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Growth dynamics of saffron cod (*Eleginus gracilis*) and Arctic cod (*Boreogadus saida*) in the Northern Bering and Chukchi Seas

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ABSTRACT

Saffron cod (*Eleginus gracilis*) and Arctic cod (*Boreogadus saida*) are two circumpolar gadids that serve as critically important species responsible for energy transfer in Arctic food webs of the northern Bering and Chukchi Seas. To understand the potential effects of sea ice loss and warming temperatures on these species' basic life history, information such as growth is needed. Yet to date, limited effort has been dedicated to the study of their growth dynamics. Based on a large sample of otoliths collected in the first comprehensive ecosystem integrated survey in the northern Bering and Chukchi Seas, procedures were developed to reliably estimate age from otolith growth zones and were used to study the growth dynamics of saffron and Arctic cod. Annual growth zone assignment was validated using oxygen isotope signatures in otoliths and otolith morphology analyzed and compared between species. Saffron cod attained larger asymptotic sizes (L_∞=363 mm) and achieved their maximum size at a faster rate (K=0.378) than Arctic cod (L_∞=209 mm; K=0.312). For both species, regional differences in growth were found ($p<0.01$). Saffron cod grew to a significantly larger size at age in the northern Bering Sea when compared to the Chukchi Sea, particularly at younger ages. Arctic cod grew to smaller asymptotic size but at faster rates in the more northerly central (L_∞=197 mm; K=0.324) and southern Chukchi Sea (L_∞=221 mm; K=0.297) when compared to the northern Bering Sea (L_∞=266 mm; K=0.171), suggesting a possible cline in growth rates with more northerly latitudes. Comparison of growth to two periods separated by 30 years indicate that both species exhibited a decline in maximum size accompanied by higher instantaneous growth rates in more recent years.

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1. Introduction

Arctic (*Boreogadus saida*) and saffron cod (*Eleginus gracilis*), two federally managed species in the U.S. zones of the northern Bering, Chukchi, and Beaufort Seas, are considered to be the most abundant fish species in the sub-polar and polar regions (NPFMC, 2009). Both species are essential components of polar food webs and act to transfer energy from plankton to upper trophic levels (Craig et al., 1982; Whitehouse, 2011). While the distribution of these species overlap to some extent, saffron cod are more demersal with a more southerly, nearshore distribution, whereas Arctic cod are more pelagic and are often associated with offshore sea ice with a more northerly residence (Barber et al., 2008). Saffron cod are reported to be a resident species in nearshore areas of the Chukchi and are linked to low salinity conditions (Wong et al., 2013). Nearshore populations of saffron cod have been found as far south as the Gulf of Alaska (Laurel et al., 2007). Arctic cod, in contrast, are principally centered north of the Bering Strait but reportedly extend farther south into the northeast and southeast Bering Sea during years of extended cool pool from more extensive ice (Lauth, 2011). While the exact factors that are responsible for partitioning these species' niches is uncertain, temperature and ice cover probably play a major role. Laurel et al. (2015) demonstrated that juvenile Arctic cod show a cold-water, stenothermic growth response compared to the warmer water, eurythermic growth response of saffron cod under laboratory conditions. Hence, under changing environmental conditions in the Arctic, the physiological response of these species to environmental variability is likely to exert some influence on their distribution, competition for food resource, growth, and survival.

Our ability to manage the living marine resources will be predicated on understanding potential biological responses to environmental variability and in predicting the effects of climate change on individual species, ecosystem processes, and community structure. At the individual species level, growth is a fundamental

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life history process that is often linked to environmental conditions such as temperature (Jobling, 1981). Understanding population dynamics, bioenergetics, and energy flow through the Chukchi and northern Bering Sea ecosystems will require baseline estimates of growth and its intrinsic spatial variability, which for both species is not well documented in the scientific literature. For instance, phenotypic plasticity in growth of North Atlantic cod (*Gadus morhua*) has been reported on relatively small spatial scales (Olsen et al., 2005), with high-latitude populations growing faster at colder temperatures than populations of the same species at lower latitudes (Hutchings et al., 2007). Furthermore, evidence is emerging that the oceanography of the northern Bering and Chukchi Sea is quite complex with high inter-annual and spatial variability in processes such as temperature, stratification, and ice cover (Danielson et al., this issue). These processes are likely important for structuring different growth phenotypes through mediating metabolism (Purchase and Brown, 2001). Extreme environmental variability in the Arctic may play a similar role in structuring phenotypic growth variability in Arctic cod, in particular, yet limited data have been collected in a comprehensive spatiotemporal way in order to evaluate the extent of growth variation.

