adaptation strategies known to the Arctic marine fish fauna:

Amphidromic Strategists.—The amphidromous life history strategy is significantly different from the strategies of other Arctic and subarctic marine fishes. For this reason, we created a new life history strategy grouping, *amphidromic strategists*. Amphidromous strategists (that is, Dolly Varden char; Least Cisco, and Bering Cisco; Broad and Humpback Whitefish; and Inconnu) strongly exhibit K selection traits (Craig, 1984) and are similar to salmonic strategists with respect to migratory behavior, occupation of multiple habitats, and parental investment in young. Unlike the salmonic strategists they are iterperous and long-lived (>20 years). Density-dependent factors operating in freshwater overwintering sites result in a relatively steady state. The Arctic Cisco life cycle in the Alaska Beaufort Sea involves a long-distance migration of young-of-the-year (YOY) juveniles between the McKenzie River, Canada and Colville River, United States. Overwintering of immature ciscoes (generally <7–8 year old fish) in Alaskan waters occurs in salinity-influenced areas of the delta and thus the species shares some anadromous characteristics with the salmonic strategists. The abundance of migrant YOY ciscoes is variable and survival rates, at least during early life phases, are similar to the opportunistic strategists.

The amphidromic strategists include key, iconic species of Arctic marine fishes. Long-term harvest records for Arctic Cisco from a small fishery in the Colville River provide information about trends in population abundance for the species in Alaskan habitats. Upon reaching age 7–8 (average age of maturity), the ciscoes return to Canada to spawn. Information about Arctic Cisco from the McKenzie River is extremely limited. Dolly Varden stocks spawn and overwinter in rivers and streams originating in the Brooks Range, Alaska (with perennial springs) in the eastern sector of the Alaska Beaufort Sea. Arctic Cisco, Least Cisco, and Broad Whitefish freshwater habitats are farther west in the Sagavanirktok River and westward of Prudhoe Bay. For the latter two species, habitats are located in low-lying rivers that are usually connected to lakes. Maintaining the connectivity and quality of freshwater and coastal habitats is critical for these species long-term sustainability. The combination of delayed reproduction, low reproductive effort, and increased longevity adapts the organism to fluctuations in recruitment and management concepts described for periodic strategists apply.

Cryophilic Strategists.—The Arctic Cod and Ice Cod have strong ice affiliations in their life histories although the latter species is rarely encountered in U.S. waters. The Arctic Cod is a keystone species and its association with cold temperatures and sea ice presents a special case referred to herein as the *cryophilic strategist*. King and McFarlane (2003) classified the gadids with the intermediate strategists. Like its congeners in the south, Arctic Cod are widespread and abundant; however, unlike the other cods, the Arctic Cod is a small and short–lived species. They are the most important forage species in the Chukchi and Beaufort Seas and share many of the life traits of opportunistic strategists including a medium resiliency with respect to its population dynamics (table 6.1). The relative importance of the ice edge ecosystem (Alexander, 1992) in the life cycle of this species is ecologically different enough that we classified them in a unique Arctic grouping. The life cycle association beneath the sea surface ice may provide refuge habitat and special food web dynamics that can dampen the effects of density-independent factors on population and possibly stock abundance. Genetic stock information is not yet available and, although ongoing research suggests the presence of large schools over slope waters (Crawford and others, 2012), the species is also a coastal dominant nearer to shore. The role of ice in the reproductive ecology of Arctic Cod is not known.

Most of our understanding about Arctic Cod in United States waters is from data and information collected from nearshore environments. The abundance of Arctic Cod in coastal waters of the Alaska Beaufort Sea varies greatly from year to year and even between adjacent sites within a year (Craig and others, 1982; Palmer and Dugan 1990; Wiswar and Fruge 2006) although in the Canadian Arctic, large schools move into some discrete areas with some predictability (Welch and others, 1993). This often-large influx makes Arctic Cod by far the most abundant fish in nearshore waters (Crawford and Jorgenson, 1996; Fechhelm and others, 1996; Gillispie and others, 1997). In a recent acoustic survey, Crawford and others (2012) observed large schools of unconfirmed Arctic Cod over shelf break and slope waters of the Chukchi and Beaufort Seas. Estimates of summer cod abundances have been as high as 12–27 million fish in Simpson Lagoon, Alaska (Craig and Haldorson, 1981), and 900 million fish in a small area off Cornwallis Island in the Canadian Arctic (Crawford and Jorgenson, 1996). Interannual variations in patterns of abundance of Arctic Cod in coastal waters may be related to the timing, frequency, and magnitude of westerly storm events relative to the location of water masses and currents relative and spatial distributions and sizes of schooling cod over shelf and slope waters (for example, passive transport inshore). In contrast, some segment of the Arctic Cod population may actively migrate inshore in response to the abundance of invertebrate prey in coastal waters.

