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A multidisciplinary approach to understanding the population structure of an exploited Southern Ocean top predator, the Antarctic toothfish, to improve sustainability and marine spatial planning

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Antarctic toothfish, *Dissostichus mawsoni*

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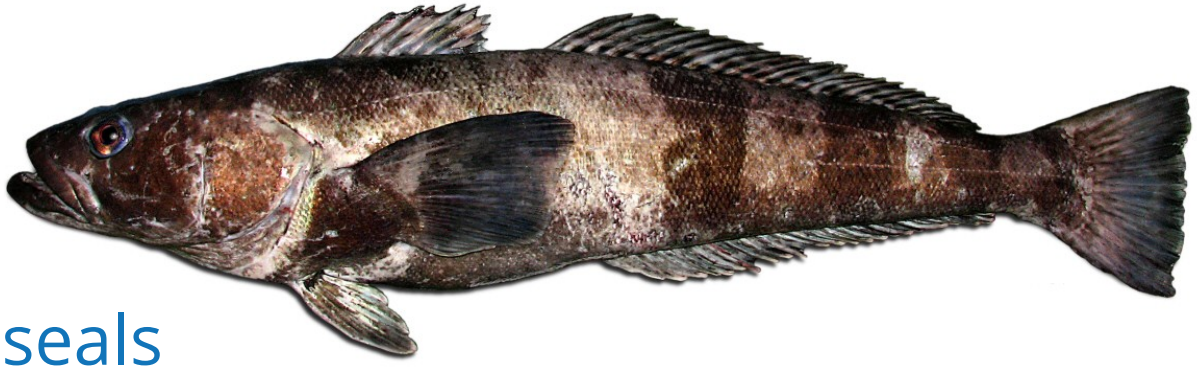
The fish



- Suborder Notothenioidei
- Reaching 1-2 meters in length, the largest of the Antarctic fish
- Important prey species for whales and seals
- Circumpolar distribution, inhabits continental shelf, slope, offshore sea mounts

The fishery

- Marketed with *D. eleginoides* as Chilean Sea Bass
- Most lucrative fishery in the Southern Ocean
- Managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)

Antarctic toothfish fishery
Catch levels

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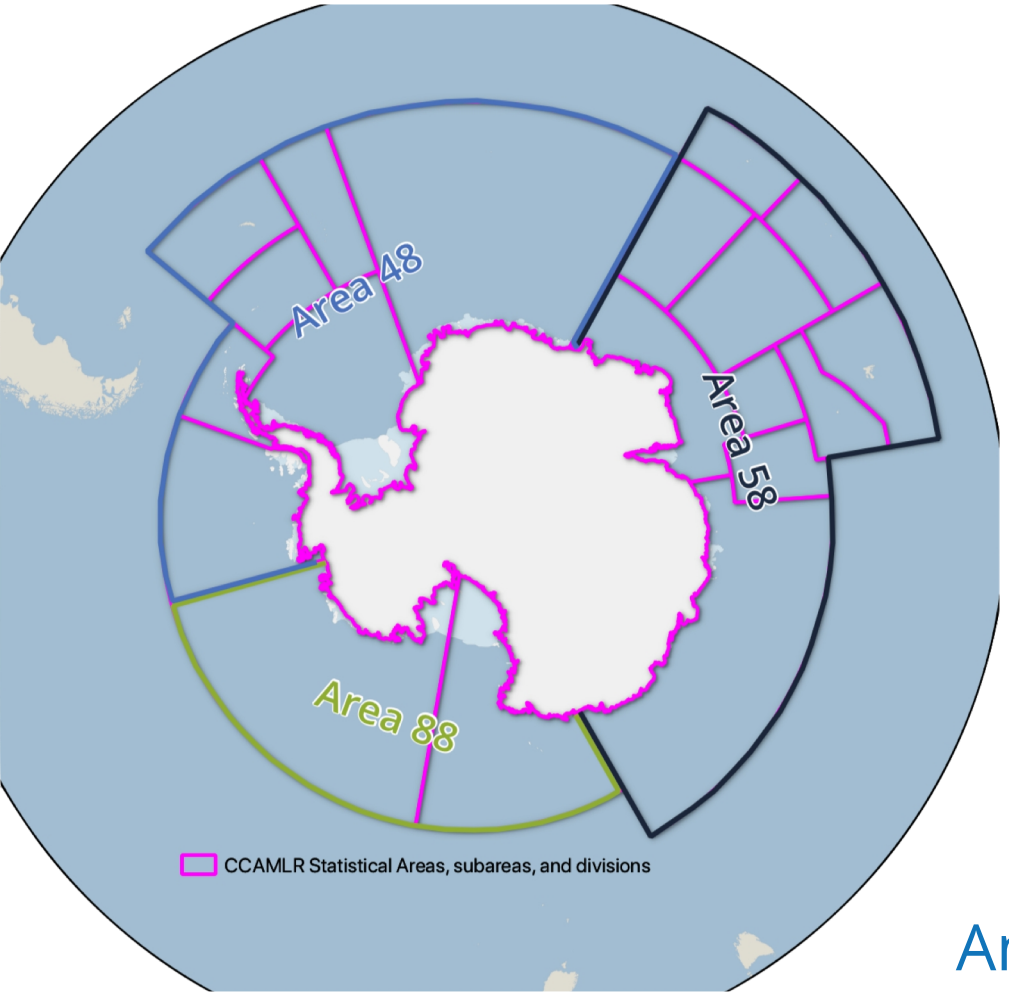