The National Marine Fisheries Service, the agency responsible for managing U.S. marine living resources in the Arctic (NPFMC, 2009), has historically conducted periodic but spatially limited assessments of benthic fishes using bottom trawls (Sample and Wolotira, 1985). However, not until 2012 was a fully integrated ecosystem assessment incorporating oceanographic and biological sampling across the entire trophic structure conducted. The 2012 Arctic Ecosystem Integrated Survey (Arctic Eis) was conducted in partnership between the University of Alaska, Fairbanks (UAF), National Marine Fisheries Service (NMFS) and the Bureau of Ocean and Energy Management (BOEM). Biological data including length, weight, and age structures (otoliths) for Arctic cod and saffron cod were collected across a systematic sampling design over an extensive area from the northern Bering Sea, Bering Strait, and Chukchi Sea. As an essential component of the overall Arctic Eis research goals, we analyzed the growth dynamics of Arctic cod and saffron cod collected during the 2012 survey operations. Specifically our objectives were to 1) develop an age determination procedure for estimating the age of fish from otoliths, 2) characterize the growth dynamics both in terms of population age compositions and estimating growth curves, and 3) examine spatial variation in growth among regions of the Chukchi and Northern Bering Seas. While the biological data and otoliths collected during the 2012 Eis survey were the focus of this study, otoliths (and length data) collected during previous 1976–1979 baseline NMFS surveys were analyzed to provide a comparison of growth separated by 30 years. Different methods of sample preparation were explored to establish the best age determination procedures, including quality control practices (Kimura and Anderl, 2005) to estimate statistical measures of precision. Furthermore, the annual growth increment periodicity was evaluated for saffron cod using otolith stable oxygen isotope (^{18}O) signatures as a proxy for seasonal water temperature cycles (Helser et al., 2014). Growth curves using the von Bertalanffy (von Bertalanffy, 1938) function were fit to length-at-age data for both species and by regions to explore spatial differences in growth. Because of the paucity of literature on saffron and Arctic cod otolith ageing, otolith growth was estimated using otolith morphometric measurements, including otolith weights, to characterize relative differences in otolith morphometry and growth between the species

2. Methods

2.1. Sample collection

Otoliths collected for this analysis were sampled as part of the Arctic Eis conducted during the summer and fall of 2012 in the northern Bering and Chukchi Seas. This was the first comprehensive marine resource survey focused on a fully integrated ecosystem data collection program including oceanographic and biological data. Here we provide a brief description of the execution of field sampling as it relates to growth dynamics of Arctic and saffron cod, but greater details can be found in Goddard et al. (2014) and Murphy et al. (2003). During the 2012 Arctic Eis survey, biological data for Arctic and saffron cod were collected at sampling stations occupied by two research-purposed industry-chartered vessels spanning 17.5° of latitude (63–72.5°N latitude). Each vessel followed roughly the same standard grid survey sampling framework with sampling stations every 30 miles along E–W transects. The 180 foot FV *Bristol Explorer*, which used surface trawls to target the pelagic fish community, sampled 61 stations over the entire grid from August 1 to September 31. Near-surface hauls were made using a 400/601 Cantrawl[1] with a typical trawl 198 m long with a horizontal and vertical spread of 50 m and 25 m, respectively. Lengths (mm) and weights (g) of Arctic cod and saffron cod were recorded and otoliths extracted at sea or whole fish frozen for later processing in the laboratory. Sex of these fish was not recorded. The 160 foot FV *Alaska Knight* employed 83-112 Eastern bottom trawl to sample the benthic fish community only in the Chukchi Sea, from just north of the Bering Strait (63.1°N latitude) to Barrow Canyon (72°N latitude) covering 71 stations from August 9 to September 24. Hauls were conducted over bottom for 15 min at a speed of approximately 3 knots maintained at a constant heading. When possible the tow was conducted near the center of a $55.6 \times 55.6\ \text{km}^2$ grid cell. As in the surface trawls, catches were sorted by species and subsampled to estimate the total catch in weight and numbers. For both the surface and bottom trawl fish a two-stage random sampling strategy was used to obtain biological data. In the first stage, a simple random sample of length (fork, mm) was taken from the subsampled catch in number. A subsample of otoliths for ageing was then taken from the second stage with a target number or approximately 5 otoliths per 1 cm length class. Fork length was measured to the nearest millimeter and weight to the nearest gram. Sex for both Arctic cod and saffron cod was identified from bottom trawl catches.

Age data for the 1976 and 1979 NMFS baseline survey in the Chukchi and northern Bering Seas were collected during bottom trawling operations on the NOAA ship *Miller Freeman*. Stations during the 1976 survey were sampled in the southeastern Chukchi Sea from the Bering Strait north to Point Hope (68.3°N latitude) and in the northern Bering Sea and Norton Sound from St. Mathews Island (63.1°N latitude) north to the Bering Strait. The 1979 NMFS survey did not conduct trawling operations in the Chukchi Sea, and for the purposes of a retrospective comparison in this study stations sampled in the Northern Bering Sea south of the Bering Strait (including Norton Sound) were combined with the 1976 data and analyzed together. Both the 1976 and 1979 NMFS surveys used 30-min bottom trawls with a similar 83-112 Eastern net construction as the 2012 Eis bottom trawl survey. A total of 249 and 186 standard bottom trawl stations (in the regular grid) were sampled during the 1976 and 1979 NMFS surveys, respectively. More detail of these baseline surveys can be found in Wolotira et al. (1977) and Sample and Wolotira (1985).

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.