Although there has been considerable speculation regarding the environmental parameters that drive inshore migrations, the data often are contradictory. For instance, in the Chukchi Sea, Fechhelm and others (1984) determined that catches increased when water temperatures increased and salinities decreased, but the opposite was noted by Griffiths and others (1998) in the Sagavanirktok River Delta. In Prudhoe Bay, Moulton and Tarbox (1987) noted highest densities in frontal areas bordering low salinity and high temperature surface waters and high salinity and low temperature bottom waters, perhaps an area of high productivity. In another Chukchi Sea study, Gillispie and others (1997) determined there was no association between abundance and any environmental parameter and they hypothesized that food availability may underlay fish movements. Thorsteinson (1996) reported the presence of high numbers of YOY Arctic Cod in surface waters of Camden Bay, Alaska, and hypothesized their vertical distribution and separation from older cod as an avoidance mechanism from cannibalism noted in other gadids.

The autumn and winter behavior of Arctic Cod throughout the Arctic, but particularly in the U.S. Chukchi and western Beaufort Seas, is poorly understood. In the Beaufort and Chukchi Seas, at least some fish spend winters under nearshore ice (presumably spawning) (Lowry and others, 1980; Craig and Haldorson 1981; Fechhelm and others, 1984; Schmidt and others, 1987; Craig 1989b; and Thorsteinson and others, 1990). However, whether the bulk of the population overwinters and spawns in shallow waters is not known (Craig and others, 1982). For instance, Craig and others (1982) reported spawned-out cod both near the coast and 175 km (109 mi) off Prudhoe Bay. Arctic Cod have been reported to spawn near the bottom along the ice edge (Ponomarenko, 1968) and underneath ice (Andriyashev, 1954). Ponomarenko (1968) reported that in the autumn and winter, large, spawning-oriented migrations occurred in the Russian Arctic and that spawning in the Barents Sea may have occurred from nearshore to hundreds of kilometers off the coast. Thus far, the most complete study of winter behavior off North America was completed by Benoit and others (2008; 2010) in Franklin Bay, eastern Beaufort Sea. They determined that after spawning during the early winter (perhaps over deep waters in the Amundsen Gulf [D. Benoit, Université Laval, Quebec, Canada, oral. commun., 2013]), large numbers of fish either migrated to, or were passively carried into, waters primarily deeper than 180 m in Franklin Bay. Migration out of these waters coincided with spring phytoplankton blooms and the beginning of feeding. Whether cod in the western Beaufort Sea or Chukchi Sea perform similar migrations is not known, although fish that apparently spawned in winter in Simpson Lagoon had departed by February (Craig and others, 1982; Craig and Haldorson, 1986).

In other research in the Northeast Water Polynya (Greenland Sea), Fortier and others (2006) tested a hypothesis that the survival of Arctic Cod larvae is limited at sea ice cover greater than 50 percent and sea-surface temperature less than 0 °C. The authors described variable recruitment rates in a spring and summer cohort of cods. Although only a low percentage (12 percent) of the spring cohort survived to winter, their larger size was described as having evolutionary significance with respect to the survival and persistence of this cohort. The existence of multiple cohorts in Arctic Cod from the Chukchi and Beaufort Seas is suggested in the length frequency distributions of many coastal surveys.

Resiliency

Many environmental factors affect the population dynamics of any particular species. Stock assessments for Arctic marine fish have not been done and the population dynamics for the species listed in this report are not known. For the present, the qualitative evaluation of population resilience based on life history traits (table 6.1) suggests the time requirements for recovery of dominant species from a large-scale mortality event such as an oil spill. Quantitative approaches to evaluate the magnitude of population effects and recoveries of hypothetical oil spills on well-studied fishery species in the southeastern Bering Sea have considered the cumulative effects of natural and anthropogenic changes in mortality rates over the species life cycle in space and time (Laevastu and others, 1985). The many information gaps (chapter 3) in understanding of distribution and abundance of life history stages, population processes, and effects (positive and negative) of climate change, sea ice, and ocean acidification preclude a defensible quantitative approach. Long-term data and integrative science approaches are needed and may be an area where traditional ecological knowledge and Bayesian analysis could guide resilience thinking and science planning with respect to managing and protecting this component of marine ecosystem goods and services.