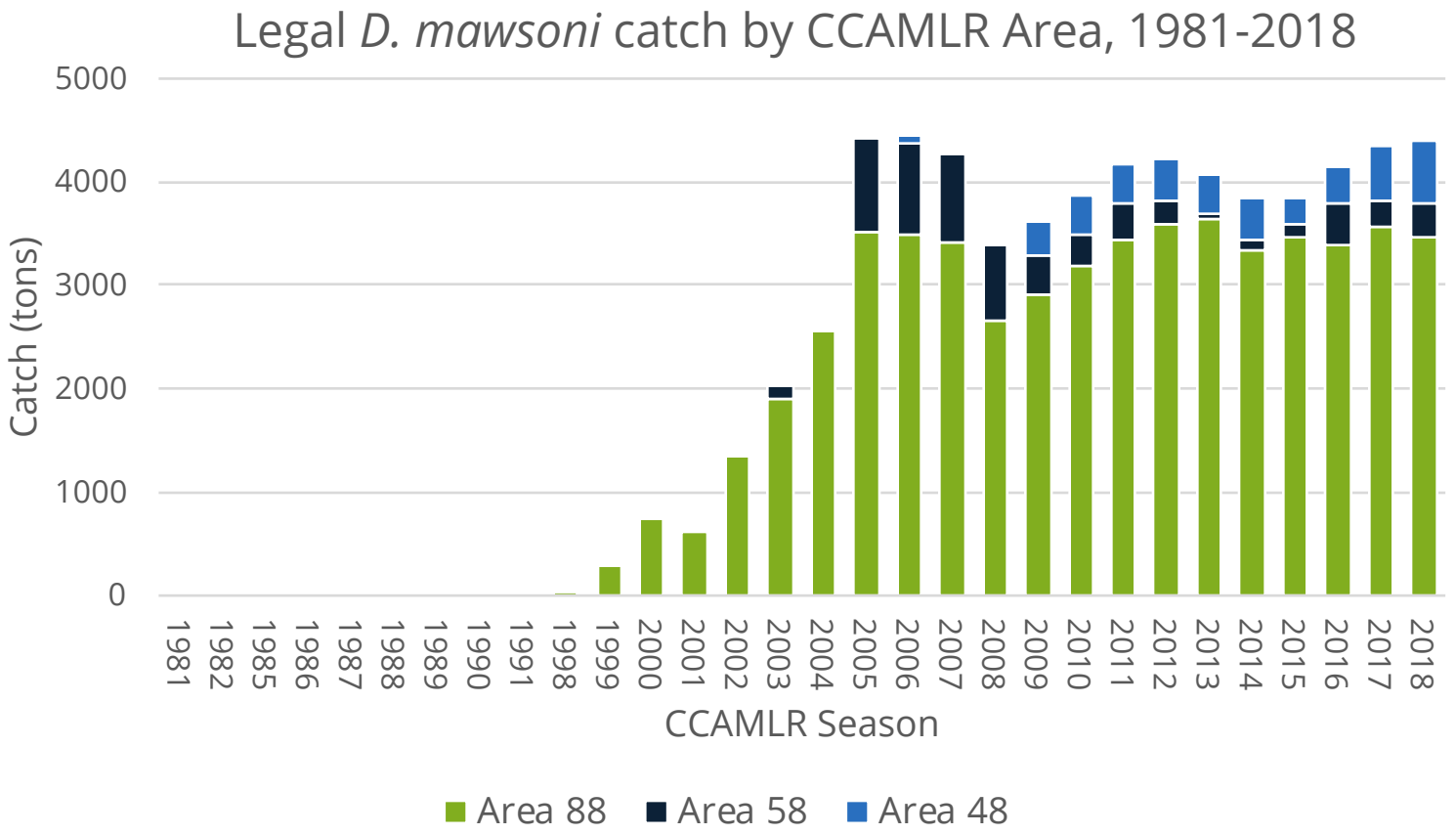

Antarctic toothfish catch levels increased significantly from 1999-2005, before leveling off

Data available from https://www.ccamlr.org/

Antarctic toothfish fishery
Catch value

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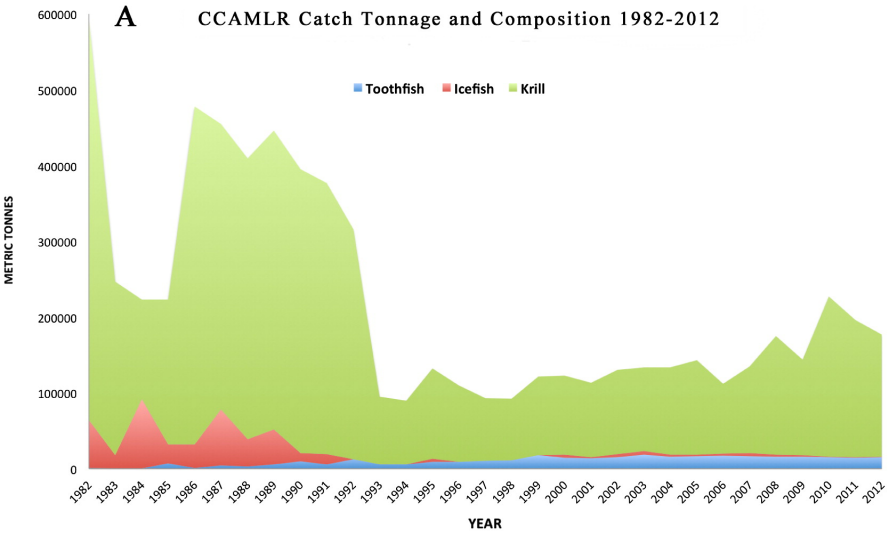

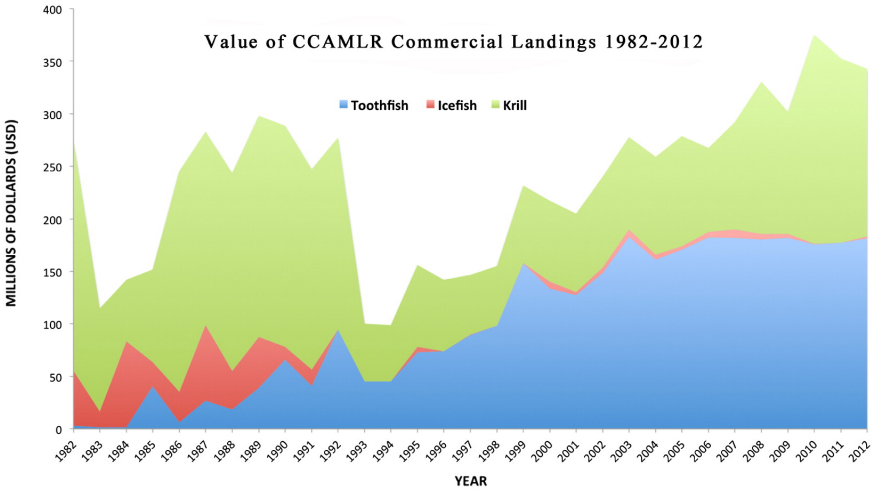

The increasing value of toothfish can be seen to drive the increase in catch levels

Brooks CM (2013) Competing values on the Antarctic high seas: CCAMLR and the challenge of marine-protected areas The Polar Journal 3:277-300 doi:10.1080/2154896X.2013.854597

Antarctic toothfish fishery ***Management***

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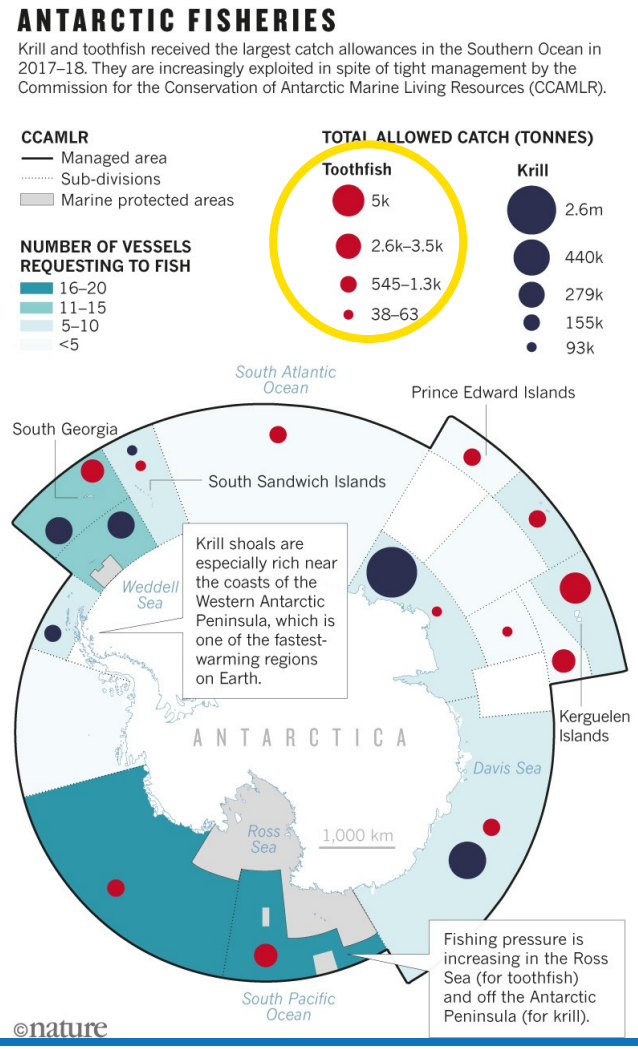

- The major Southern Ocean fisheries managed by CCAMLR are for **krill** (largest by **volume**) and **toothfish** (largest by **revenue**)
- Fisheries are managed via **Conservation Measures** which dictate the:
  - Total allowable catch sizes
  - Catch area
  - Type of equipment allowed
- Despite these measures, **Illegal, Unreported, and Unregulated (IUU)** fishing continues to a significant extent, and may represent up to 10% of the legal catch

