Arctic cod (*Boreogadus saida*)*

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Biology

Arctic cod (*Boreogadus saida*) is a highly abundant, trophically important pelagic fish species inhabiting Arctic and sub-Arctic marine ecosystems. In the North American Arctic, surveys have indicated large abundances of Arctic cod in the Beaufort Sea, Chukchi Sea, and Canadian Arctic archipelago, although under cooler environmental conditions they can also be found further south in the Bering Strait and northern Bering Sea (Hop and Gjøsæter, 2013; Helser et al., 2017). This species is most frequently found at depths less than 300 m, but has been found as deep as 930 m (Crawford et al. 2012).

Arctic cod is a cold-water, stenothermic species that utilizes habitat under sea ice differentially throughout its life cycle for reproduction, protection, and sustenance (Drost et al., 2016; Laurel et al., 2016). Rapidly warming conditions and the subsequent loss of these ice-associated niches, along with other corresponding physical, chemical, and biological changes in the region, pose a great threat to this species' ability to thrive (Drost et al., 2016).

Arctic cod are relatively fast-growing and short-lived, reaching maximum ages of 7-8 years, but individuals ≥4 years are rarely encountered (Fig.

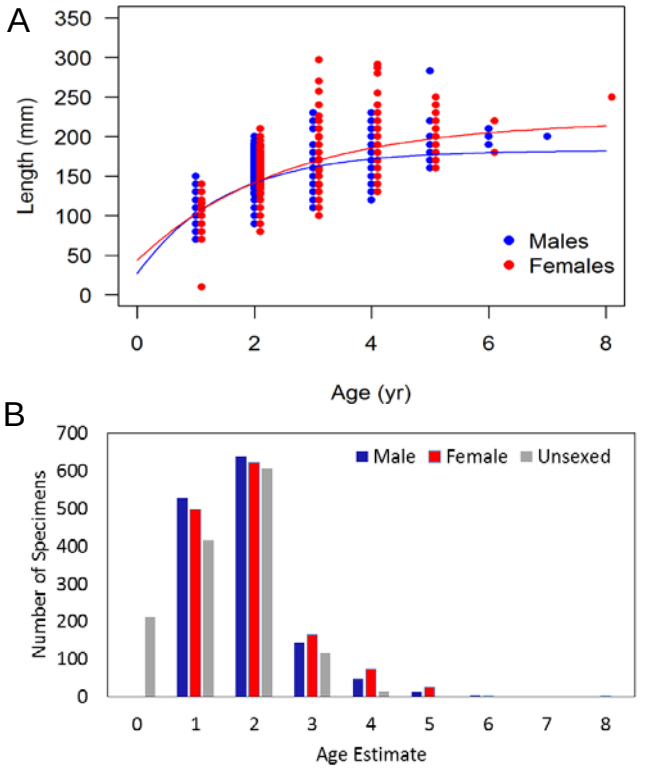

Figure 1
A) Length-at-age data fit with von Bertalanffy growth functions for male and female Arctic cod collected from trawl surveys in the Arctic, Beaufort Sea, Chukchi Sea, and Bering Sea from 1976-2017. B) Number of male, female, and unsexed specimens displayed for each age estimate produced from specimens Arctic cod collected during trawl surveys in the Arctic, Beaufort Sea, Chukchi Sea, and Bering Sea from 1976-2017 (n = 4135).

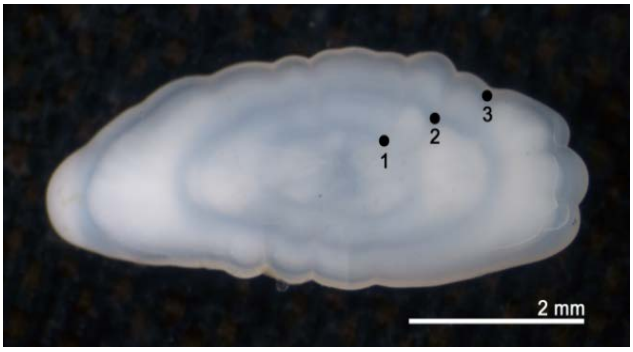

Figure 2
Arctic cod otolith with a clear proximal surface. Collected from a 150 mm fish in the Beaufort Sea on 7 August 2008. Viewed with reflected light.

1) (Hop and Gjøsæter, 2013; Helser et al., 2017). Males of this species mature at a younger age than females (2 and 3 years, respectively), and spawning takes place in the late fall and early winter under the ice cover of arctic shelves (Bouchard and Fortier, 2011; Hop and Gjøsæter, 2013). Fertilized eggs rise to the ice-water interface and hatch after an incubation time ranging from 45 to 90 days.