Marine Fishery Science in Support of Ecosystem-Based Management

Fishery research in the Arctic is challenging given the rough weather conditions, presence of sea ice, short open-water season, irregular seafloor topography, and great depths off the continental shelf. Despite these challenges, important Arctic fish studies have been accomplished since 2002. Notable is an earlier Arctic expedition in 2004 by the Russian American Long-Term Census of the Arctic, which was sponsored by NOAA and the Russian Academy of Sciences. BOEM, in cooperation with other agencies and several universities (including University of Alaska, University of Washington, University of Maryland, and University of Texas), has been investigating fish use and ecological process in the Chukchi and Beaufort Seas. The results of recent (2008–12) and ongoing marine fish studies (2013), when available, are expected to make important new contributions to our understanding of Arctic marine fish diversity, population dynamics, and community interactions. These contributions will be significant in their role in ushering a new era of fishery ecosystem-based management by the United States and its circum-arctic partners.

An important step in this synthesis process was the identification of general research needs and their priority in near- and long-term science activities. In many instances these complement or address similar needs that were previously identified for systematics of Arctic fishes (for example, Collette and Vecchione, 1995; Mecklenburg and others, 2011); life history and environmental relations (for example, Reist and others, 2006; Mueter and others, 2009; DeGange and Thorsteinson, 2011; von Biela and others, 2011; Hollowed and others, 2013) or quantitative population ecology (for example, Monterio, 2002; Katsanevakis, 2006; Wilson and Orsmeth, 2009). A Structured Information Management process (Bayesian analysis) involving expert opinions is recommended for priority setting and addressing the most relevant Arctic issues in an ecosystem-based structure (for example, Holland-Bartels and Pierce, 2011; Jay and others, 2011). Although a broad list of science themes for further consideration is provided, it should be noted that, if implemented, many of the specific needs identified in the species accounts would be addressed over the long-term.

The Chukchi and Beaufort Seas differ with respect to geographic setting, expanse of continental shelves, regional oceanography, and freshwater-marine interactions. The differences affect ecological processes and the patterns of species occurrence in shelf and slope habitats. The presence of sea ice is an important feature in both seas as it relates to environmental temperatures, light penetration, habitat for species, and more than 100 marine fish, including the Pacific salmon that are known from the region. Life history information is lacking for most, is best for adult stages, and is best known for species occurring nearest to the shore. Major limitations of existing information relate to the absence of large-scale fisheries and lack of related resource assessment surveys. This lack is beginning to be addressed in light of changing Arctic conditions, but needs much greater scientific attention to abundance patterns and dispersal processes, population dynamics, physiological requirements, and community relationships.

A commitment to long-term data collection within an integrated science framework is needed to develop quantitative population understanding (similar to current fisheries research and assessment surveys in the Bering Sea). Logistical, technological, and cost considerations have limited the practicality of early spring and winter surveys. As a result, under-ice resource information is inadequate for evaluation of effects such as those that might be related to an oil spill in winter months.

A combination of laboratory, field, and modeling approaches is needed to estimate the effects of climate effects and ocean variability on production cycles and the distribution, abundance, and movement behaviors of Arctic marine fishes. As appropriate, these approaches should incorporate local and traditional ecological knowledge. Research and monitoring should focus on key species in Chukchi and Beaufort Seas fish assemblages in strategic locations (for example, Distributed Biological Observatories (long-term monitoring sites and biological hotspots) and include studies of human interactions. Human interactions extend beyond subsistence activities and may include changes associated with increases in marine transportation and OCS oil and gas activities on important biological habitats and ecosystems.

Crosscutting technology-analytical themes for integrated research are needed to make best use of historical and new data collection. Modern geospatial tools are needed to effectively and efficiently investigate distribution and abundance patterns of marine fishes in time and space. Greater reliance on modern scientific technologies and their fishery applications, such as gliders, remote sensing, telemetry, genetics, cellular and molecular biology, and quantitative ecology (for example, predictive models) is needed to establish species environmental relationships, address existing gaps about relative importance of habitats, understand natural variation in fluctuating stocks, and accurately assess anthropogenic effects.

