Ice Cod to Pacific Cod

Ice Cod (*Arctogadus glacialis*)

(Peters, 1872)

Family Gadidae

Ice Cod (*Arctogadus glacialis*) 221 mm, Chukchi Borderland, 2009. Photograph by C.W. Mecklenburg, Point Stephens Research.

Note on taxonomy: *Evidence from morphology and molecular genetics demonstrates that* Arctogadus borisovi *(Dryagin, 1932) is a junior synonym of* A. glacialis [1]. *Data on fish originally identified as* A. borisovi *are included here*. Commmonly referred to as Polar Cod in North America.

Colloquial Name: *None within U.S. Chukchi and Beaufort Seas*.

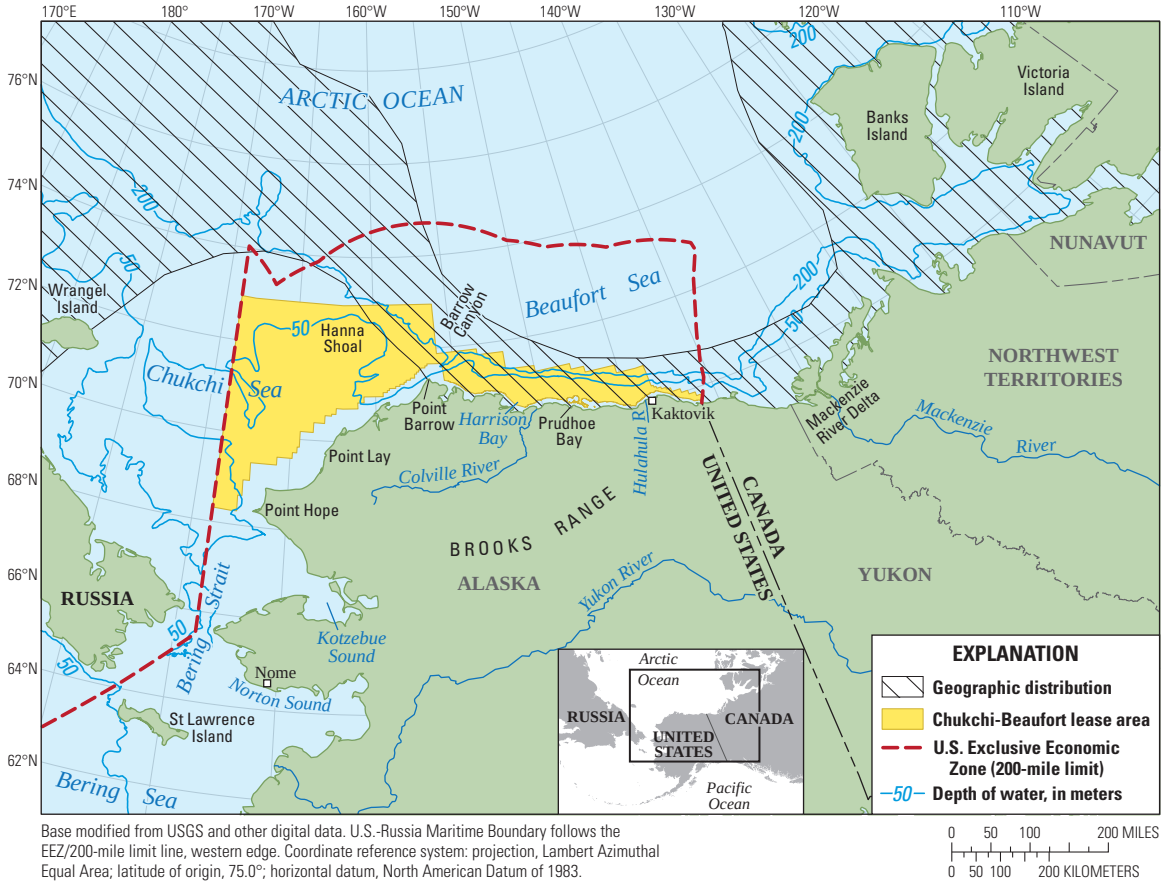
Ecological Role: The ecological role of the species in marine ecosystems of the U.S. Chukchi and Beaufort Seas is not as significant as Polar and Saffron Cod.

Physical Description/Attributes: An olive brown to bluish gray cod with darker fins and head. For specific diagnostic characteristics, see *Fishes of Alaska* (Mecklenburg and others, 2002, p. 291–292) [2]. Swim bladder: Present; no otophysic connection [2]. Antifreeze glycoproteins in blood serum: Unknown.

Range: *U.S. Beaufort* [2] *and Chukchi Sea* [3, 4]. Worldwide, circumpolar, northward to at least 81°41’N; Arctic Canada south to southern tip of Greenland, east through Barents Sea to East Siberian Sea and Chukchi Sea [2–4].

Relative Abundance: *Rare in U.S. Beaufort Sea (two specimens captured north of Point Barrow)* [2] *and Chukchi Sea (one specimen found on beach at Wainwright)* [4].Abundant to at least as far eastward to deep waters off Tuktoyaktuk Peninsula and off Capes Bathurst and Parry, Canada [6–8].

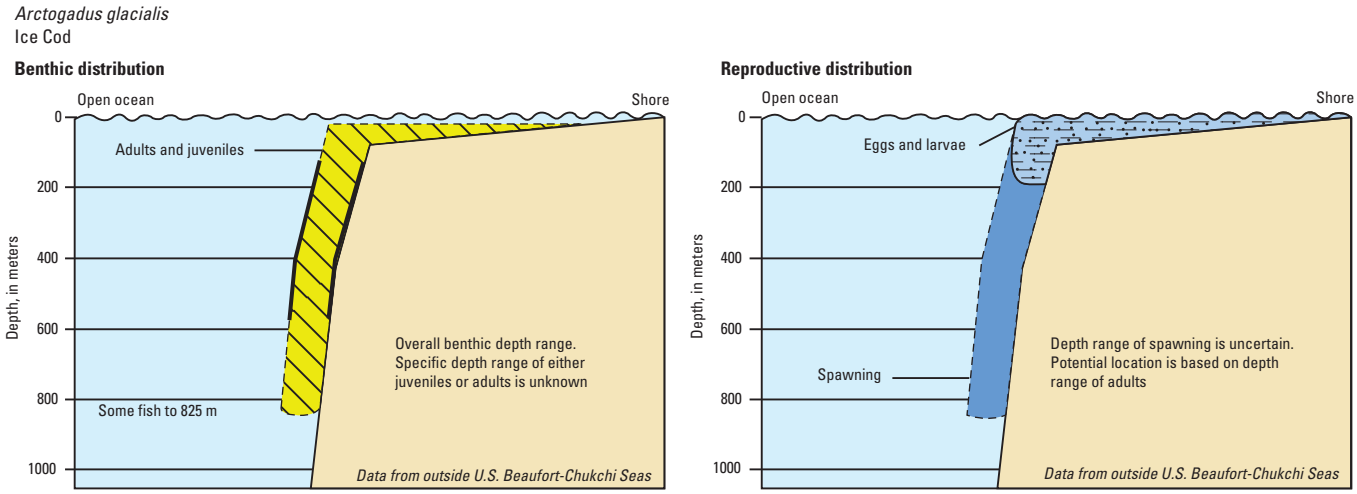
Ice Cod
Arctogadus glacialis



Base modified from USGS and other digital data. U.S.-Russia Maritime Boundary follows the EEZ/200-mile limit line, western edge. Coordinate reference system: projection, Lambert Azimuthal Equal Area; latitude of origin, 75.0°; horizontal datum, North American Datum of 1983.

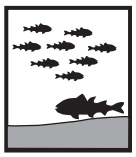
Geographic distribution within Arctic Outer Continental Shelf planning areas [5] of Ice Cod (*Arctogadus glacialis*) based on review of published literature and specimens from historical and recent collections [3, 4].

Depth Range: 5–930 m, on continental shelf and upper slope [1, 2]. Highest abundance is found off Europe at 300–400 m [9]. In northeast Greenland fjords, abundant at 120–575 m [10]. Eggs and larvae are pelagic [11] but specific depths unknown.

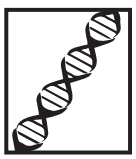


Benthic and reproductive distribution of Ice Cod (*Arctogadus glacialis*).

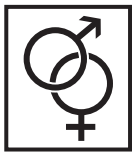
Habitats and Life History
Eggs—Size: Unknown. Time to hatching: Unknown. Size: Unknown. Habitat: Pelagic [11].
Larvae—Size at hatching: Unknown. Size at juvenile transformation: Unknown. Days to juvenile transformation: Unknown. Habitat: Pelagic [11].
Juveniles—Age and size: Unknown. Habitat: Cryopelagic and benthic [9].
Adults—Age and size at first maturity: Unknown. Females 25–26 cm long (TL) have been found with ripening gonads [12]. Maximum age: At least 11 years [13]. Maximum size: 60 cm TL [2] and 1.2 kg [12]. Habitat: Nearshore to well offshore [4, 8, 14]. Cryopelagic and benthic [5], throughout the water column (including near the seafloor) as well as under ice and within ice cracks [10, 15, 16].
Substrate—Unknown.
Physical/chemical—Temperature: -1.7 to about 4 °C [10], may prefer temperatures of about 1 °C or less [1, 10]. Salinity: Marine, estuarine, and occasionally fresh waters from near the coast to well offshore [8, 14].
Ice dependence—Although characterized as an ice-associate, also found well away from ice, sometimes in large numbers [10, 17].



Behavior
Diel—Unknown.
Seasonal—Unknown.
Reproductive—Unknown.
Schooling—Forms schools [2].
Feeding—Opportunistic pelagic feeder [9].

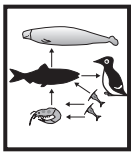


Populations or Stocks
There have been no studies.

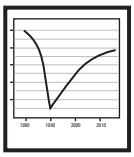


Reproduction mode
Mode—Oviparous [11].
Spawning season—Ripe fish were observed in October and during the summer in the European Arctic [9, 10].
Fecundity—Unknown.