Brooks CM, Ainley DG, Abrams PA, Dayton PK, Hofman RJ, Jacquet J, Siniff DB (2018) Antarctic fisheries: factor climate change into their management Nature 558:177-180 doi:10.1038/d41586-018-05372-x

Lack M (2008) Continuing CCAMLR's Fight against IUU Fishing for Toothfish WWF Australia and TRAFFIC International

Southern Ocean Marine Protected Areas

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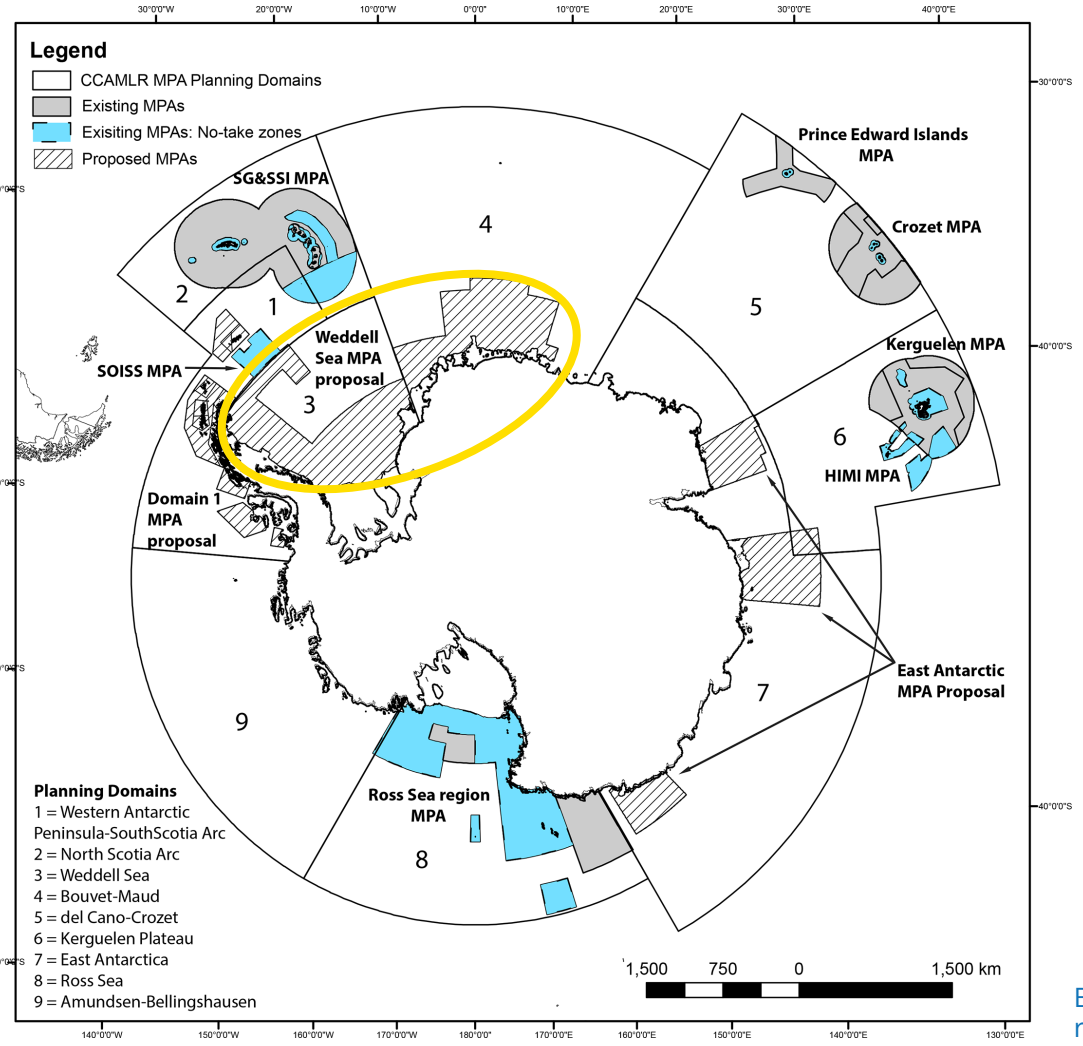

- CCAMLR implemented the world's largest no-take Marine Protected Area (MPA) in the Ross Sea region in 2016
- The Ross Sea MPA was designed to include areas important to the life history of Antarctic toothfish
- New MPAs around the Southern Ocean have been proposed over the past decade, but none have been passed due to a lack of consensus
- An understanding of the life history connectivity of Antarctic toothfish in the Weddell Sea is of particular importance for the ultimate implementation of this MPA

Brooks CM, Chown SL, Douglass LL, Raymond BP, Shaw JD, Sylvester ZT, Torrens CL (2020) Progress towards a representative network of Southern Ocean protected areas PloS one 15:e0231361 doi:10.1371/journal.pone.0231361

The Weddell Sea MPA

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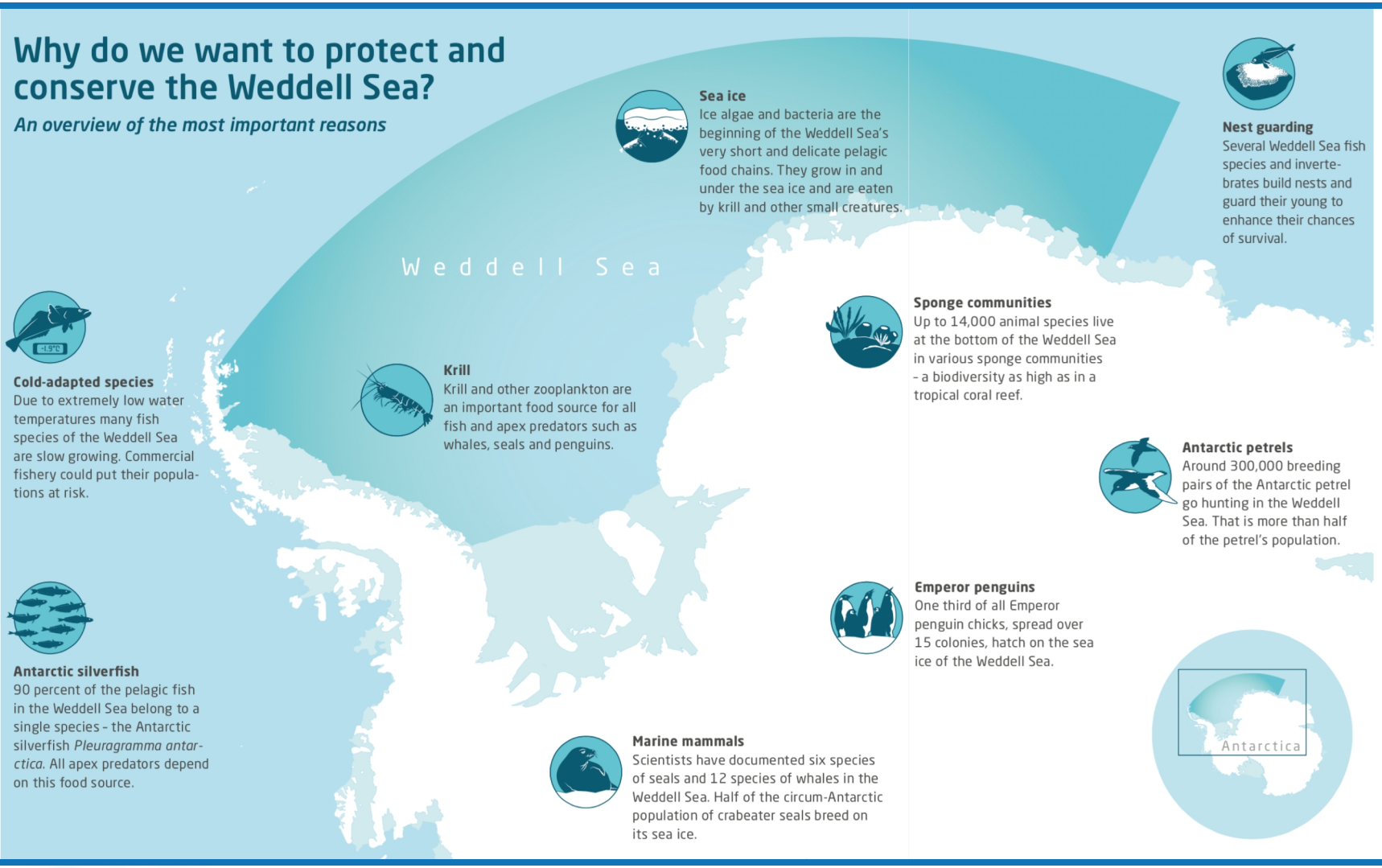