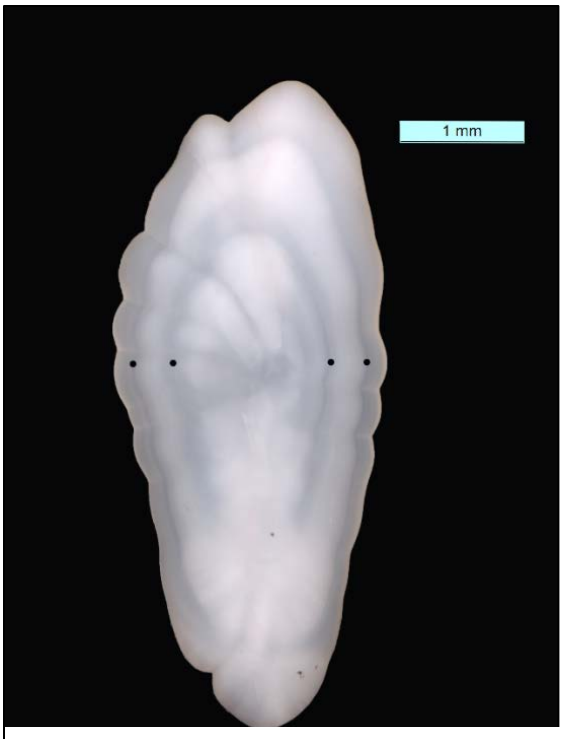

Figure 3
Clear Arctic cod otolith surface pattern. Collected in August 2013 from a 130 mm female. Age estimate is 2 years. Viewed with reflected light.

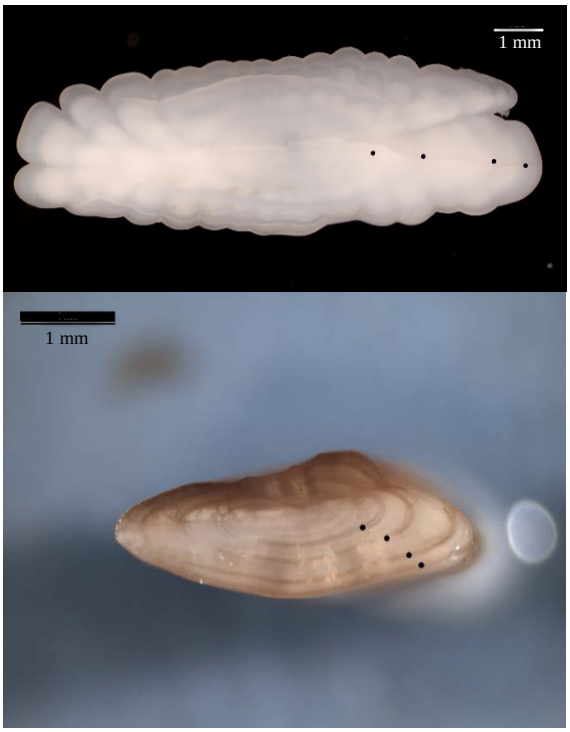

Figure 4
Clear Arctic cod otolith surface and burn pattern. Collected in August 2017 from a 287 mm female in the Bering Sea. Age estimate is 4 years. Viewed with reflected light.

This species is an abundant predator of zooplankton and epibenthic fauna (Buckley & Whitehouse, 2017; Moulton & Tarbox, 1987) and is remarkably efficient at assimilating and channeling energy flow to higher trophic levels (Hop and Gjøsæter, 2013). This efficient transformation of energy into growth, paired with its ubiquity in Arctic and sub-Arctic ecosystems, have established Arctic cod as a very important prey species for a variety of marine mammals, birds, and other fish (Buckley & Whitehouse, 2017; Craig et al., 1982).

Arctic cod is federally managed in U.S. zones and is not currently targeted in any commercial fisheries; however, preliminary assessments by the North Pacific Fishery Management Council (NPFMC) have identified an Arctic cod fishery as one that could be commercially viable, pending the collection of "data sufficient for effective management and impact analysis," (Helser et al. 2017; NPFMC, 2009). To that end, and in light of a rapidly changing ecosystem, it has become

increasingly important to continue monitoring and collecting data on this species.

Current age determination methods

Being that Arctic cod is a relatively short-lived species, and that its otoliths often exhibit a clear surface pattern, surface examination is typically the most efficient method of age determination. Immersing otoliths in water and viewing using a dissecting microscope with reflected light will generally reveal a clear surface pattern and no further processing is necessary (Figs. 2, 3).