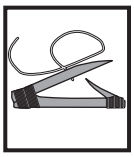
Food and Feeding
Food items—Crustaceans (for example, mysids, copepods, and amphipods), fishes, and polychaetes comprise much of the diet of this species. Fishes assume a greater part of the diet in larger cod [15, 18, 19].
Trophic level—3.82 (standard error 0.61) [20].



Biological Interactions
Predators—Commonly, bearded seals and narwhals in the Canadian Arctic [21, 22].
Competitors—Unknown.

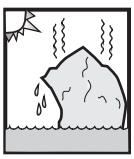


Resilience
Medium, minimum population doubling time: 1.4–4.4 years (Preliminary *K* or Fecundity) [20].

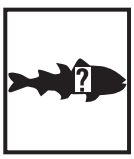


Traditional and Cultural Importance
None reported. Form only a small part of the subsistence fisheries in the Canadian Arctic [8]. Commercially fished for fishmeal and oil in Norway, Greenland and northern Siberia [23].

Commercial Fisheries
Currently, Ice Cod are not commercially harvested.



Potential Effects of Climate Change
Unknown.



Areas for Future Research [B]
Little is known about the ecology and life history of this species. Although information should improve with increased sampling, the role of this species in the gadid assemblage and how this might change with global warming is of research interest. Spawning areas and other important habitats remain to be described.

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Arctic Cod (*Boreogadus saida*)

(Lepechin, 1774)

Family Gadidae

Arctic Cod (*Boreogadus saida*) 174 mm TL, Chukchi Sea, 2004. Photograph by B.A. Sheiko and C.W. Mecklenburg, Russian Academy of Sciences and Point Stephens Research.

Colloquial Name: Iñupiat: *Iqalugaq*, *Uugaq* [1]. *Tomcod* [2].

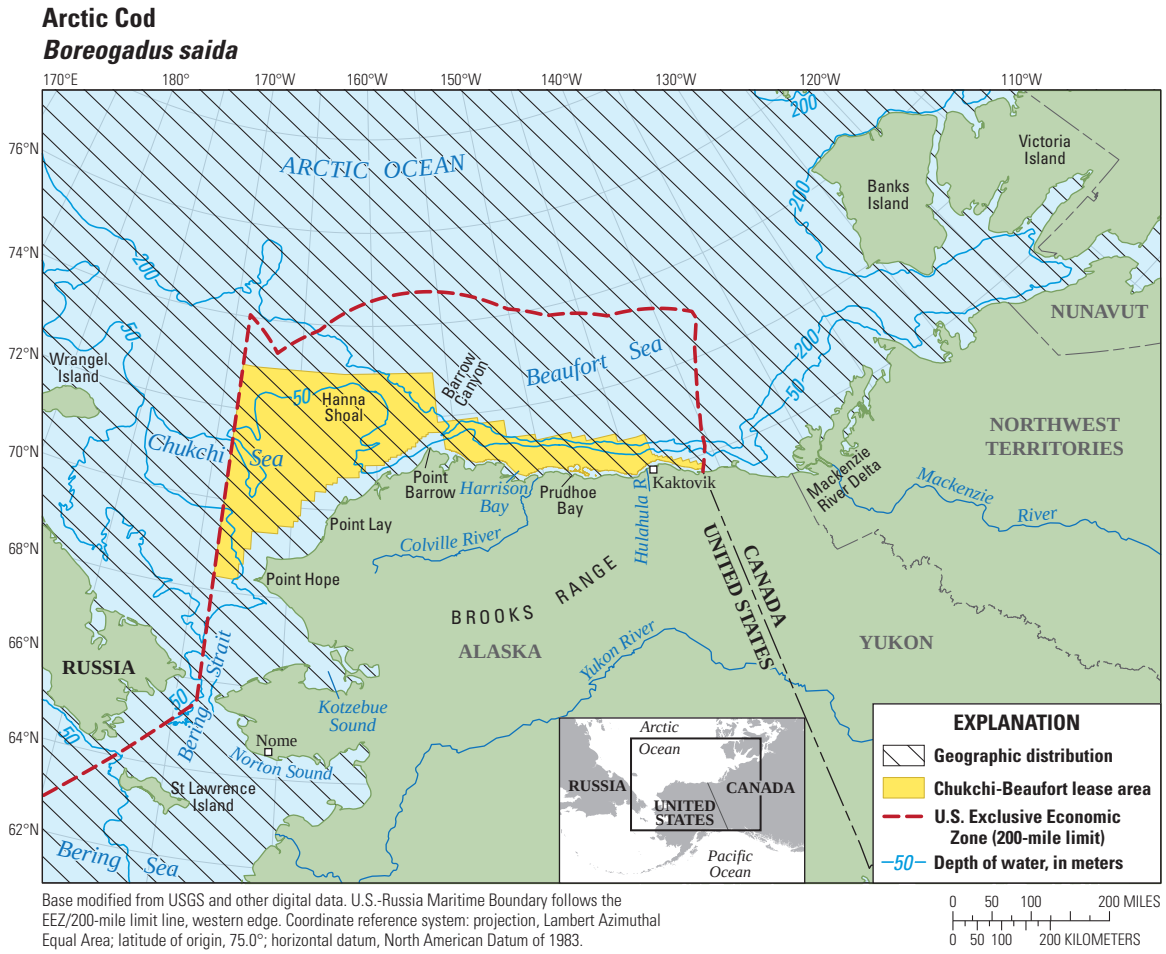
Notes on Taxonomy: *Boreogadus saida is referred to as both "Arctic Cod" and "Polar Cod" in North American scientific literature. The American Fisheries Society and Society of Ichthyologists and Herpetologists recommend using "Polar Cod" for Boreogadus saida to bring consistency with European conventions and this recommendation is gaining in acceptance in contemporary reporting and publications. We chose to use "Arctic Cod" for Boreogadus saida in this report to ensure consistency with the vast majority of Alaskan literature and to avoid confusion with Ice Cod, which has been referred to as Polar Cod by North American researchers. Anyone using literature that does not specify the scientific name must read carefully to decide which species is meant. However,* A. glacialis *is rare in Arctic Alaska waters, and most references to Polar Cod from that region that do not provide the scientific name will refer to* B. saida.

Ecological Role: Arctic Cod play a vital role in anchoring Arctic food webs in the U.S. Chukchi and Beaufort Seas. The small fish is one of the main consumers of plankton that flourish around sea ice. Arctic Cod compose 92 percent of all fish in numbers and 80 percent in weight in a 2008 western Beaufort Sea fish survey [3], and this species comprises the forage base for a wide range of marine mammals and birds. A recent model predicted a mass loss of most Arctic Cod within 30 years because of rising temperatures and receding ice pack. Key interactions between sea ice, Arctic Cod biology, and marine ecosystem function must be better understood to identify possible effects of climate change and cumulative effects of human activities.

Physical Description and Attributes: Brownish back and sides with violet or yellowish sheen covered with tiny black dots, and silvery white lower sides and belly. Fins are dusky yellow or gray, and dorsal and caudal fins are edged in white. For specific diagnostic characteristics, see *Fishes of Alaska* (Mecklenburg and others, 2002, p. 290) [4]. Swim bladder: present. Antifreeze glycoproteins in blood serum: Present [5].

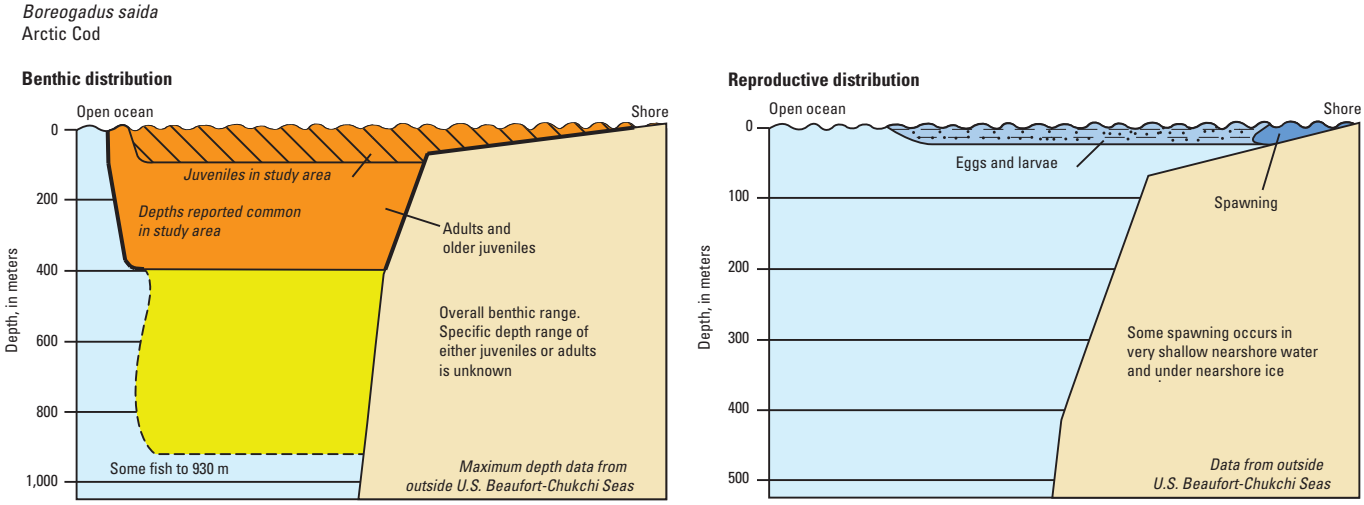
Range: *Throughout U.S. Chukchi and Beaufort Seas from very shallow, neritic waters to well offshore (although abundance hundreds of kilometers offshore is poorly known)* [6–9]. A circumpolar species, documented in Chukchi Sea northward nearly to the North Pole at 88°26′N, 126°26′E. In continental shelf waters, west and south of U.S. Chukchi Sea from Siberian Arctic to Olyutorskiy Bay in western Bering Sea and to Bristol Bay in eastern Bering Sea; and east of U.S. Beaufort Sea continuous throughout the Canadian Beaufort Sea [10, 11].

Relative Abundance: *Very abundant in U.S. Chukchi and Beaufort Seas* [9, 12–15].