Since 2013, the Alfred Wegener Institute has worked to provide the scientific basis for the establishment of a large MPA in the Weddell Sea region on behalf of CCAMLR

Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung (2016) Weddell Sea - 8 Reasons for a Marine Protected Area. https://www.awi.de/nc/en/about-us/service/press/press-release/germany-is-proposing-a-marine-protected-area-in-antartica.html.

Antarctic toothfish
Life history hypothesis

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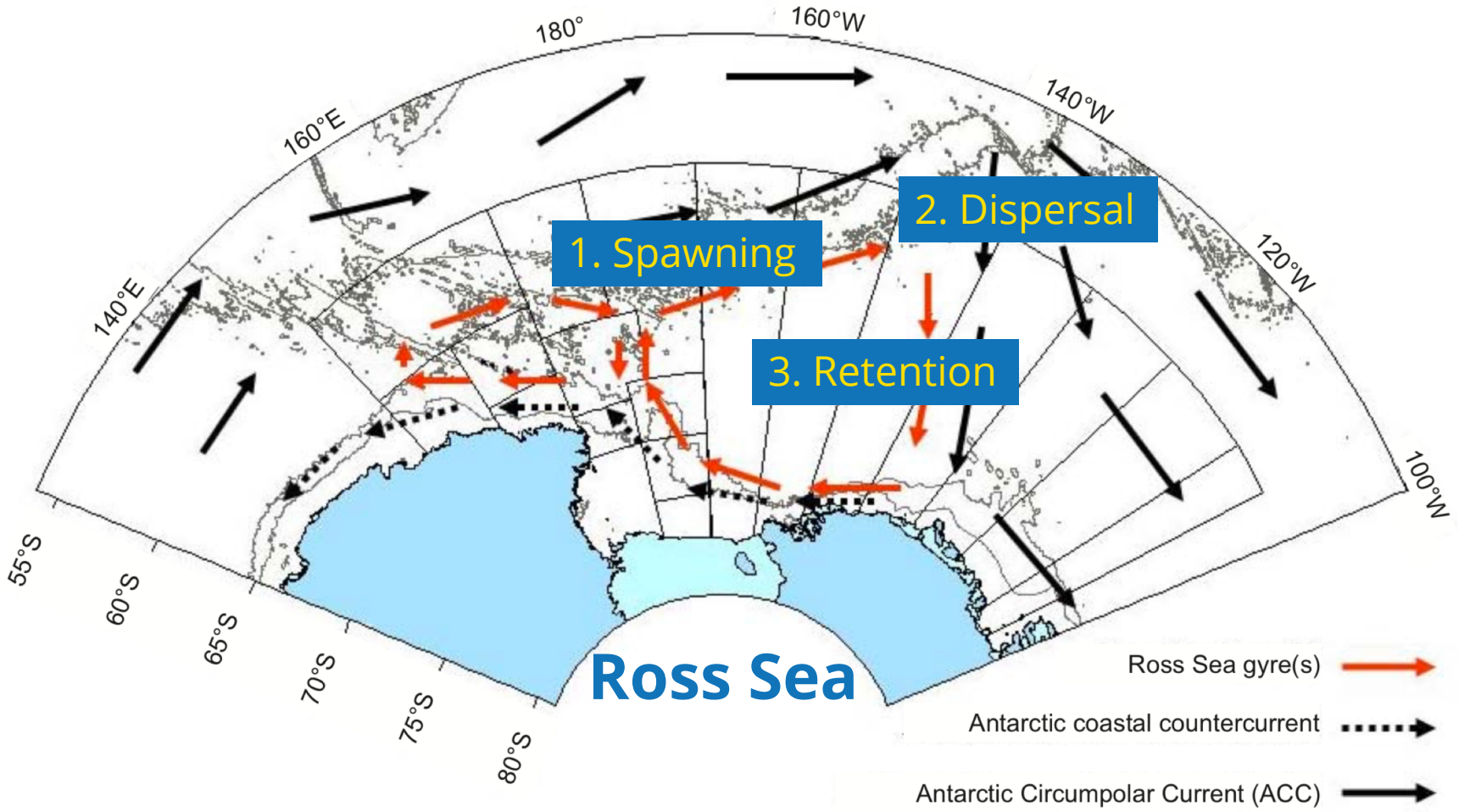

Our knowledge of Antarctic toothfish population structure is largely based on research carried out in the Ross Sea region, where the fishery for toothfish has existed the longest

Ashford J et al. (2012) Does large-scale ocean circulation structure life history connectivity in Antarctic toothfish (*Dissostichus mawsoni*)? Canadian Journal of Fisheries and Aquatic Sciences 69:1903-1919 doi:10.1139/f2012-111