Occasionally, the surface pattern of an Arctic cod otolith is not clear enough for surface examination alone to be sufficient (Figs. 4, 5). If this is the case, age readers then implement the break-and-burn or break-and-bake method to enhance the banding pattern (Matta and Kimura, 2012); which of the two is used is left to the age reader's discretion. Of the two aforementioned methods, break-and-burn is generally faster, but great care must be taken not to over-burn the otolith as this will result in reduced visibility of the annual marks and may cause portions of the reading surface to fracture.

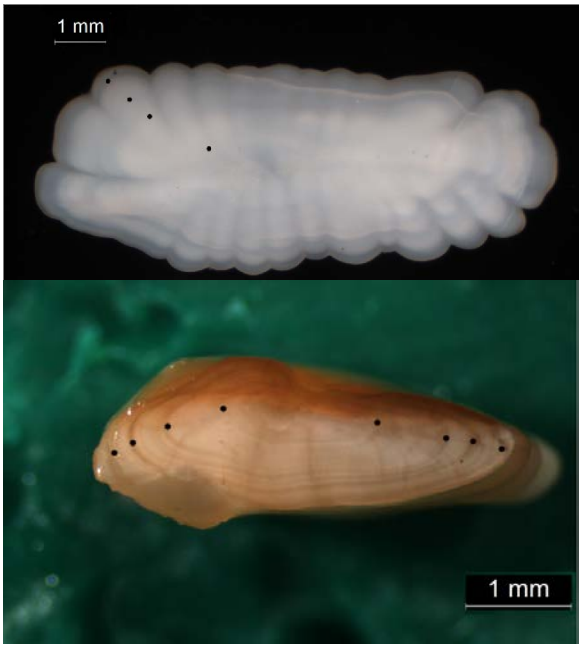

Figure 5
Vague Arctic cod otolith surface and burn pattern. Collected in August 2017 from a 283 mm male in the Bering Sea. Age estimate is 4 years. Viewed with reflected light.

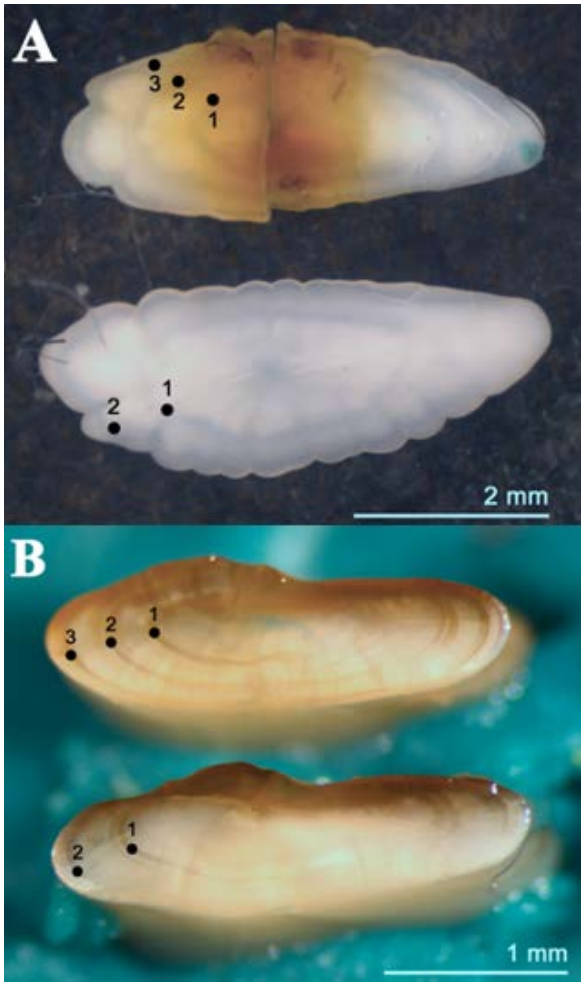

Figure 6
Otoliths from two 160 mm Arctic cod with first annual marks that differ in size. A) Proximal surface views, and B) break-and-burn views. Upper specimen has a small first annual mark and an age estimate of 3 years. (Surface of upper specimen has undergone break-and-burn treatment). Lower Specimen has a large first annual mark and an age estimate of 2 years. Both specimens captured in the Beaufort Sea in August 2008. Viewed with reflected light.