Chukchi and Beaufort Seas Marine Ecosystem Studies

The Interagency Arctic Research Policy Commission (IARPC) published a conceptual model for the U.S. Arctic marine ecosystem as part of its planning for integrated, process-oriented research in the Chukchi and Beaufort Seas (Wiese and others, 2013). An IARPC team is using this framework to develop priority needs for future ecosystem research. The team has highlighted the importance of winds, currents, and advection on nutrient dynamics and consequent plankton distribution and production (Wiese and others, 2015). Additionally, the effects of changes in sea ice and other drivers in the ecosystem on energy pathways (benthic and pelagic systems), ecosystem structure and function, and the phenology and location of key elements of the food web (hot-spots, hot-times, biodiversity), including access for subsistence activities are seen as research priorities. In coastal waters, nearshore changes caused by ice, winds, currents, and freshwater runoff and their implications for biota and communities, especially changes in the habitats of fish, seabirds, and marine mammals and subsequent implications for subsistence use and culture are included in the planning process. The role of humans within the marine ecosystem as predators, as a source of perturbation, and as receivers of ecosystem services, will be an objective of future Arctic marine ecosystem research.

In Arctic Alaska important subsistence fisheries are located in seas projected to experience rapid transitions in temperature, pH, and other chemical parameters caused by global change, especially ocean acidification (Mathis and Questel, 2013). Many of the marine organisms that are most intensely affected by OA contribute substantially to Alaska's local traditional economies and subsistence way of life. Management concerns about OA effects on marine organisms and ecosystems relate to food web and community interactions, are interdisciplinary in nature, and are far reaching with respect to their potential consequences: reduced calcification rates; significant shifts in key nutrient and trace element speciation; shifts in phytoplankton diversity; reduced growth, production and life span of adults, juveniles, and larvae; reduced tolerance to other environmental fluctuations; changes to fitness and survival; changes to species biogeography; changes to key biogeochemical cycles; changes to food webs; reduced sound absorption; reduced homing ability; reduced recruitment and settlement; changes to ecosystem goods and services; and changes to behavior responses. The rate and extent of change in pH in the northeastern Chukchi Sea suggests the importance of the region as a bellwether for other coastal seas (Mathis and Questel, 2013).

Information Gaps: Priority Marine Fishes

Twenty-one or about 20 percent of marine fish species are identified as high priority [A] in chapter 3 (table 6.2). These species are important in Arctic food webs and human economies or are of potential commercial interest or indicator status in long-term monitoring. The species comprise a mix of marine ecosystem goods (7 being of subsistence importance) and services (8 having food web values). Six species may support viable commercial fisheries someday. The most conspicuous members of the nearshore fish assemblage (charr, ciscoes, and whitefish) are the best known of the Arctic fish fauna, but fishery information is dated and population understanding is non-existent. Additionally, Pacific salmon already are becoming important in recreational fisheries and in some villages (for example, Nuiqsut) the increasing abundance and potential interaction with traditional food species is of concern. Most species identified are common to both seas (13 species) or to the Chukchi Sea only. As new data become available in BOEM studies, it is possible that the true relative abundance of species such as Greenland Halibut especially on shelf and slope habitats across the Beaufort Sea will become better known. Its potential as a marine dominant in these habitats is an intriguing gap in our understanding of this ecosystem.

Walleye Pollock has the greatest potential to be a target of large-scale industrial fisheries in the Chukchi Sea. In chapters 4 and 5, potential changing ecosystem conditions and distributional shifts are discussed in light of warming effects. Currently, cold water temperatures in the Chukchi and Beaufort Seas are limiting to Pollock and it has been hypothesized that the persistence of low temperatures in the northern Bering Sea will for the foreseeable future, inhibit large-scale shifts in fishable biomass to the north. If, in the future, warming favors a northward shift, this species effects on the Arctic marine fish assemblage would be significant. The effects on other congeners, especially Arctic and Saffron cods, is hypothesized here to result in a rearrangement of dominance structure through competition and predation in a warmer, pelagic ecosystem through changes in top-down and bottom-up processes, respectively.