Geographic distribution within Arctic Outer Continental Shelf Planning Areas [16] of Arctic Cod (*Boreogadus saida*) based on review of published literature and specimens from historical and recent collections [11, 17].

Depth Range: Larvae: *Maximum depth unknown. Surface to at least 20 m* [12]. Juveniles: *Maximum depth unknown. Near surface to 75 m* [9, 18]. Older juveniles and adults: *Maximum depth could be 930 m (the species' maximum recorded depth) but such depths have not been sampled in the U.S. Chukchi and Beaufort Seas. Found throughout the water column, abundant from surface waters to at least 400 m* [9, 12, 19] and deeper (500 to 1,000 m in the United States Beaufort Sea, Kathleen Wedemeryer, Bureau of Ocean Energy Management, Alaska OCS Region, oral commun., October 13, 2015). Elsewhere, Arctic Cod are found from barely subtidal waters to depths of 930 m [20]. Spawning: Shallow nearshore waters and under nearshore ice [21, 22].



Benthic and reproductive distribution of Arctic Cod (*Boreogadus saida*).

Habitats and Life History

Although Arctic Cod are assumed to both spawn and live *under* ice in Arctic Alaskan waters, virtually no surveys have been conducted to determine the importance of this habitat to Arctic Cod in the Alaskan Arctic. Throughout its range, Arctic Cod occupy a remarkably wide breadth of habitats. They occupy all parts of the water column in estuaries and off river mouths and in shallow subtidal waters, and are found many hundreds of kilometers off the coast [6, 21, 23, 24]. *These fish are often associated with ice* although they have been captured during spring and summer in the northern Bering Sea at least 300 km (186 mi) away from the nearest floe or pack ice *and are abundant along the U.S. Chukchi and Beaufort Seas in seasonally ice-free areas* [6, 25]. However, they can be found in very large numbers under ice and are often seen in cracks, crevices, and in melt-water ponds on the ice [20, 26, 27].

Eggs—Size: 1.5–1.9 mm [28, 29]. Time to hatching: *Unknown.* Elsewhere, between 26–90 days; highly variable, apparently dependent on water temperature [30, 31]. Habitat: *Planktonic. Location unknown.*

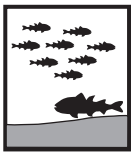
Larvae—Size at hatching: *6 mm* [32] Size at juvenile transformation: 27–50 mm [30, 33]. Days to juvenile transformation: *Unknown.* In the Russian Arctic, the larval stage lasts about 2 months [30]. Habitat: *Pelagic. Location poorly understood.* Elsewhere, found under ice [34].

Juveniles—Habitat: *Poorly known. Some pelagic juveniles are found in near-surface waters away from ice* [18, 35]. *Some young-of-the-year recruit from the plankton directly into inshore habitat, but it is likely that others remain well offshore (to at least 175 km off Prudhoe Bay)* [6, 18] *in near-surface waters* [6, 32]. *Large numbers of juveniles were found in shallow U.S. Beaufort Sea lagoons* [36]. Elsewhere, juveniles are common under ice [20, 26, 27, 37]. *However, in the Alaskan Arctic, they also are very abundant in the summer well away from ice* [6, 8, 38]. In other areas, in offshore waters and in the absence of ice, smaller fish tend to inhabit shallower depths in the water column than do larger individuals [32, 39, 40].

Adults—Age and size at first maturity: *A few fish, possibly only males, are mature at 1year and around 100 mm FL. Most fish mature at –3 years (120 mm FL and larger) and males may mature about 1 year earlier than females* [6, 19]. Maximum age: *In study area, 7–8 years* [15]. Maximum size: 46 cm TL [41]. Habitat: Adults are common under ice [20, 26, 27, 37]. *However, in the Alaskan Arctic, they also are very abundant in the summer well away from ice* [6, 8, 38].

Physical/Chemical—Temperature: *Preferred temperatures poorly known, but probably about –1.5–5 °C* [12, 13, 42], *although sometimes they are abundant in waters as warm as 10 °C* [8, 43]. *Documented between -2.0 and 13.5 °C* [43, 44]. Elsewhere, to -2.1 °C [45]. In Bering Sea, mainly -2.0 to -0.7 °C [45]. In the Canadian High Arctic, larvae are reported to develop only at temperatures less than 3.0 °C [46] and in the Russian Arctic, less than 5 °C [30]. Juveniles may favor warmer waters than adults [8, 39]. Salinity: *Documented from 0 to 32.6 practical salinity units (psu)* [10, 43, 44] and elsewhere to 34.9 psu [17]. All life stages live in marine waters. Although occasionally abundant in brackish waters [43], low abundance in such areas as the Mackenzie River estuary may reflect general avoidance of very low salinity waters [47].
Ice Dependence—Although it is clear that many Arctic Cod live under ice, it is unclear whether these fish are ice *associated or ice dependent* [27, 48]. The hypothesis that Arctic Cod are ice dependent is derived from a number of inconclusive observations. Examples include:

4. Known to spawn along the ice edge [49] and under ice [23, 50]. However, whether spawning is limited to ice or a near-ice area is unknown. For instance, Arctic Cod eggs have been taken in May around the ice-free Pribilof Islands, Alaska [51]. In addition, surveys of possible spawning in ice-free areas have not been conducted during the overwinter, for instance, the Bering Sea.
5. *Juveniles and adults are very abundant under ice* [52], *but can be extremely abundant during summer in relatively warm water and ice-free conditions* [9, 12, 32, 44].
6. The relationship between ice densities, water temperatures, and fish growth and survival is uncertain. In the Greenland Sea, larvae living in low-ice, relatively warm waters survived better than those in thicker ice and colder (<0 °C) temperatures, implying that the lengthening of the ice-free season may result in improved recruitment and larger populations in Arctic Cod in the short term [50]. This has also been noted among polynyas in Arctic Canada [48]). In addition, juvenile and adult Arctic Cod in the northeast Chukchi Sea grew fastest in a warmer-water year [15]. However, this position has been challenged by some authors based on the hypothesis that Arctic sea warming will reduce sea ice habitat and allow sub-Arctic or temperate taxa to replace this species [50].



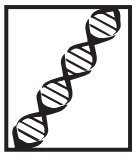
Behavior
Diel—*Unknown.* Elsewhere, from January to April, post-spawning adults in the eastern Beaufort Sea rise in the water column at night [52].
Seasonal—*Poorly understood* [6]. *Current information suggests that throughout their range, fish move into nearshore waters in the summer. Precise time and intensity varies between locations and between years at the same location* [6, 13, 53, 54]. *In the U.S. Beaufort Sea, relatively scarce in shallow waters immediately after ice-out, but move into shallow waters as the season progresses* [6, 7, 53]. *However, ringed seal diet studies in the nearshore of Arctic Alaska* [55], *and other fish surveys* [44, 56], *imply that at least some Arctic Cod overwinter in nearshore waters under ice. In nearshore waters, schools can move quickly through an area* [44, 57] or reside in the same location for weeks [58]. *Proportion of population migrating into shallow waters is unknown; many fish might not migrate into the shallowest waters* [19, 38]. *In summer, Arctic Cod are by far the most abundant fish in Alaska Arctic nearshore waters* [14, 15]. *For example, estimates of summer cod abundances in Simpson Lagoon have been as high as 12–27 million fish* [44].

Data regarding the environmental parameters driving inshore migrations are often contradictory. *For instance, in the U.S. Chukchi Sea, catches increased when water temperatures rose and salinities decreased* [38], *but was the opposite in the Sagavanirktok River Delta of the U.S. Beaufort Sea* [59]. *In Prudhoe Bay of the U.S. Beaufort Sea, highest densities were noted 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* [60]. *Another U.S. Chukchi Sea study found no environmental-parameter-associated abundance; authors hypothesized that food availability might underlay fish movements* [15].

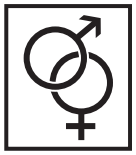
Thus far, the most complete study of winter behavior was in Franklin Bay, eastern Canadian Beaufort Sea. It was documented that after spawning during the early winter (perhaps over deep waters in the Amundsen Gulf; (D. Benoit, Université Laval, 2010), very large numbers of fish either migrated, or were passively carried, into 180 m or deeper depths and did not feed during this time. Migration out of these waters began with an abrupt upward migration and coincided with phytoplankton blooms and the onset of feeding [52]. Similar work in the nearby Amundsen Gulf demonstrates a similar pattern [61].

Reproductive—*Poorly known.* In the Arctic in general, spawning occurs near the bottom along the ice edge [49] and under ice [23], whether limited to under-ice areas is unknown. For instance, eggs have been found in

May around the ice-free Pribilof Islands [51]. The winter (spawning-season) behavior throughout the Arctic is very poorly known. *In the U.S. Chukchi and Beaufort Seas, at least some fish spend winters under nearshore ice (presumably spawning)* [38, 44, 56, 62]. *However, whether the bulk of the population overwinters and spawns in shallow waters is unknown. For instance, spawned-out cod were reported both near the coast and 175 km off Prudhoe Bay* [6]. In the autumn and winter, large, spawning-oriented migrations occurred in the Russian Arctic and spawning in the Barents Sea may have occurred from near shore to hundreds of kilometers off the coast [49].
Schooling—*Schooling behavior under ice has not been studied. In ice-free areas, very large schools are formed, often millions of individuals* [6, 44]. *This species often schools by size class* [8]. *The amount of cohesion of fish schools in Arctic Alaska is unknown,* although in the Canadian Arctic some schools stay together for at least 1–2 months in summer [24, 58].
Feeding—*Prior to spawning, a few nearly ripe fish in Simpson Lagoon were still feeding* [44], whereas in the Canadian Arctic, feeding ceases for several months beforehand [52].

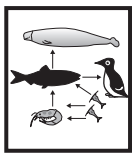


Population or Stocks
Initial research underway in U.S. Chukchi and Beaufort Seas and Arctic Ocean. Microsatellite markers imply some population structure among Chukchi Sea, Canadian and Siberian Arctic Cod, and potentially low differentiation between those from Hudson Bay and the eastern Beaufort Sea [63]. The genetics research indicates very little structuring across the United States Beaufort Sea with respect to the three dichotomies of east/west; coastal/slope; and riverine/marine water influence (Kathleen Wedemeyer, Bureau of Ocean Energy Management, oral commun,, October 13, 2015). A single circum-artctic population with only minor differences is currently hypothesized.