Antarctic toothfish
Life history hypothesis

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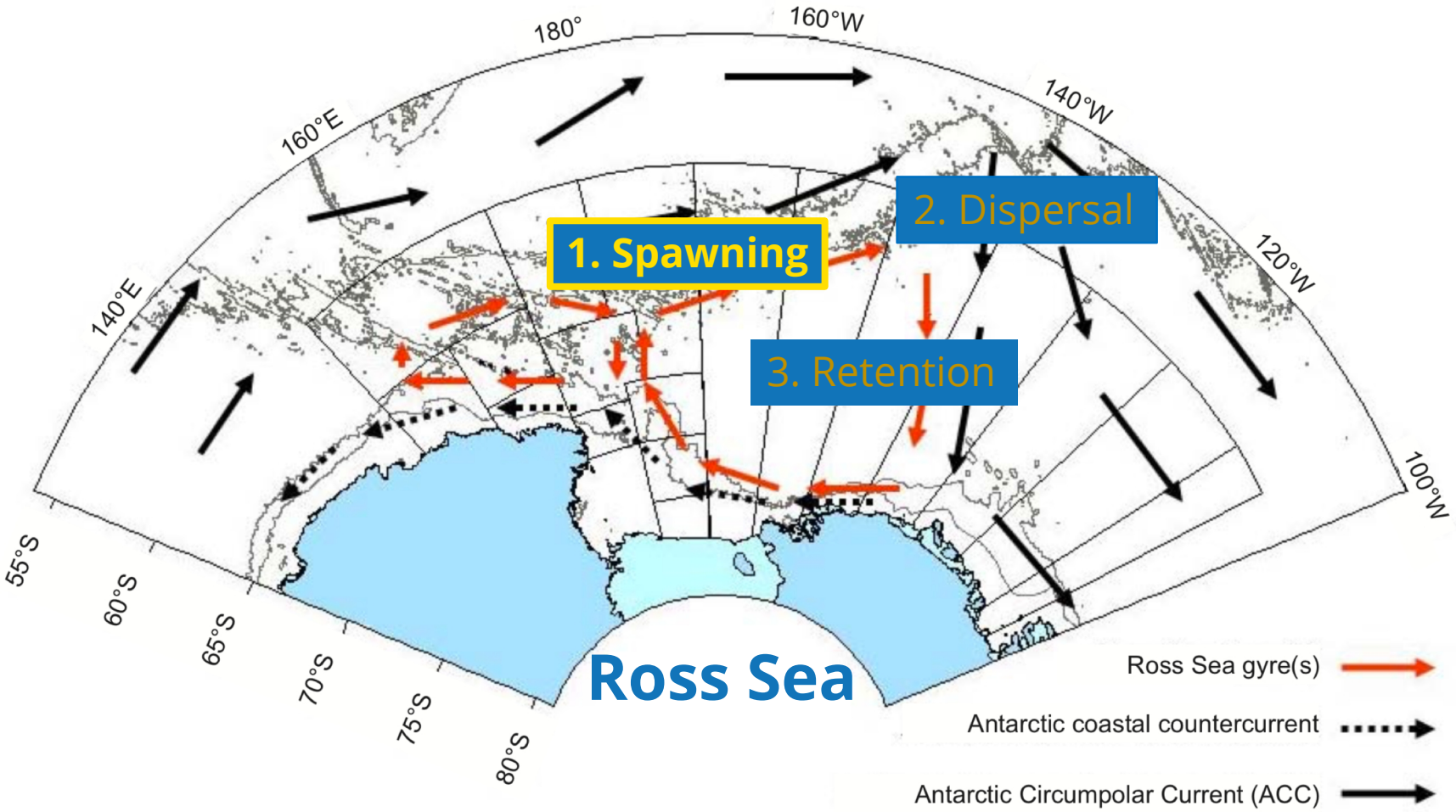

1. Spawning

- Antarctic toothfish spawn on offshore seamounts
- Spawning appears to take place during the Winter and Spring, and may last for several months
- Adults reach sexual maturity after 2 years, and may not spawn annually (skip-spawning)

Hanchet S, Dunn A, Parker S, Horn P, Stevens D, Mormede S (2015) The Antarctic toothfish (*Dissostichus mawsoni*): biology, ecology, and life history in the Ross Sea region Hydrobiologia 761:397-414 doi:10.1007/s10750-015-2435-6

Antarctic toothfish
Life history hypothesis

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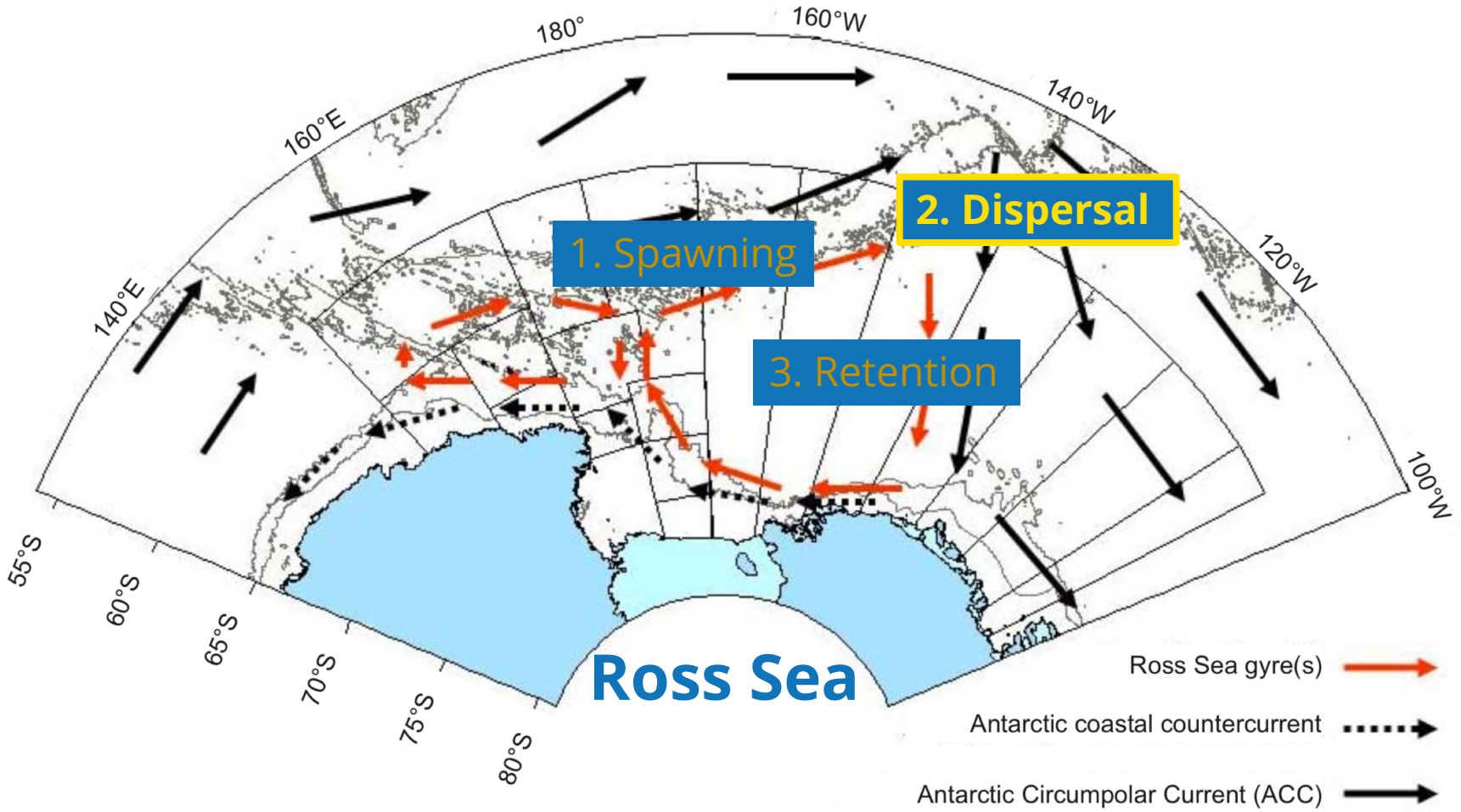

2. Dispersal

- Post-spawning, Antarctic toothfish larvae disperse via shoreward currents away from offshore seamounts and towards the continental shelf
- Development occurs on the shelf where access to high-quality prey aids in development and in achieving neutral buoyancy

Hanchet S, Dunn A, Parker S, Horn P, Stevens D, Mormede S (2015) The Antarctic toothfish (*Dissostichus mawsoni*): biology, ecology, and life history in the Ross Sea region Hydrobiologia 761:397-414 doi:10.1007/s10750-015-2435-6