Arctic Cod, Capelin, and Dolly Varden have circumpolar distributions and for reasons related to ecological significance and food security make them of interest in monitoring programs like the Arctic Council's Arctic Monitoring and Assessment Programme. The colonizing potential of many other priority species from the Bering Sea lends similar support to the candidacy as indicators of climate change. Such selections must be based on a fuller suite of ecological indicators in an interdisciplinary monitoring design. That design should include pelagic and benthic marine ecosystem components, nearshore and offshore components of the survey region, and species whose values are representative of local concerns, information needed by resource managers, and species such as Arctic Cod, that are key to ecosystem function. The 21 species and collective fishery component of the Arctic marine ecosystem identified herein, would strategically contribute to the matrix of habitats, food webs, life history adaptations, Arctic and other zoogeographic patterns, and human uses that should be considered in a comprehensive experimental design. The composition of species is varied enough that processes important to the distribution and abundance of all marine fish and higher level consumers will be highlighted and strengthened by their inclusion in an integrated approach.

The information gaps identified for each of these species are similar to those of all other species. The needs were categorized in the species accounts (chapter 3) into eight life history, habitat, population, and ecological areas that are of importance for baseline development, environmental assessment, and fisheries management. The priority species identified inhabit all of the marine habitats and represent the major adaptive strategies discussed in this report (table 6.2). The significance of these features in future research and monitoring is, that lower priority species ([B] in chapter 3) may not be emphasized in field collections; they will be sampled and important information about them will more slowly accrue. In this way, new information about their life histories and ecological roles will emerge.

Table 6.2. Characteristics of high priority [A] species in the Chukchi and Beaufort Seas.

[Priority determinations and high-priority species are described in chapters 2 and 3, respectively. **Status:** Fisheries reflects commercial potential as hypothesized by colonization potential, or for Pacific Salmon, existing fisheries in the southeastern Chukchi Sea, as well as potential expansions. For Pacific Herring, there is longstanding interest in Port Clarence, Kotzebue Sound, Alaska. **Abundance:** X, indicates "common" occurrence in Chukchi and Beaufort Seas. If common in one sea but not the other, the sea is indicated. Pollock is "uncommon," but listed for the Chukchi Sea because of its colonizing potential. **Adaptive strategy:** Incorporates information about major habitats in life-cycle context]

Common name	Species characteristics				
	Status	Abundance	Adaptive strategy	Food web position	Habitat orientation
Pacific Herring	Fisheries	Chukchi	Linked Marine-Estuarine	Intermediate	Pelagic
Capelin	Ecological	X	Linked Marine-Estuarine	Intermediate	Pelagic
Arctic Smelt	Ecological	X	Nearshore Marine	High	Pelagic
Arctic Cisco	Subsistence	Beaufort	Amphidromy	Intermediate	Pelagic
Broad Whitefish	Subsistence	X	Amphidromy	Intermediate	Pelagic
Humpback Whitefish	Subsistence	X	Amphidromy	Intermediate	Pelagic
Least Cisco	Subsistence	X	Amphidromy	Intermediate	Pelagic
Pink Salmon	Fisheries	Chukchi	Anadromy	High	Pelagic
Chum Salmon	Fisheries	Chukchi	Anadromy	Intermediate	Pelagic
Dolly Varden	Subsistence	X	Amphidromy	High	Pelagic
Inconnu	Subsistence	Chukchi	Amphidromy	High	Pelagic
Arctic Cod	Ecological	X	Marine	Intermediate	Demersal
Saffron Cod	Subsistence	X	Nearshore Marine	Intermediate	Demersal
Walleye Pollock	Fisheries	Chukchi	Marine	High	Demersal
Arctic Staghorn Sculpin	Ecological	X	Marine	Intermediate	Benthic
Fourhorn Sculpin	Ecological	X	Marine	Intermediate	Benthic
Arctic Sand Lance	Ecological	X	Marine	Intermediate	Pelagic-Demersal
Bering Flounder	Fisheries	X	Marine	Intermediate	Benthic
Yellowfin Sole	Fisheries	Chukchi	Marine	Intermediate	Benthic
Arctic Flounder	Ecological	X	Nearshore Marine	Intermediate	Benthic
Greenland Halibut	Ecological	Uncommon	Marine	High	Benthic