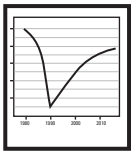
Reproduction
Mode—Separate sexes, oviparous. Fertilization is external.
Spawning season— *Poorly understood*. Over the species' entire geographic range, spawning occurs under ice floes from November to at least April, perhaps peaking in January and February in the Beaufort Sea [6, 15, 31, 49]. *The capture of spawned-out adults in May, 175 km off Prudhoe Bay, implies that some spawning may continue well into the spring* [6]. *The capture of newly hatched larvae in July in the northeastern Chukchi Sea* [33] and as late as July and August in Tuktoyaktuk Harbor, Northwest Territories, and near Baffin Bay [64, 65], also may imply late spawning. However, eggs fertilized in February will often remain as larvae into July [30].
Fecundity—*Unknown.* Elsewhere, 9,000–33,251 eggs, apparently in one batch [28, 29]. Females may not spawn every year [6]. However, in a laboratory study, several females spawned in two successive years, implying that some fish are capable of spawning more than once in their lives and in sequential years [46].

Food
Food items—Larvae: *Unknown.* In Hudson Bay, pelagic larvae under ice feed on nauplii and eggs of those copepods feeding on under-ice phytoplankton [34]. Juveniles and Adults: *Diets vary with fish size and location, although epibenthic or pelagic crustaceans (for example, mysids, isopods, copepods, gammarid and hyperiid amphipods, and shrimps), as well as larval fish, polychaetes, chaetognaths, and small fishes (such as other Arctic Cod), are important. Fish living under ice often target ice-associated crustaceans such as amphipods* [6, 57, 66-68]. Feed primarily on copepods and amphipods in northern Bering Sea [69]. *Diets also may vary with season. In Simpson Lagoon of the Alaskan Beaufort Sea, mysids, amphipods, isopods were most important during the summer and mysids dominated during the winter* [44].
Trophic level—3.6 [70].



Biological Interactions
Predators—Arctic Cod are an extremely important prey for a wide range of predators and are possibly the most important forage fish in the U.S. Chukchi and Beaufort seas. *They are consumed by at least 8 fish species, 17 bird species, and 3 marine mammal species* [19, 38, 67, 71–75]. *The major predators of Arctic Cod in the Alaska Beaufort Sea are considered to be, in order of importance, Arctic Cod (cannibalism), ringed seals, Beluga whales, and seabirds (particularly Black-legged Kittiwake, Thick-billed Murre, Ivory Gull, Black Guillemot, Glaucous Gull, loons, Ross' Gull, Arctic Tern, and Sabine's Gull)* [67]. *Almost all studies were conducted during summer months, although it has been shown that in the Alaskan High Arctic they form a major part of the diet of ringed seals (particularly important to pups) throughout the year* [55, 67] *and bearded seals in the U.S. Chukchi Sea from at least November through June* [71]. Arctic Cod appear to be particularly susceptible to beach strandings, caused by predators or storms [6, 58].

Competitors—*Likely competitors are other schooling midwater feeders, particularly Walleye Pollock, but also Dolly Varden, whitefish species, Capelin, and Pacific Sand Lance.*



Resilience

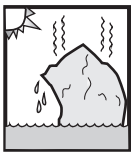
Medium, minimum population doubling time: 1.4–4.4 years (K=0.22; t_m=2-5; Fecundity =30,000) [76].

Traditional and Cultural Importance

In the past, this was a fairly important human subsistence species in the Alaskan High Arctic. For instance, it was reported that Arctic Cod were heavily fished through the ice off Barrow in the winter [77]. *Over time and today, Arctic Cod are of only limited importance as food fish* [1, 78–80]. Arctic Cod appear to be of more importance in Canadian subsistence fisheries of the Barrow Strait and Hudson Bay where they are widely caught and consumed [58, 81].

Commercial Fisheries

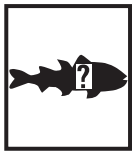
Arctic Cod are not commercially harvested in the U.S. Chukchi and Beaufort Seas. The commercial fishery for Arctic Cod is small and limited to Russian vessels fishing primarily in the northwest Russian Arctic [82].



Potential Effects of Climate Change

Climate change may influence the numbers of Arctic Cod through a number of mechanisms. (1) Assuming that this species is in some way ice-dependent, a poleward shift in distribution would be expected with retreating ice. (2) There is some evidence that survivorship of Arctic Cod larvae increases with earlier ice break-up, more frequent winter polynyas, a warmer (ocean) surface layer, and increased river discharge [83], all possible effects of warming conditions. (3) Arctic Cod coming under increased competition for resources from some northward-migrating species would be expected, particularly from Saffron Cod and possibly Walleye Pollock. (4) Greater periods of ice-free conditions likely will alter predation patterns, but in ways that are not yet predictable. Receding ice may increase predation. In Resolute Bay, North West Territories, fish under heavy ice cover were less aggregated than when the bay was relatively ice-free. When ice drifted into the bay, fish would move under it [84]. In Hudson Bay, a sharp decrease in the abundance of Arctic Cod coincided with an approximately 50 percent decrease in summer ice cover [85]. However, the millions of Arctic Cod inhabiting the ice-free Simpson Lagoon in the summer do not appear to suffer heavy predation [44]. Reduced ice pack can be argued to cause an increase or decrease predation depending on predator. For instance, reduced ice pack would decrease resting habitat for seals, while making Arctic Cod perhaps more available to cetaceans or seabirds [48]. (5) Food availability and growth rates will change, although the direction and intensity of this change are unknown. As an example, fish in the northeast Chukchi Sea grew fastest in warmer water years [15] and larvae residing in the low-ice, relatively warm waters in Greenland survived better than those under thicker ice [50]. (6) Effects on Arctic Cod predators are unknown, but may be substantial. For instance, retreating pack ice near Point Barrow led to reduced Arctic Cod availability for Black Guillemots and subsequent reductions in nestling growth and brood size [86]. (7) Effects of predation by Arctic Cod on prey are unknown but the species mid-level role in transferring energy from low to high trophic levels is hypothesized to be significant. Local effects of Arctic Cod predation on prey concentrations also may be significant. For instance, feeding by large schools of adult Arctic Cod in the Canadian Arctic may be sufficiently intense as to cause localized depletion of zooplankton [24]. The effects of possible changes in Arctic Cod distribution and abundance, in association with climate warming, may have profound, cascading effects on the Arctic marine ecosystems. The effects of increasing ocean acidification on Arctic Cod food webs dynamics and developmental biology are of concern. The protocols for capturing, transporting, breeding, and rearing larvae through adult stages in the laboratory have been tested and described [87, 88] making empirical studies of thermal sensitivity to warming using an Arctic Cod model possible. New information is available describing the thermal limits of cardiac function on Arctic Cod [89, 90], effects of warming and ocean acidification on metabolism and performance on Arctic Cod and Atlantic Cod (*Gadus morhua*) [91], and temperature-dependent growth and swimming behaviors of Arctic Cod, Saffron Cod, Walleye Pollock, and Pacific Cod [92]. In general, the results suggest optimal food conversion for juvenile Arctic

Cod in Cold waters (0 °C), near optimal growth at 5 °C, and diminished growth and condition with increasing temperatures above this (detrimental effects above 16 °C). Differential acute effects of warming on larvae and adults further suggest the potential role thermal limitations of younger-aged cod may have on the Arctic Cod distribution in coastal waters.



Areas for Future Research [A]

Considering the species central role in Arctic marine ecosystems dynamics, relatively little focused research attention has been given to Arctic Cod in Arctic Alaska. In particular, the role of sea ice in the species' life cycle, though speculated, is not well understood. The location and timing of spawning locations and presence of stock structures are unknown. Information is needed regarding population movements and behaviors, particularly during winter months, and with respect to the relative important habitats in slope, shelf, and nearshore, and deeper areas of the Canada Basin. The latter need is of particular importance because a recent model predicted a mass extinction of most Arctic Cod within 30 years [93]. However, the model appears to be at least partially based on the assumption that there are no Arctic Cod well offshore of northern Alaska, although no surveys have been conducted there. The use of Autonomous Underwater Vehicles to investigate Arctic Cod ecology should be explored. There needs to be new and continued empirical research to determine the seasonal effects of changing temperatures, ocean acidification, and ice coverage on the reproduction ecology and population growth and condition of Arctic Cod. An additional experimental priority is for toxicological research on the potential effects of spilled, dispersed, and weathered oil on Arctic Cod under Arctic conditions. Accurate assessments of species interactions and effects of human developments and climate changes will require that the population dynamics of the species are understood and that abundance patterns and population parameters are monitored over time.

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Saffron Cod (*Eleginus gracilis*)

(Tilesius, 1810)

Family Gadidae

Saffron Cod (*Eleginus gracilis*), 233 mm, Chukchi Sea, 2007. Photograph by C.W. Mecklenburg, Point Stephens Research.

Colloquial Name: Iñupiat: *Uugak* [1]. This species and the Arctic Cod are called Tomcod (not to be confused with *Microgadus proximus*).

Ecological Role: This is a species of major ecological importance, particularly in the Chukchi Sea. Saffron Cod are believed to be a major competitor of Arctic Cod and changes in sea ice associated with warming may give the species a competitive advantage.

Physical Description/Attributes: Mottled brown to gray-green body washed with yellow. Ventral areas are white to yellow, pectoral fins are yellow, and margins of dorsal and anal fins are white. For specific diagnostic characteristics, see *Fishes of Alaska* (Mecklenburg and others, 2002, p. 293) [2]. Swim bladder: Present [2]. Antifreeze glycoproteins in blood serum: Present [3].