Antarctic toothfish
Life history hypothesis

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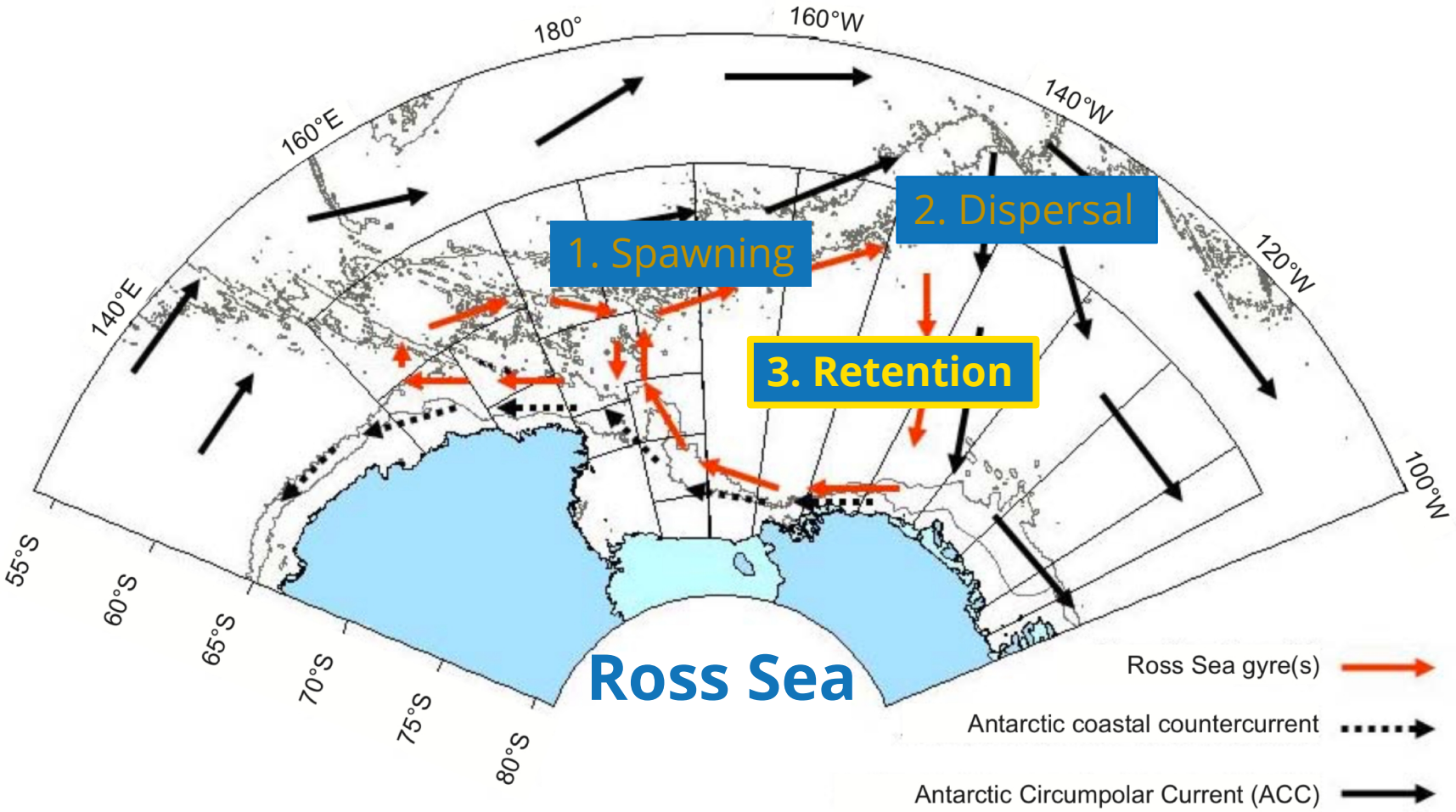

3. Retention

- Adults return to the shelf where they are retained in regional populations, regaining strength on the shelf prior to further spawning migrations
- Slope currents have the opportunity to divert individuals from their local populations, promoting connectivity between regions

Hanchet S, Dunn A, Parker S, Horn P, Stevens D, Mormede S (2015) The Antarctic toothfish (*Dissostichus mawsoni*): biology, ecology, and life history in the Ross Sea region Hydrobiologia 761:397-414 doi:10.1007/s10750-015-2435-6

Antarctic toothfish ***Weddell Sea***

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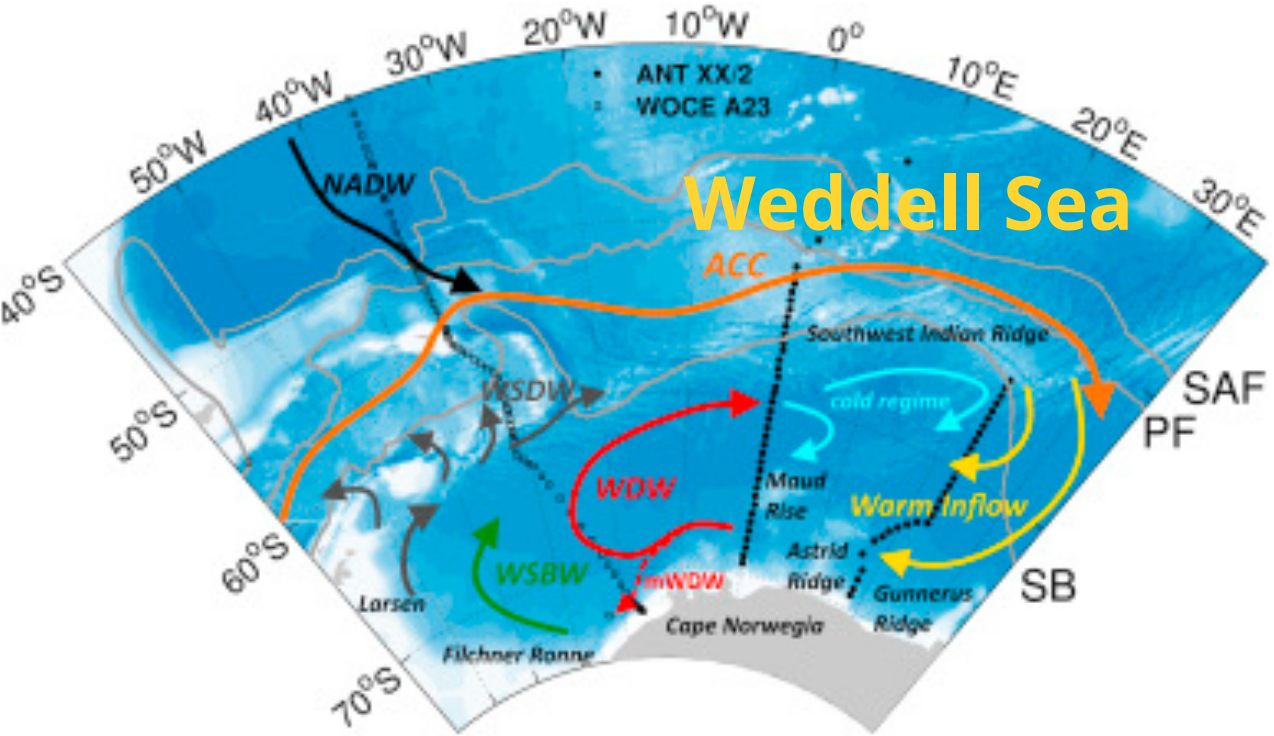

The bathymetry and hydrography of the Weddell Sea region mirror many aspects of the Ross Sea system, supporting a similar set of hypotheses regarding Antarctic toothfish life history connectivity, which are also supported by preliminary data on life history traits and distribution data from the area

Ryan S, Schröder M, Huhn O, Timmermann R (2016) On the warm inflow at the eastern boundary of the Weddell Gyre Deep-Sea Research Part I: Oceanographic Research Papers 107:70-81 doi:10.1016/j.dsr.2015.11.002

Söffker M et al. (2018) Annex to WS-DmPH-18 report: Towards the development of a stock hypothesis for Antarctic toothfish (*Dissostichus mawsoni*) in Area 48 CCAMLR Scientific Papers Working Group on Fish Stock Assessment WG-SAM-18/33 Rev. 1