Fishery Objectives for Ecosystem-Based Management

It is within an ecosystem context and interdisciplinary science approach that the long-term and most outstanding fishery research and resource assessment needs for the Chukchi and Beaufort Seas will be addressed most appropriately. This is particularly true because, with respect to continued offshore oil and gas development in the Chukchi and Beaufort Sea Planning Areas, the science needs for NEPA requirements, oil-spill damage assessment, ecological restoration, and assessment of climate change effects, are not the same (Holland-Bartels and Pierce, 2011). Thus, within the context of current national policy for the United States Chukchi and Beaufort Seas (for example, White House, 2013) and planning for interagency marine ecosystem framework (for example, North Pacific Research Board [Chukchi Sea], Bureau of Ocean Energy Management [Beaufort Sea], and Interagency Arctic Research Policy Committee [IARPC] [Chukchi and Beaufort Seas]), five science areas are identified having fishery objectives for possible address:

- Evaluate biological responses of populations and communities to natural and anthropogenic stressors with improved seasonal and geographic information on the distribution and abundance, life histories, habitats, community structure, and demographics for Arctic marine fishes.
- Determine how variability in environmental conditions (for example, temperature, salinity, light penetration, pH, water masses, and currents) influences ecological processes (advection of nutrients, zooplankton prey, and early life stages; recruitment; competition; feeding; reproduction; population growth and survival) and the abundance, and distribution of fish species, including the potential for Bering Sea species to move into high Arctic waters.
- Describe onshore-offshore linkages (physical and biological) for key species in a life history context focusing on seasonal habitats, food webs, and biological interactions.

- Determine physiological requirements of Arctic fish condition and health with emphasis on (1) effects of environmental factors responsible for changes in demographic rates, (2) environmental tolerances and preferences, and (3) effects of hydrocarbon contaminants and dispersants.
- Investigate the diversity and biogeography of Arctic marine fish through improved understanding of systematic, taxonomic, and phylogenetic relationships.

Fishery Research Priorities for United States Chukchi and Beaufort Seas

These broad fishery objectives are interconnected and would best be addressed in an integrated science approach as envisioned by the IARPC. Regular synthesis efforts are part of the planned process and, with the amount of ongoing BOEM research on Alaska Arctic fishes nearing completion, such activity should be supported. Within the objectives described in section, "Fishery Objectives for Ecosystem-Based Management," several recommendations that step-down for priority consideration are offered here. These recommendations specifically relate to the major information gaps identified in the marine fish species accounts and synthesis goals of this study.

Marine Fish Systematics, Taxonomy, and Phylogenetics

Systematists study the diverse forms of life and determine the evolutionary relations among them. There is a continuing need to support the collection, analysis, and archive of specimen vouchers in fisheries investigations. Concurrently, continued, or expanded, museum studies are needed to resolve systematic problems and update fish diversity evaluations. New fishery surveys collect large amounts of materials; voucher specimens should be retained to confirm field identifications. Field data and existing historical records should continue to be evaluated in light of new taxonomic and phylogenetic understanding to update regional resource inventories. Reliable comparisons of fauna across international boundaries are difficult due to widespread problems with taxonomic identifications, nomenclatural issues, and lack of attention to standard systematic conventions. For the harmonization and congruency goals of the Arctic Council to be effectively realized, considerable attention to the evaluation of historical ichthyological data (through education and coordination) by many countries (for example, Russia) will be needed for effective marine conservation across the Arctic Basin. Finally, it has been more than a decade since the first edition of the *Fishes of Alaska* (Mecklenburg and others, 2002) was published. There have been many scientific advances in taxonomic knowledge and understanding since 2002. The recently published baseline assessment (Mecklenburg and Steinke, 2015) and atlas and guide to *Pacific Arctic Marine Fishes* (Mecklenburg and others, 2016) fill the need for an update of the taxonomy, diagnostic characteristics, geographic distribution, and basic habitat of the marine fishes of the Alaskan Arctic region. The same authors, with additional collaborators from around the Arctic region and with funding primarily from the Norwegian Ministry of Foreign Affairs, are building on the Pacific Arctic atlas and guide to produce a reference covering the entire Arctic region which also includes summary information on life history and diet. The primary objective of the Pacific Arctic and pan-Arctic works is to provide baseline references for identifying marine fish species of the Arctic region and evaluating changes in diversity and distribution. A critical component of the ongoing research is completion of a pan-Arctic DNA barcode reference library. These works are critical to help prevent errors and inform future research.