Age determination problems

Preliminary ageing of Arctic cod otoliths has revealed a great deal of ambiguity associated with the placement of the first annual mark. Difficulty in establishing a consistent, objective criterion stems from the fact that the size of the first strong mark is highly variable (Fig. 6). Frequently, in specimens where the first clear annual mark is larger, it is common to also observe a smaller, vague mark between it and the core. In other specimens, these smaller marks may be as strong

as the larger annual marks or they may be absent altogether. To that end, it is unclear whether or not these small marks should be counted as annual marks when they are weak or moderate, or potentially even added when absent. Currently, these first year observations can be placed into one of three categories: 1) a weak or moderate small mark observed near the core, 2) a strong small mark observed near the core, or 3) a strong large mark with no small marks observed near the core (Figs. 7, 8).

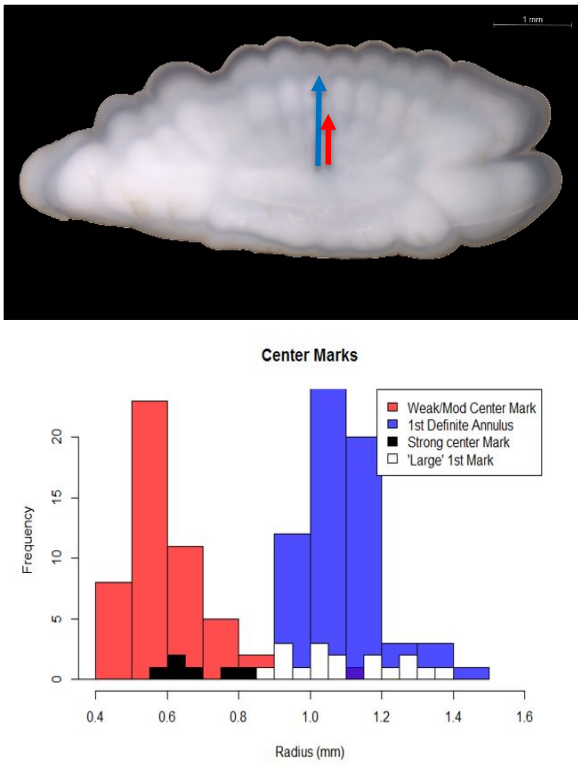

Figure 7
Radius measurements of 84 Arctic cod specimens comparing the frequency and size of small and large marks as they relate to the three aforementioned categories: 1) a weak or moderate small mark observed near the core, 2) a strong small mark observed near the core, or 3) a strong large mark with no small marks observed near the core.

In order to establish the best possible ageing criteria, the otoliths from 84 Arctic cod specimens were assigned to one of the three aforementioned categories and the radii (mm) of the small (when applicable) and large marks were measured (Figure 7). The vast majority (80-90%) of the specimens had a weak to moderate small mark (~0.5 mm radius) with a strong large mark occurring at slightly more than 1 mm. A small number of otoliths had very strong small marks that occurred at less than 1 mm, including some that were around 0.5 mm, and hence would seem to correspond to the vague small mark observed in Category 1 specimens. In these cases, the second mark was approximately the same radius as in other otoliths, though slightly larger than average (approximately 1.2-1.3 mm). While these measurement comparisons have shown marked consistency in the size of the first and second marks among specimens, they are limited in their ability to determine under what circumstances the small marks near the core represent true annual marks.

To that end, additional information will be necessary to confidently identify the true first annual mark. Stable oxygen isotope analyses (commonly utilized for age validation) will be very helpful in clarifying the placement of the first annual mark—if these marks near the core represent true annual marks then we would expect to see corresponding ^{18}O peaks in the data. Work in this area has been started, but the results from an initial study conducted by Helser et al. (2017) on both saffron and Arctic cod were inconclusive with regard to Arctic cod (Helser et al. 2017). In this study, Helser et al. (2017) found that that ^{18}O peaks do not always correspond precisely to translucent zones on the otoliths, even if the number of ^{18}O peaks matches the number of counted annual marks. Furthermore, while some otoliths had peaks of ^{18}O near the core (<0.5 mm), others did not. Expanding on this initial stable oxygen isotope study (primarily by increasing the sample size) and focusing on getting the highest resolution possible per specimen is a clear next step in addressing these first year concerns.

Provisionally, only strong marks are being counted as valid annual marks by the AFSC Age and Growth Program. All distinct translucent zones with a radius greater than 0.8 mm in the dorsal-ventral axis should be counted as annual marks, and weak or moderate marks near the core should be treated as checks. In circumstances where there is a strong translucent zone occurring

near the core, and the radius is less than 0.8 mm in the dorsal-ventral axis, we flag the specimen with code Y (for first year) in the comments, whether it is counted or not (as the categorization of a 'strong' mark is subjective in nature). This will help to keep track of problematic specimens that can be revisited to aid in the resolution of the first year issue or enable us to revise ages once a decision has been made at a later date.