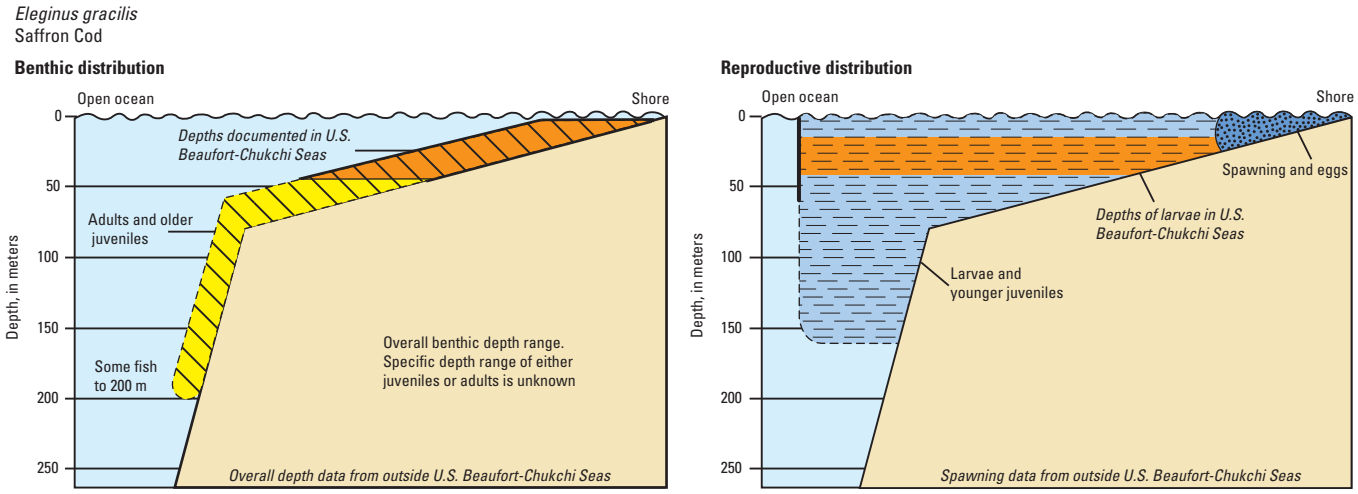
Range: *U.S. Chukchi and Beaufort Seas* [4]. Elsewhere in Alaska, from Bering Sea and Gulf of Alaska to Sitka, southeastern Alaska. Worldwide, from Sea of Japan and Sea of Okhotsk to East Siberian Sea and eastward in Arctic to Melville Sound, Bathurst Inlet, Nunavut [4].

Relative Abundance: *Patchily abundant in U.S. Chukchi and Beaufort Seas* [7–10] eastward to Cambridge Bay, Nunavut [6]. Most abundant species during summer in northern Bering and southern U.S. Chukchi Seas [12]. Abundant from Sea of Japan and Sea of Okhotsk to eastern Bering Sea [13–15] and central Gulf of Alaska [16]. Appears to be increasing in abundance in Prince William Sound [17].

Base modified from USGS and other digital data. U.S.-Russia Maritime Boundary follows the EEZ/200-mile limit line, western edge. Coordinate reference system: projection, Lambert Azimuthal Equal Area; latitude of origin, 75.0°; horizontal datum, North American Datum of 1983.

Geographic distribution of Saffron Cod (*Eleginus gracilis*) within Arctic Outer Continental Shelf Planning Areas [5] based on review of published literature and specimens from historical and recent collections [2, 4, 6].

Depth Range: Shallow, nearshore to 200 m, typically less than 50 m [18–20]. *Four pelagic larvae taken in U.S. Chukchi Sea between 18 and 36 m* and in Bering Sea from 0–162 m. Largest catches were in less than 60 m [21]. *One pelagic juvenile was taken in U.S. Chukchi Sea in midwaters between 45 m and surface* [22]. Older juveniles recruit to very shallow near-shore waters [23–26]. However, off Hokkaido, Japan, and the Kuril Islands, Russia, juveniles are abundant to depths of at least 200 m [27]. Spawning occurs in shallow waters [23, 28, 29] to at least 32 m in the western Pacific Ocean [27].



Benthic and reproductive distribution of Saffron Cod (*Eleginus gracilis*).

Habitats and Life History

Eggs—Size: 0.8–1.7 mm [27, 30]. Time to hatching: 28–49 days [30]. Habitat: Demersal, non-adhesive [27, 30–32].

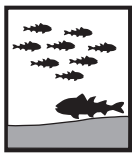
Larvae—Size at hatching: *3.5–3.9 mm SL* [31]. Size at juvenile transformation: 24–27 mm SL [21]. Days to juvenile transformation: Unknown. Habitat: Pelagic [17, 21].

Juveniles—Age and size: 21–35 cm FL [21, 31]. Habitat: Early juveniles are pelagic, becoming more benthic as fish mature [21]. In Gulf of Alaska, closely associated with nearshore eelgrass beds [16, 17].

Adults—Age and size at first maturity: *Very little research has been conducted.* Generally, maximum age, growth rates, and age at first maturity vary with location. Off Hokkaido, Japan, few mature as early as one year and all are mature by 2 years [33]. In Siberian Chukchi Sea, fish mature at 4–5 years. Overall, fish mature at 21.0–35.0 cm FL [31]. Maximum age: 19 years in Canadian Beaufort Sea, [34]. Maximum ages are highly variable among geographic locations [7, 27, 35]. In Siberian Chukchi Sea, fish live to 15 years. Maximum life spans steeply decline to the south. Fish living in Peter the Great Bay, in Sea of Japan, only reach about 8 years of age [27]. Maximum size: 55 cm TL [2] and possibly to 63 cm TL [6]. Females are slightly heavier at length than males. Habitat: Benthic and midwater [2, 36–39]. Shallow, nearshore and, at least around Kodiak Island and Sea of Japan, often associated with eelgrass [16, 40].

Substrate—Soft and hard sea floors [41]. Sandy-stone or gravel bottoms for spawning [32].

Physical/chemical—Temperature: *Unknown.* Elsewhere, between -1.7 and 11.7 °C in southeastern Bering Sea [42]. In Amundsen Gulf, a large mortality event occurred when fish encountered 18.0 °C waters flowing out of Coppermine River [11]. Spawn between -1.8 and 1.8 °C [27, 32, 34, 43]. Eggs remain viable at water temperatures of somewhat greater than -3.8–8.0 °C [43]. Salinity: Primarily marine and brackish waters [36–39], although described as entering both rivers and lakes [43], and not ascending upstream of river mouths [32]. In Russia, spawning occurred only at 27 parts per thousand or more [32]. Temperatures higher than 1.2 °C and salinities less than 21 parts per thousand are reportedly unfavorable for egg and larval survival [27, 32, 44].



Behavior

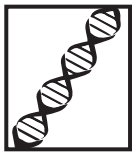
Diel—Unknown.

Seasonal—*Juveniles recruit to very shallow near-shore waters in summer* [23–26]. *Movements of juvenile and adults are not well known.* Generally, Saffron Cod have relatively circumscribed movements, with a limited winter inshore and summer offshore migration [29]. However, large numbers move into shallow waters of the Yukon Territory, Canada and southeastern Beaufort Sea in early summer [28] and *fish in northern Bering Sea may move northwards into U.S. Chukchi Sea in summer* [45]. *Alongshore movements may be quite limited. One fish tagged in the Arctic National Wildlife Refuge only moved 30 km in 3 years* [46]. *Locations of overwintering grounds are not well known. Some fish overwinter in nearshore estuarine and marine waters and these aggregations may be limited to specific geographic areas* [34, 47–49].

Reproductive—*Spawning behavior and locations are poorly understood.* Throughout their geographic range, some spawning occurs in shallow waters [23, 28, 29]. In Russia, fish spawned in areas with strong tidal currents and sandy-stone or gravel bottoms [32].

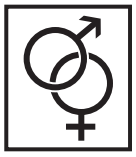
Schooling—Schools, sometimes in high densities [40].

Feeding—*Feed throughout the year at least in U.S. Chukchi Sea and* northern Bering Sea [23]. Juveniles in White Sea feed during day and night. Fish fed among rockweed patches during day and over sand at night. They also fed in the water column on the flood tide [50].



Populations or Stocks

Initial investigations on genetic diversity and stock structure are underway at the University of Alaska Fairbanks.



Reproduction

Mode—Separate sexes, oviparous. Fertilization is external.

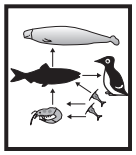
Spawning season—*Winter in U.S. Chukchi Sea* [23]. Mainly, December–February throughout Alaska [31]. Elsewhere, from December to at least May [29, 37] and off Kamchatka Peninsula, Russia, perhaps as late as June [43].

Fecundity—4,900–690,000 eggs, varies with location [27].

Food and Feeding

Food items—*Fishes (for example, Arctic Cod, Capelin, Fourhorn Sculpin, and Saffron Cod) and crustaceans (for example, amphipods, isopods, mysids, and shrimps) often are very important, and priapulids, polychaetes, clams, insects, pteropods, and plant material also are consumed* [11, 23, 35, 36, 51–53]. Juveniles prey on zooplankton [35]. Larger fish prey on a wide range of benthic and epibenthic organisms. During spawning season, adults reportedly feed heavily on Saffron Cod eggs [19].

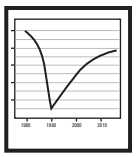
Trophic level—4.1 [54].



Biological Interactions

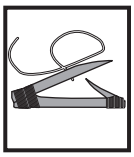
Predators: *Very important prey for ringed seals from at least Nome, Alaska (during at least mid-summer to December) to the U.S. Chukchi Sea (throughout the year)* [55, 56]. *Important summer food for belugas to at least as far north as Wainwright* [57, 58]. *Other predators include Arctic Lamprey and Fourhorn Sculpin* [20, 23]. Additional predators that have been reported include Great, Plain, and Thorny Sculpins, Pacific Cod, Pacific Halibut, Arctic Smelt, Saffron Cod, Black-legged Kittiwake, Common and Thick-billed Murres, bearded and ribbon seals, Steller sea lion, harbor porpoise, Beluga, Fin, Humpback, Ninke, and Sperm whales [59–67].

Competitors: *Likely co-occurring gadids including Arctic Cod, Ice Cod, Pacific Cod (including ogac), and Walleye Pollock* [7, 21, 68].



Resilience

Medium, minimum population doubling time: 1.4–4.4 years (t_m=2–3; Fecundity=4,900) [69].