Enhance Species Accounts

A more complete understanding of the multi-dimensional temporal and spatial aspects of population maintenance is achievable by incorporating age-specific food habits information (included in the species accounts) in the life zone schemata developed for vertical distribution. This application would allow a novel visualization of life history stage, habitat, and trophic linkages and would especially be valuable for environmental assessments including those associated with National Oceanic and Atmospheric Administration needs for evaluating Essential Fish Habitat (for example, Rosenberg and others, 2000; National Oceanic and Atmospheric Administration, 2013).

Advanced Geospatial Technology for Biodiversity Assessments

Modern geospatial tools are urgently needed to most effectively and efficiently investigate distribution and abundance patterns of marine fishes in time and space. The application of existing fishery data within a Geographic Information System environment would allow users to (1) explore fishery environmental relationships, and (2) determine population responses to changing ocean at multiple scales of resolution. Advanced geospatial analysis tools are needed for NEPA and climate change assessments, marine spatial planning, fisheries management applications, and emergency response in the unforeseen event of an Arctic oil spill. Research applications of modern technologies would focus attention on (1) geographic coverage of sampling, and (2) reporting of data (standards and automations) such that more dynamic, quantitative geospatial analyses are possible.

Advance Scientific Technologies in Fisheries Applications

Greater reliance on modern scientific technologies and their applications, such as remote sensing, telemetry, genetics, cellular and molecular biology, and quantitative ecology (for example, predictive models) is needed to establish species environmental relationships, address existing gaps about relative importance of habitats, understand natural variation in fluctuating stocks, and to more accurately assess effects of proposed offshore oil and gas activities. As an example, the validation and use of environmental DNA (eDNA) approaches to rapid biodiversity assessments should be explored for through-the-ice sampling applications.

Life History and Ecological Traits

Information about status and trends, habitat requirements, relative distribution and abundance, and knowledge of life history stages of marine fish is incomplete and unavailable for large expanses of Arctic nearshore, shelf, and slope waters and should be developed for indicator species (that is, species that are broadly distributed, of subsistence or ecological significance, readily available for vulnerability assessments, and deemed sensitive to offshore oil and gas development and climate changes, see, for example, Parrish and others, 2003; Roessig and others, 2004; and Logerwell and others, 2015). Onshore-offshore linkages (physical and biological) associated with life history requirements (for example, seasonal movements and migrations and ontogenetic shifts in prey preference) have not been described. Many well studied marine fishes show shifts in diet over time with increasing size moving from low to higher trophic levels (and from smaller to larger prey sizes).

Quantitative Ecology

A commitment to long-term data collections is needed to develop population understanding. The new research that is currently underway will improve scientific understanding of abundance patterns, habitat relations, life history parameters, trophic relations and bioenergetics (including predators, for example, Brown and others, 2002), and genetic diversity and structure, for some species. Logistical, technological, and cost considerations have limited the practicality of early spring and winter surveys. As a result, under-ice resource information is limited and inadequate for evaluation of effects such as those that might be related to an oil spill in winter months. As of 2016, Arctic fieldwork is expected to continue in late summer sampling periods and significant information gaps will remain with respect to spatial and temporal coverage and life stage coverage. The data requirements for estimating population parameters are substantial and an initial focus on fewer indicator species (common species in Chukchi and Beaufort Seas) may be a useful short-term approach to understanding change in representative marine habitats. The inclusion of bioenergetics components in coupled population models should be explored as part of efforts to evaluate population effects of climate change.

Empirical Data in Support of Field Work and Population Models

Laboratory studies are needed to investigate the causal mechanisms responsible for shifts in distribution or changes in population rates (growth, recruitment, and survival) and to determine the environmental preferences (for example, temperature and temperature-salinity relationships) of key Arctic species. Inferences drawn from correlations established in the field do not directly address mechanisms and their effects with respect to single or multiple stressors. Mueter and others (2009, p. 108) recognized the need for an analysis of biodiversity shifts of marine fishes in the northern Bering Sea: "*Although biological responses to past temperature changes provide some basis for predicting future changes, such predictions are fraught with danger because extrapolating observed relationships beyond the historical range of temperatures cannot account for potential thresholds or non-linearities. To be able to predict where the fish is going one has to gather biological and ecological field data and the results of experiments that provide an estimate of the fish environmental preferences.*"

Laboratory experiments are needed to understand the effects of variable environmental conditions on physiological processes and animal health. Processes of special concern include feeding and digestion, assimilation and growth, fish behavior (responses to stimuli such as orientation and swimming speed), and reproduction. Collectively, these processes are integral to an overall assessment of fish condition and health. They are dependent on key water properties, including temperature, salinity, light penetration, and oxygen concentration. Animal health also is affected by the presence of toxic substances, infectious pathogens, and parasites. Experiments are needed to examine the effects of ocean acidification on the development, behaviors, and productivity of key species, their food supplies, and natural predators.