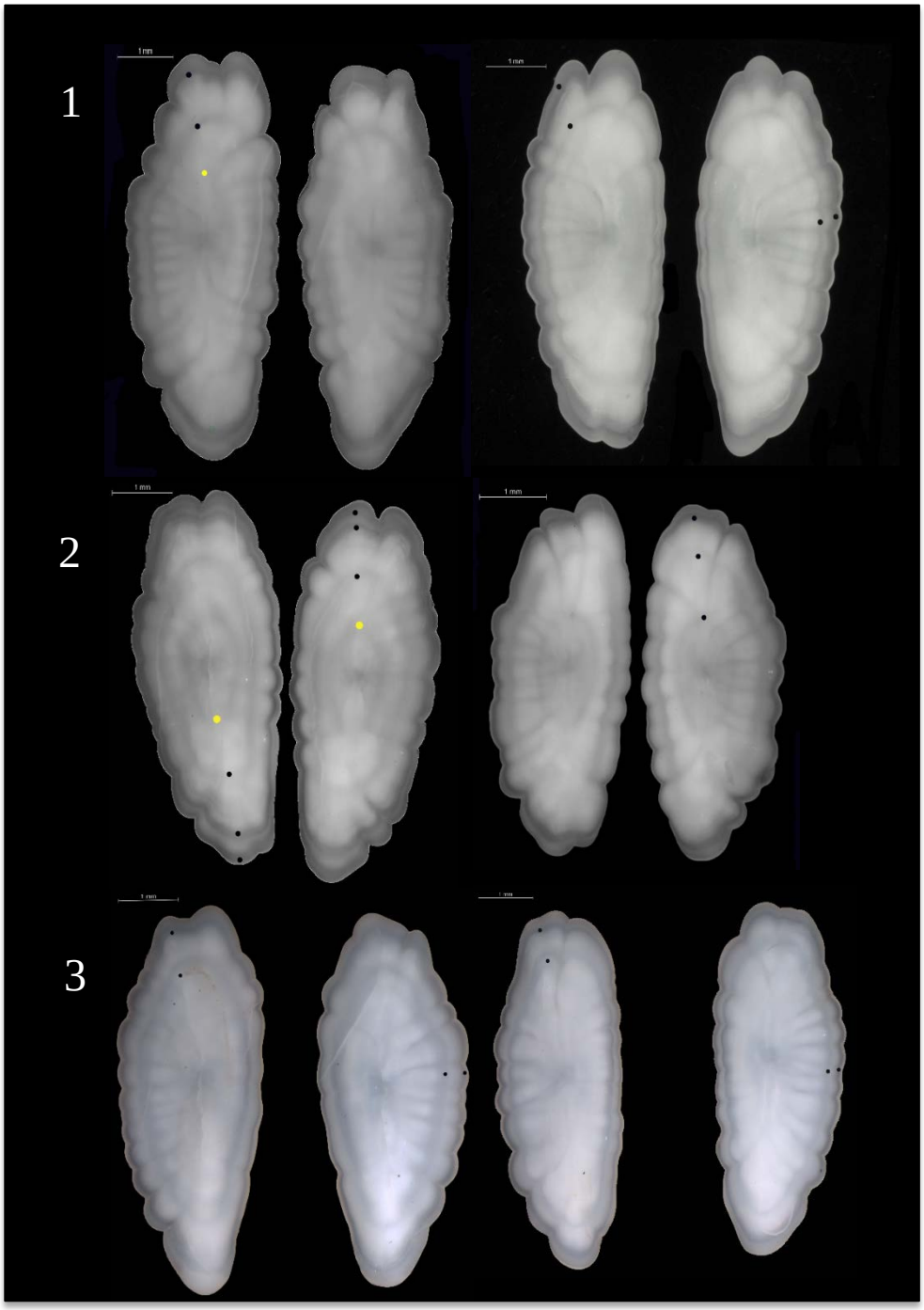

Figure 8

Categorization of first-year problems encountered while ageing Arctic cod: 1) weak or moderate mark near the core, 2) strong mark near the core, and 3) large first annual mark with no observable mark near the core. Images taken using reflected light, white scale bars scaled to display 1 mm for each individual pair of otoiths (n = 6 pairs).

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