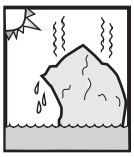


Traditional and Cultural Importance

Commonly taken in subsistence fisheries in both the U.S. Chukchi and Beaufort Seas and in the Bering Sea, usually through the ice by both hook and line and gill nets [1, 24, 37, 70]. Historically, this was an extremely important species to the Inuits residing along the Bering Sea of Alaska where fish were commonly taken during spring as soon as the ice melted from the nearshore, but were particularly important in November, when the pack ice returned. Large numbers of Saffron Cod were utilized by the inhabitants of Norton Sound. They are used as food for both man and dog [71].

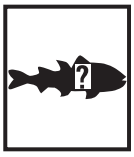
Commercial Fisheries

Currently, Saffron Cod are not commercially harvested.



Potential Effects of Climate Change

Uncertain. Reproducing in Arctic as well as Boreal waters [4], this is a somewhat eurythermic species, apparently able to function within a relatively wide temperature range. Assuming that such coldwater-adapted competitors as Arctic Cod are negatively effected, the reduced competition could be beneficial to the Saffron Cod population. This is supported by new experimental studies that indicate juvenile Saffron Cod growth rate responded positively to increasing temperatures ranging from 0 to 16 °C and above [72].



Areas for Future Research [A]

Little is known about the ecology of this species. It is an important forage fish, subsistence resource, and competitor of Arctic Cod. Information about seasonal habitats and life history and stocks structure of the populations is needed. Initial laboratory and modeling studies suggest the competitive capacity of Saffron Cod with respect to Arctic Cod and other gadids. Additional studies are needed to evaluate the effects of temperature and other population limiting factors, including competition, on this species.

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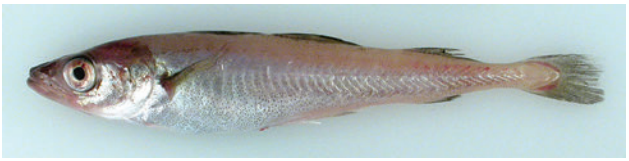
Walleye Pollock (*Gadus chalcogrammus*)

Pallas, 1814

Family Gadidae



Walleye Pollock (*Gadus chalcogrammus*) juvenile, 141 mm, Bering Strait, 2007. Photograph by C.W. Mecklenburg, Point Stephens Research.

Scientific name: Previously called *Theragra chalcogramma* (Pallas, 1814), this species was recently returned to its original genus *Gadus* on the basis of morphological and molecular evidence [1].

Colloquial Name: *None within U.S. Chukchi and Beaufort Seas*.

Ecological Role: Current information on the distribution and abundance of this species suggests it could be of low to moderate ecological importance in some parts of the Chukchi Sea and offshore waters north of Barrow, Alaska. This is a key species in ecosystem dynamics of the Gulf of Alaska, Prince William Sound, and Bering Sea [2].

Physical Description/Attributes: Olive green to brown with dark mottling and blotches on back, and interrupted dark brassy olive stripes on upper sides. Fins are brown, dusky gray, or black. For specific diagnostic characteristics, see *Fishes of Alaska* (Mecklenburg and others, 2002, p. 295) [3]. Swim bladder: Present; no otophysic connection [3]. Antifreeze glycoproteins in blood serum: Unknown.

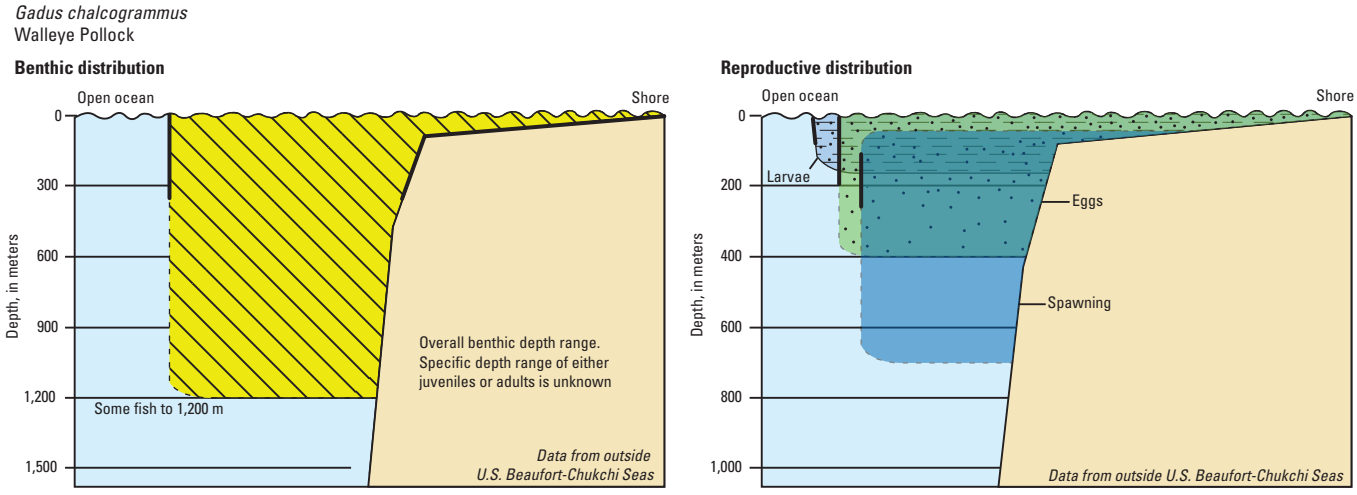
Range: *U.S. Chukchi and Beaufort Seas* [4–6]. Elsewhere, through Bering Sea, Aleutian Islands and Gulf of Alaska south to Carmel, central California and west to Seas of Okhotsk and Japan [3]. Also found in Barents Sea off Norway, where it used to be called *Theragra finnmarchica* [1].

Relative Abundance: *Common in U.S. Chukchi and rare in U.S. Beaufort Sea* [1, 4, 5, 8, 9]. Elsewhere, abundant in Sea of Japan, northern Kuril Islands, Kamchatka Peninsula, Russia, and throughout Bering Sea southward to southeastern Alaska and Puget Sound [10–15].

Base modified from USGS and other digital data. U.S.-Russia Maritime Boundary follows the EEZ/200-mile limit line, western edge. Coordinate reference system: projection, Lambert Azimuthal Equal Area; latitude of origin, 75.0°; horizontal datum, North American Datum of 1983.

Geographic distribution of Walleye Pollock (*Gadus chalcogrammus*) within Arctic Outer Continental Shelf Planning Areas [7] based on review of published literature and specimens from historical and recent collections [1, 3, 8].

Depth Range: Entire water column, from surf zone to 1,200 m, commonly at 400 m or less, though large numbers have been taken at 800–1,000 m in Bering Sea [13, 16, 17]. Spawning occurs from 46 to 700 m, most commonly between 100 and 250 m on deeper continental shelf and upper continental slope [18–20]. Pelagic eggs are from 0 to 400 m, typically less than 200 m in Gulf of Alaska and eastern Bering Sea [21–23]. Pelagic larvae are from 0 to 153 m, typically 60 m or less in Gulf of Alaska and eastern Bering Sea [22, 24–26].



Benthic and reproductive distribution Walleye Pollock (*Gadus chalcogrammus*).

Habitats and Life History

Eggs—Size: 1.2–1.8 mm [27, 28]. Time to hatching: 25.5 days at 2 °C and 14 days at 5 °C [29]. Habitat: Pelagic, in deep water, rising to shallower water as they develop [3, 22, 30].

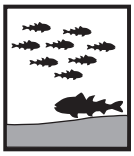
Larvae—Size at hatching: 3.0–4.0 mm SL [28]. Size at juvenile transformation: About 2.5–4.0 cm SL [20, 29]. Days to juvenile transformation: 60 days [29]. Habitat: Epipelagic, over continental shelf and slope [3, 27, 28, 31].

Juveniles—Age and size: 2 months to 2–7 years [29] and 2.5 cm SL to 20–48 cm FL [32, 33]. Habitat: Semi-benthic, in nearshore waters [3, 34, 35] and then migrate somewhat deeper as they mature [34–36]. Taken among eelgrass and kelp [37].

Adults—Age and size at first maturity: In eastern Bering Sea, a few males matured at 20 cm FL (2 years), 50 percent were mature at 31 cm (3 years), and 100 percent were mature at 48 cm (about 7 years) [32]. For females, size and age at maturity varied somewhat with location and year. On average, a few matured at 25 cm FL, 50 percent at 37.4 cm (4 years), and virtually all by 56 cm [33]. In the Gulf of Alaska, 50 percent of females matured at 42 cm FL and 5 years [38]. Older females are perhaps somewhat larger at age than are males. Maximum age: 33 years [20]. Maximum size: 91 cm TL [3]. Habitat: Semi-demersal to pelagic [3]; commonly associated with outer shelf and slope but also uses a wide variety of habitats including nearshore eelgrass and kelp beds, large estuaries (such as the Puget Sound), coastal embayments, and open ocean basins (such as the Aleutian Basin of Bering Sea) [30, 37].

Substrate—Sand, gravel, mud, silt, and bedrock [20, 37].

Physical/chemical—Temperature: -*1.8*–12 °C; rare in waters less than 0 °C [6, 30, 39, 40]. Salinity: Marine [20]. *Found at 31.3–33.5 ppt in U.S. Chukchi Sea* [6].



Behavior

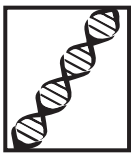
Diel—They make limited day-night vertical migrations, moving into shallow waters at dusk and night, then deeper during day [25, 41, 42]. Juveniles aggregate near sea floor during day then disperse and move shallower at night [30, 35, 43]. Juveniles often associated with tentacles of medusae during day [43, 44]. Some adults migrate into near-surface waters at night [42].

Seasonal—Young-of-the-year recruit to nearshore waters from early summer through autumn [34, 35]. Make seasonal inshore-offshore migrations, overwintering in deep part of their depth range [45]. Strong year classes have been linked to warm water years when juveniles are transported offshore and away from cannibalistic adults [46].

Reproductive—Spawning occurs in a number of discrete locations in Strait of Georgia, Gulf of Alaska, Bering Sea, and in western Pacific Ocean off Asia [30]. Fish may return to their natal sites to spawn. Females are batch spawners [27, 47], spawning at least 14 times in a season [20]. Spawning of an individual female probably takes less than 1 month [18].