The relation between field (including genetics) and laboratory data are critical to improved population dynamics and modeling. How marine fish populations (and metapopulations) respond to changing ocean conditions, which are variable in space and time, creates spatial distributions and abundance patterns (Mueter and others, 2013). Fish movements in these systems impose gradients in growth and survival through the effects of temperature, food concentration, sensory capabilities, predator density, and detection risk (Monterio, 2002; Carey and others, 2012).

Many marine fish stocks undertake seasonal horizontal migrations and the extent of these varies with age, size, and environmental conditions. Although field studies may reveal patterns at a given time and place, laboratory investigations may isolate causal effects. Using field and laboratory results, quantitative models can be used to study the effects of multiple environmental influences on population dynamics in continuous space and time (Fordham and others, 2013).

A combination of laboratory, field, and modeling approaches is needed to explore the potential effects of ocean variability on production cycles and the distribution behavior, movement, and abundance of Arctic marine fishes. Research and monitoring should focus on selected fishery resources in strategic locations to include effects of human interactions, which extend beyond subsistence use and may include effects associated with increased tankering, vessel support, and offshore construction activities on important biological habitats and ecosystems. The effects of invasive species also are an area of concern.

Participate in Regional Research and Monitoring Networks

Reference sites in biological hotspots should be estimated to support and contribute to existing long-term research and monitoring of coastal and marine ecosystems, including human interactions. Potential sites and ecological topics include: Bering Strait (marine ecosystem processes and fish distribution); Kasegaluk, Simpson, and Beaufort Lagoons (population dynamics of nearshore fish assemblages); Barrow Canyon-Hannah Shoal (benthic productivity and marine fish interactions); Capes Lisburne and Thompson (seabird colony and fishery oceanography dynamics); Point Barrow (dynamics of this transitional biogeographic zone); Boulder Patch (kelp bottom ecosystem processes); Stefansson Sound-Camden Bay (Arctic Cod ecology); Mackenzie, Colville, and Canning River deltas (onshore-offshore linkages); ice edge and polynyas (biological significance to marine fish and higher level consumers). Local residents are often the first to notice changes in fish and wildlife populations. Mechanisms should be developed to better solicit and integrate local and traditional ecological knowledge as a basic source of information.

Participate in Additional Investigations of Iñupiaq Taxonomy

Research in Kotzebue Sound (Georgette and Shiedt, 2005) demonstrated the complexities and subtleties of the Iñupiag classification system. Additional investigations are needed in concert with subsistence resource surveys to fully incorporate traditional ecological knowledge into biological research on fishery populations and their habitats.

Summary

In many respects, present day understanding of Arctic Alaska’s marine fishes is similar to what was known about the Bering Sea in the 1970s. Quantitative data are lacking or dated, but new information is slowly developing. The relationships between basic life history characteristics and population dynamics have implications for managing marine fish resources where population data are limited or non-existent. These relationships previously were used to describe strategic groups in the Northeast Pacific as an aid to fishery management. Taking a qualitative approach, we applied the criterion for these groupings to the Arctic marine fish fauna and added two new groups. One group, the amphidromic strategists, includes those Arctic fishes displaying an amphidromous life strategy. Arctic Cod, unlike other gadids, are similar to the opportunistic strategists, but because of their dependence on sea ice habitats, life history, and central role in Arctic marine ecosystems, they are considered independently as a cryophilic strategist. Long-term fishery research objectives for the Chukchi and Beaufort Seas are described in relation to information gaps and they are addressed in planned marine ecosystem research in the U.S. Arctic. Some suggestions for more immediately needed studies relate to access of existing information, description of environmental preferences for key marine species, participation in regional monitoring networks and cooperative research, and continued biodiversity assessments through field, laboratory, and museum studies.