Antarctic toothfish
Current project

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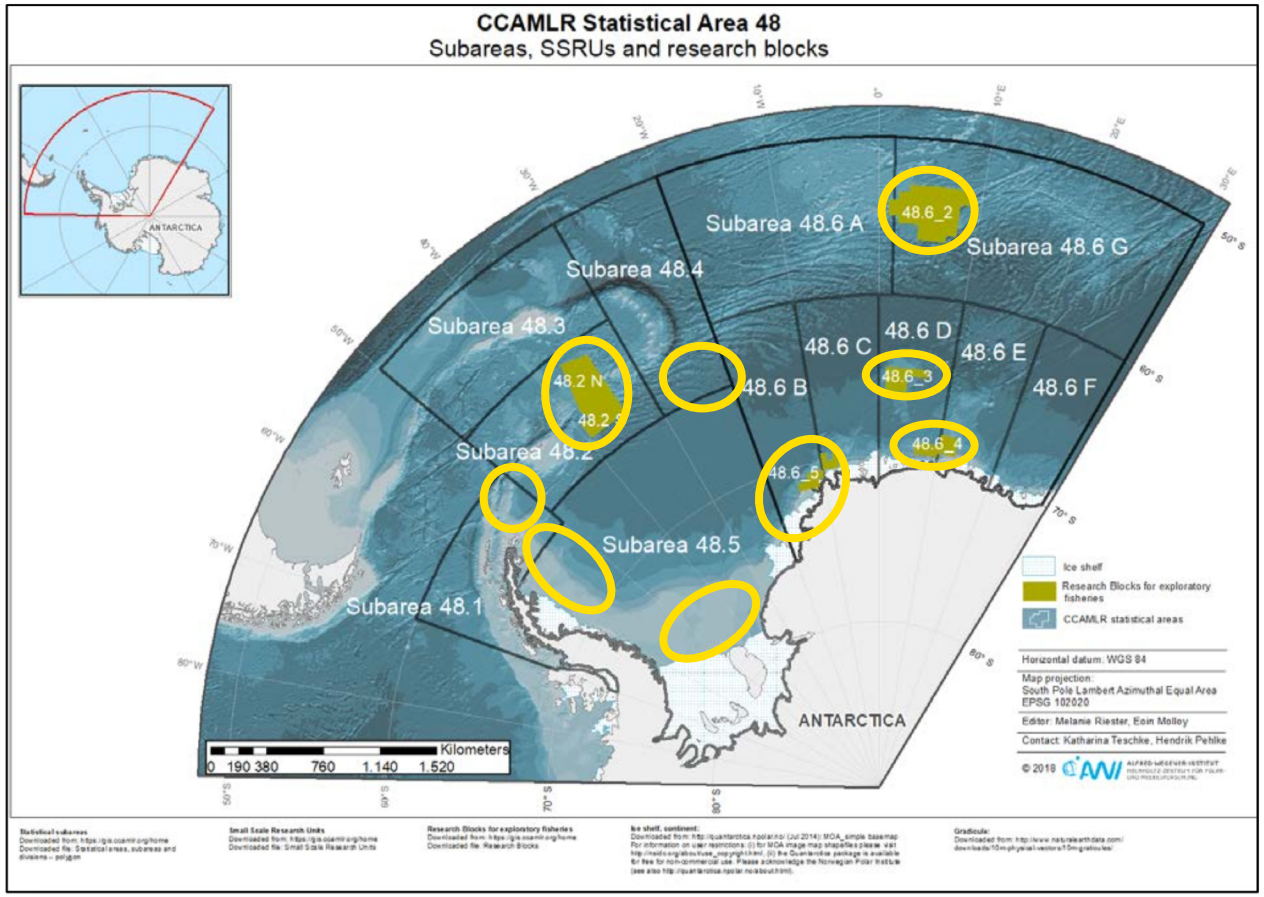

The aim of the current project is to elucidate the population structure of Antarctic toothfish in the Weddell Sea region (CCAMLR Area 48) based on samples collected from the areas circled in yellow:

- with respect to the context of circumpolar connectivity (i.e. outgroups)
- testing hypotheses grounded in prevailing hydrography
- using **next-generation sequencing** methods and **trace element analysis** in fish otoliths

Antarctic toothfish ***Genetics***

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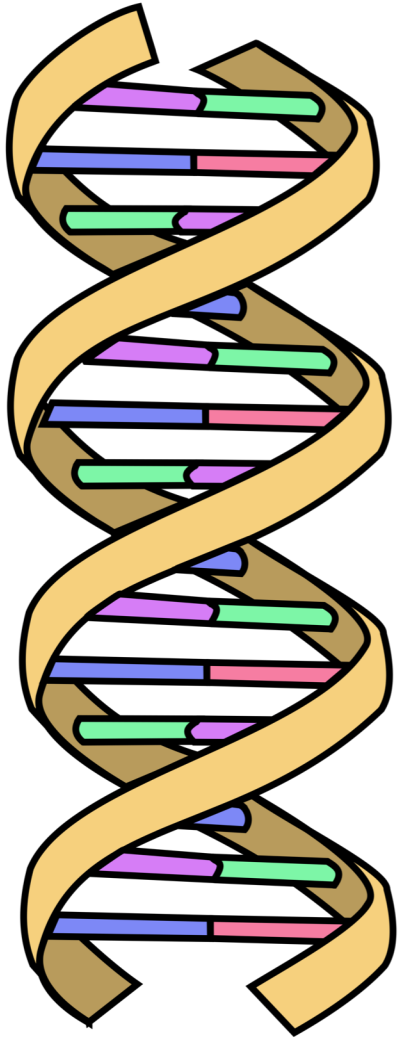

Next-generation sequencing

- Genetics work is being carried out at BeGenDiv
- ***Genetics analysis provides a relatedness-based proxy to understanding population structure***
- Optimization of a Restriction site-Associated DNA sequencing (RADseq) method based on the 3RAD pipeline described in Driller M et al. (2020)
- Optimization of otolith DNA extraction method, the products of which can be reliably processed with RADseq methods
- The aim is for the methods developed to be reproducible by other research groups and relevant for monitoring work

Driller M et al. (2020) Optimization of ddRAD-like data leads to high quality sets of reduced representation single copy orthologs (R2SCOs) in a sea turtle multi-species analysis bioRxiv:2020.2004.2003.024331 doi:10.1101/2020.04.03.024331