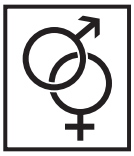
Schooling—Forms large schools [34–36].

Feeding—Juveniles and adults are mainly nocturnal feeders [48] whereas most feeding of larvae occurs during the day [25].



Populations or Stocks

There is evidence for semi-discrete populations in the Gulf of Alaska and Bering Sea, although the degree of genetic isolation of these stocks is unclear. As many as 12 stocks in waters between Japan and southeastern Alaska have been postulated [30, 38, 49, 50].



Reproduction

Mode—Oviparous [20].

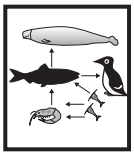
Spawning season—Over all their range, some spawning may occur throughout the year [51]. However, most spawning takes place in winter and spring, varying somewhat with location. For instance, in Gulf of Alaska, fish spawn around Shumagin Island, Alaska from about 15 February to 1 March, 15 March to 1 April in Shelikov Strait [38] and mostly April to Mid-May in southeastern Bering Sea [30].

Fecundity—58,000–1,400,000 non-adhesive eggs per season, in batches [27, 47, 52].

Food and Feeding

Food items—Larvae: Copepod naupli, larval copepods and small euphausiids [29]. Juveniles: Mainly euphausiids [48] as well as copepods and other planktonic crustaceans [29]. Adults: A wide array of midwater and benthic organisms. Smaller pollock feed primarily on zooplankton (for example, euphausiids, copepods, and gammarid amphipods). Among larger fish, copepods and euphausiids are often very important, as are a number of fish species (for example, capelin, eulachon, and lanternfishes) and shrimps. Other frequently eaten organisms include mysids, crabs, polychaetes, and cephalopods and crustacean larvae [53–56].

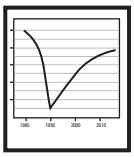
Trophic level—3.7 [57]



Biological Interactions

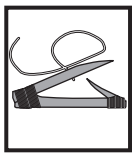
Predators—Walleye Pollock are extremely important prey for many fishes, seabirds, and mammals. A literature search discloses that at least 42 species of fishes, 18 species of seabirds, 7 species of pinnipeds, 9 species of cetaceans, and river otters prey on pollock. In Gulf of Alaska, pollock are very important prey to Arrowtooth Flounder, Pacific Cod, Pacific Halibut, and Steller sea lion [38]. In some years, juvenile pollock are a major part of the diet of older pollock [30].

Competitors—Walleye Pollock, an ecologically generalist species, compete with a very wide range of other fish species [30].



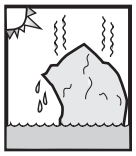
Resilience

Low, minimum population doubling time: 4.5–14 years [58].

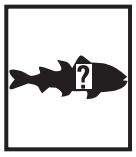


Traditional and Cultural Importance
None in study area.

Commercial Fisheries
In the United States, Walleye Pollock are not commercially harvested north of the Bering Sea. Walleye Pollock was a major food fish in southeastern Alaska and the Gulf of Alaska [59]. Commercial catches by foreign fleets began in the early 1950s and increased substantially with the advent of at-sea processing of fish for surimi. Currently, the average Alaskan harvest of pollock is 1.1 million metric tons with processed catches destined for U.S. and export markets [30, 38, 60].



Potential Effects of Climate Change
It is hypothesized that this species will become more abundant in the U.S. Chukchi and Beaufort Seas marine ecosystem changes resulting from climate change. Increased abundance will result in changes in food web dynamics such as competition with other gadid species, especially in the Chukchi Sea if benthic-pelagic energy flows become decoupled. New experimental results indicate that Walleye Pollock and Pacific Cod grow at 2–3 times the rate of other Arctic gadids when exposed to increasing temperature regimes in the laboratory that are similar to field conditions in summer in the coastal Chukchi and Beaufort Seas. This suggests a potential competitive advantage for Walleye Pollock under warming conditions [61].



Areas for Future Research [A]
Field identifications of young pollock may be confused with other gadid species, especially Arctic Cod. A rapid diagnostic (genetic) identification tool is needed for field applications as these cods may occur in mixed assemblages. Pollock are not well adapted to cold-water environments and, as temperatures warm, monitoring programs should be sufficient to detect abrupt changes in abundance. Predator-prey relationships should be established to investigate competition with other gadid species. Important spawning and overwintering habitats require delineation. Improved information about the species physiological tolerances and growth rate in Arctic waters is needed to evaluate potential climate change effects.

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Pacific Cod (*Gadus macrocephalus*)

Tilesius, 1810

Family Gadidae

Pacific Cod (*Gadus macrocephalus*) 597 mm, western Gulf of Alaska, 2005. Photograph by C.W. Mecklenburg, Point Stephens Research.

Note on taxonomy: *Based on analyses of both morphology and mtDNA, the Greenland Cod, Gadus ogac (Richardson, 1836), is a subspecies of* G. macrocephalus [1, 2].

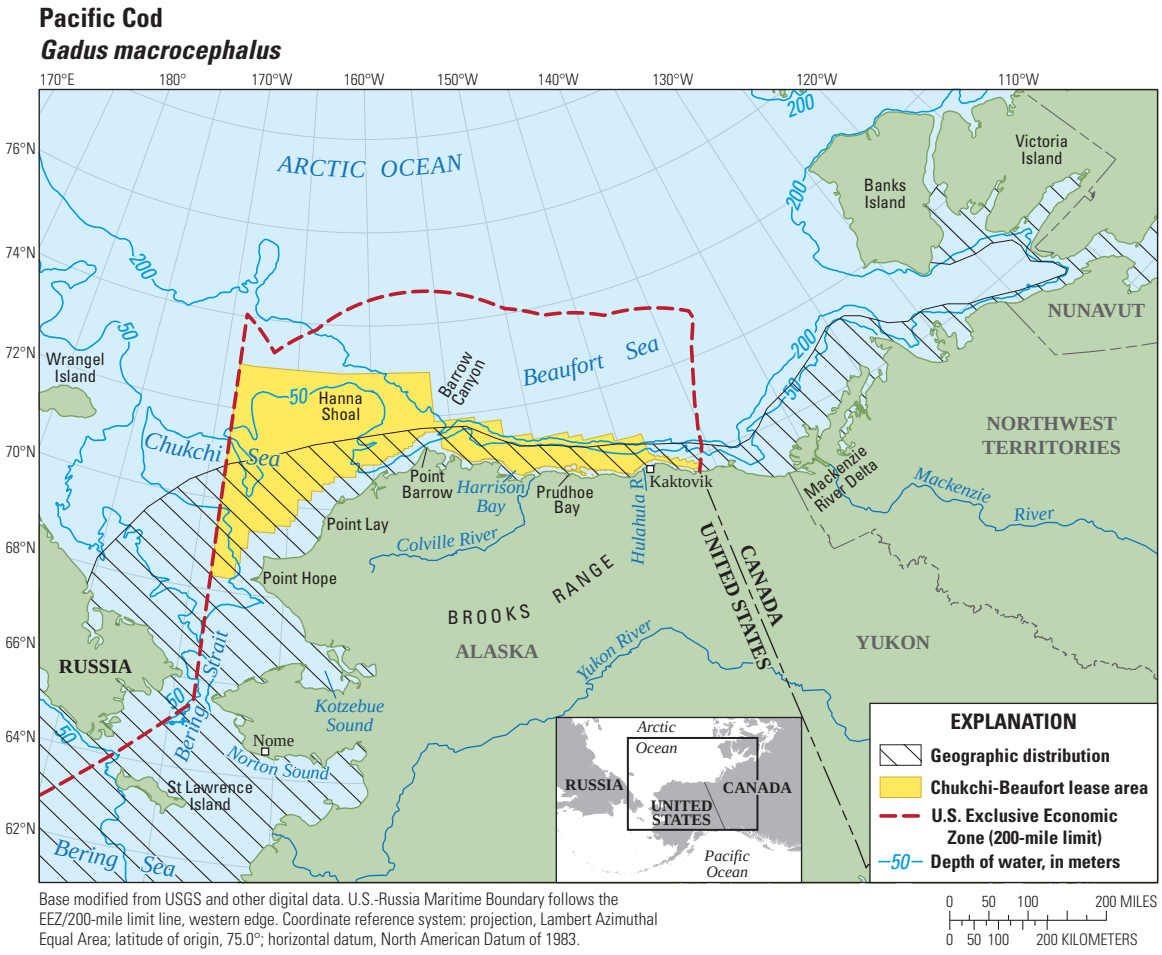
Colloquial Name: *None within U.S. Chukchi and Beaufort Seas.*

Ecological Role: Of little known ecological importance in U.S. Chukchi and Beaufort Seas. Maybe of small seasonal importance in food webs in the Bering Strait and southeastern Chukchi Sea.

Physical Description/Attributes: Robust body, large head. Light gray-brown with brown to bright golden yellow spots on back and sides to olive-blackish with no distinct spots [3, 4]. For specific diagnostic characteristics see *Fishes of Alaska* (Mecklenburg and others, 2002, p. 296) [3]. Swim bladder: Present [3]. Antifreeze glycoproteins in blood serum: Unknown.

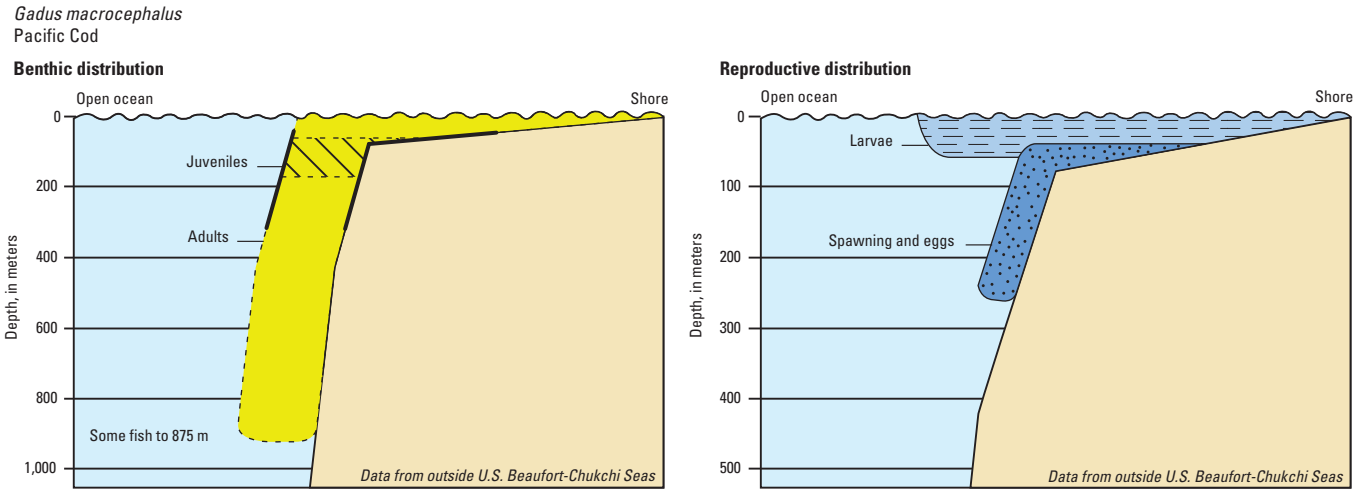
Range: *U.S. Chukchi and Beaufort Seas* [1, 3]. Elsewhere in Alaska, throughout Bering Sea, Aleutian Islands and Gulf of Alaska. Worldwide, in Pacific Ocean south to southern California and to Yellow Sea off Manchuria, China; east across Canada to west Greenland and south to Gulf of St. Lawrence. Isolated population in White Sea [1, 3].

Relative Abundance: *Uncommon in U.S. Chukchi and Beaufort Seas* [1, 3]. Uncommon in northern Bering Sea [1]. Abundant throughout Bering Sea northward to Norton Sound and Gulf of Anadyr [1, 6, 7], and southward to Seas of Japan and Okhotsk [8, 9] and Washington [10].



Geographic distribution of Pacific Cod (*Gadus macrocephalus*) within Arctic Outer Continental Shelf Planning Areas [5] based on review of published literature and specimens from historical and recent collections [1, 3, 4].

Depth Range: In water column, near surface to near bottom depth of 875 m [3], typically 50–300 m; sometimes in surf zone [11–13]. Spawning takes place at 40–265 m [14]. Fertilized eggs are benthic on continental shelf [10]. Newly hatched larvae are primarily in upper 45 m of water column (highest abundances at 15–30 m) [14], moving downward as they grow [15]. Juveniles are mainly at 60–150 m in Gulf of Alaska and eastern Bering Sea [15].



Benthic and reproductive distribution of Pacific Cod (*Gadus macrocephalus*).

Habitats and Life History

Eggs—Size: 1.0–1.2 mm [16, 17]. Time to hatching: 8.5–28 days at 11–4.5 °C. Hatching is most successful at lower temperatures [16, 18]. Habitat: Benthic [10, 16].

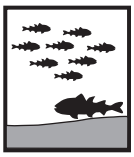
Larvae—Size at hatching: 3.0–4.0 mm [16, 17]. Size at juvenile transformation: 2.5–3.5 cm FL [14, 19]. Days to juvenile transformation: Unknown. Yolk sac is absorbed in 10 days [14]. Habitat: Pelagic and neritic [17].

Juveniles—Age and size: 2.5 cm FL to 38–81 cm TL [13, 14, 19]. Habitat: Shallow nearshore waters at [14, 17, 20], initially associated with algae and eelgrass but later in their first year some fish migrate into deeper water and over a wide range of habitats including plants, soft substrates, and mounds formed by sea cucumbers [10, 18, 21–23].

Adults—Age and size at first maturity: In eastern Bering Sea, 50 percent of females were mature at 58.0 cm TL and 4.9 years, whereas 50 percent of those in the Gulf of Alaska were mature at 50.3 cm TL and 4.4 years. A few females were mature at as small as 38 cm TL and a few were immature until about 81 cm TL [13]. Length at maturity is highly dependent on environmental factors and varies widely between areas and years. For example, off British Columbia. Canada, length at 50 percent maturity differed by almost 10 cm between samples taken in the mid-1970s and mid-1980s [24]. In Gulf of Alaska and eastern Sea of Okhotsk, females grow larger than males, although both sexes reach about the same maximum length in the eastern Bering Sea [13]. In Gulf of Alaska (although not in the eastern Bering Sea), male and female growth rates differ. Apparently, cod living in Alaskan waters grow more slowly but reach a larger size and live longer than those living off British Columbia and Washington [14]. Maximum age: 17 years [25], but rarely beyond 14 years [13]. Maximum size: 120 cm TL [3]. Habitat: Pelagic, both near the bottom and in the midwaters [14] over soft sea floors [10, 17, 22, 23].

Substrate—Cobble and rocky bottoms [10, 22, 23]. Coarse sand and cobble for spawning and eggs [14].

Physical/chemical—Temperature: -1.7–18 °C, mainly 0–10 °C [21, 26, 27]. Salinity: Eggs are in polyhaline to euhaline waters. Marine and estuarine [14].



Behavior

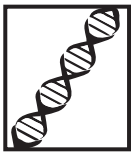
Diel—Pelagic juveniles have been found in surface waters in association with medusae [28].

Seasonal—Make annual inshore and offshore movements linked to spawning and feeding. The timing and extent of annual migrations vary with location. Annual migrations in eastern Bering Sea, eastern Aleutian Islands, and Gulf of Alaska, occur when fish attempt to avoid temperature extremes that accompany the seasonal changes [29]. Fish move offshore during winter, as nearshore waters get very cold, and move inshore during summer [30]. Farther south on both sides of the Pacific Ocean (for example, Puget Sound, Korea, and Japan), migrations to deeper waters occur during summer months to avoid excessively heated coastal waters and return inshore for the winter [10]. Some fish move fairly long distances. Pacific Cod in the eastern Bering Sea, for instance, summer on the eastern Bering Sea shelf, then move southward and deeper to the Bering Sea in the vicinity of Unimak Pass and Unalaska Island, Alaska, and in the nearby Gulf of Alaska to spawn [14].

Reproductive—Single batch spawners, releasing all eggs in a few minutes [14]. Spawning depth depends on its depth-temperature profile. For instance, off Washington and southwest Vancouver Island, British Columbia, Pacific Cod spawn in more shallow waters than those in northern British Columbia [10].

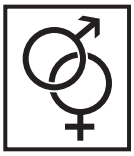
Schooling—Forms schools [14].

Feeding—Juveniles and adults are carnivorous and feed at night [14]. Feeding increases during the summer and decreases in winter [31].



Populations or Stocks

Fish in Puget Sound and the Strait of Georgia may form several semi-isolated populations from fish on the outer coast [14, 32]. Based on analyses of morphology and mtDNA, Pacific Cod are most closely related to Ogac (*Gadus ogac*) and are now considered by taxonomists to be the same species [1, 2, 33].



Reproduction

Mode—Oviparous, external fertilization [14].

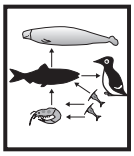
Spawning season—Can occur between January and July, although peak spawning takes place in spring in Alaska [13, 34].

Fecundity—225,000 –6,400,000 semi-adhesive eggs [14, 35]. The number of eggs produced per body length decreases with higher latitude [21].

Food and Feeding

Food items—Very wide range of benthic and water column organisms. Cod less than about 20 cm FL feed primarily on a wide range of crustaceans, such as copepods, gammarid and caprellid amphipods, mysids, and euphausiids, and some small fishes [36–39]. Larger fish add large numbers of fishes to their diets as well as shrimps, crabs, hermit crabs, polychaetes, snails, clams, squids, and octopuses [38, 40–42]. As Pacific Cod grow, they feed more heavily on fishes and less on invertebrates [43–44].

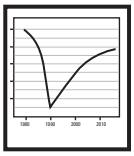
Trophic level—4.1 [45].



Biological Interactions

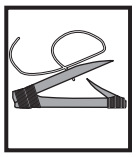
Predators—A large number of fishes, sea birds, and marine mammals. Major fish predators include Arrowtooth Flounder, Flathead Sole, Pacific Cod, Pacific Halibut, Sablefish, Spotted Spiny Dogfish, Walleye Pollock, and Yellowfin Sole [40, 46–48]. Seabirds include Common Murres, Horned and Tufted Puffins [49, 50]. Marine mammals include beluga, fin, minke, and sperm whales and orcas; bearded, harbor, northern fur, and ribbon seals; and Stellar sea lions [51–55].

Competitors—Other gadids, along with flatfishes, sculpins, poachers, and eelpouts.



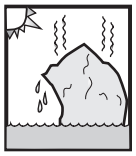
Resilience

Low, minimum population doubling time: 4.5–14 years [56].

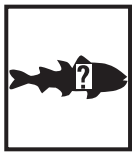


Traditional and Cultural Importance
None reported.

Commercial Fisheries
Currently, Pacific Cod are not commercially harvested.



Potential Effects of Climate Change
It might be expected that Pacific Cod abundance will increase in Arctic waters if fish from the Bering Sea move northward. The probability of this species' colonization of Arctic marine environments may be lower than for other gadid species because of its apparent fidelity to spawning locations in the Bering Sea. However, new experimental results indicate that Pacific Cod and Walleye Pollock grow at 2–3 times the rate of other Arctic gadids when exposed to increasing temperature regimes in laboratory that are similar to field conditions in summer in the coastal Chukchi and Beaufort Seas [57]. This suggests a potential competitive advantage for Pacific Cod under warming conditions.



Areas for Future Research [A]
Little is known about the ecology of this species in the study area. Whether Pacific Cod spawn in the Chukchi or Beaufort Seas is of major interest. Researchers believe that the cod display high fidelity to spawning areas in the Bering Sea and thus improved information about their migratory behavior is needed.

Remarks

This species has long been known to be present in the Beaufort Sea (see [Walters, 1955], between Point Barrow and Smith Bay) [58], under the name, *Gadus ogac* [3], and is common just over the U.S-Canadian border in Canadian waters.

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