Antarctic toothfish ***RADseq method***

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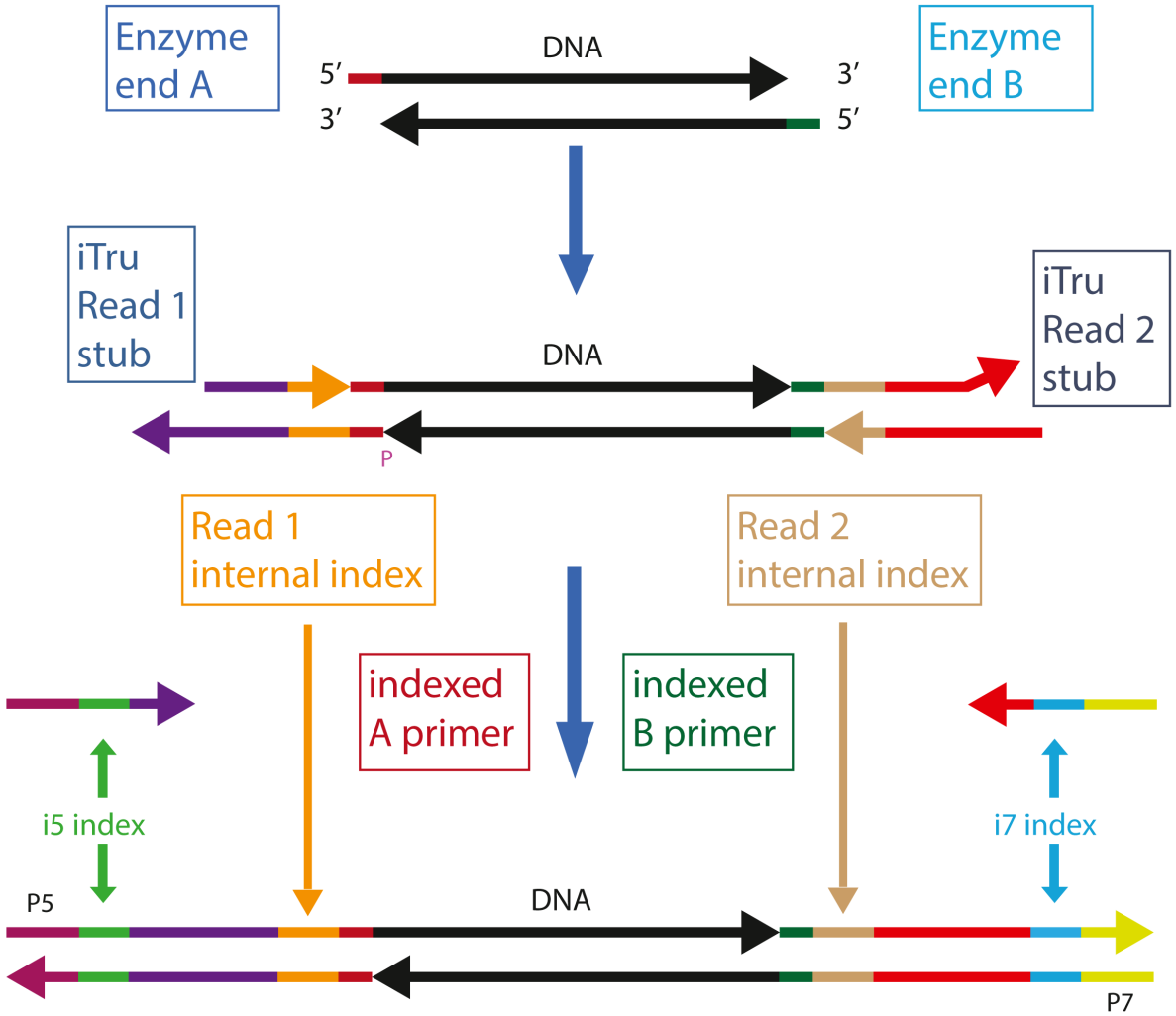
Double digested DNA Sample

Add ligase + iTru 3RAD adapters + Read 1 stub dimer digesting enzyme

Limited cycle PCR

Double stranded DNA library



This figure from Bayona-Vásquez et al. 2019 outlines the method we are implementing, which

- is optimized for low quality/quantity DNA samples
- minimizes processing steps
- reduces chimeras
- eliminates adapter-dimers
- allows for the identification of PCR duplicates

Bayona-Vásquez NJ et al. (2019) Adapterama III: Quadruple-indexed, double/triple-enzyme RADseq libraries (2RAD/3RAD) PeerJ 7:e7724 doi:10.7717/peerj.7724

Antarctic toothfish
Otolith chemistry

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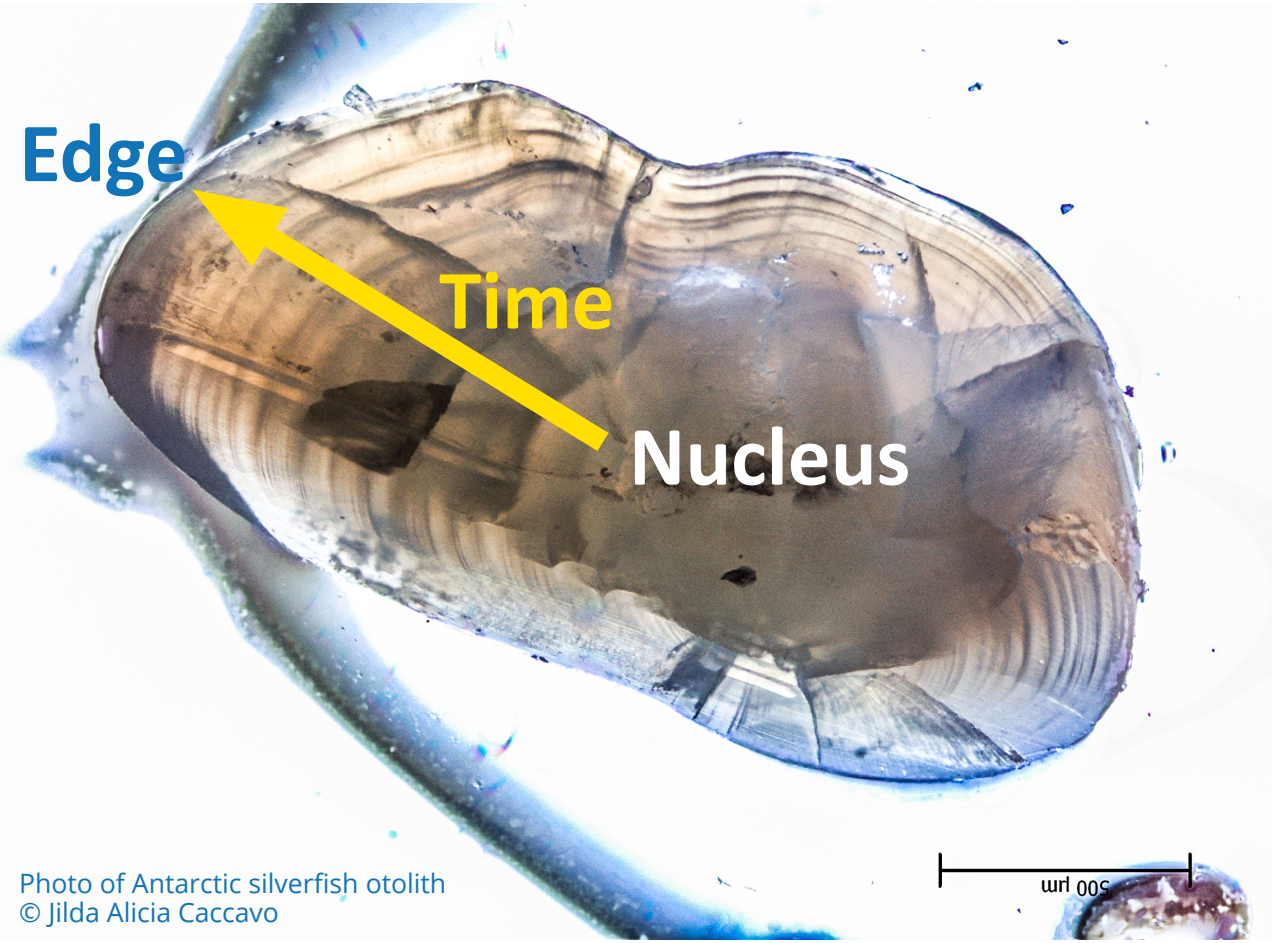

Photo of Antarctic silverfish otolith

Trace element analysis

- Trace element analysis is being carried out at AWI
- ***Trace element analysis provides a provenance-based proxy to understanding population structure***
- Edge to nucleus transects assessing a selection of more prevalent trace elements (e.g. Ba, Sr, Mg, Mn)
- Spot analysis at the otolith edge and nucleus including a wide array of trace elements to assess recent and early life water mass exposure respectively

Antarctic toothfish
Trace element analysis

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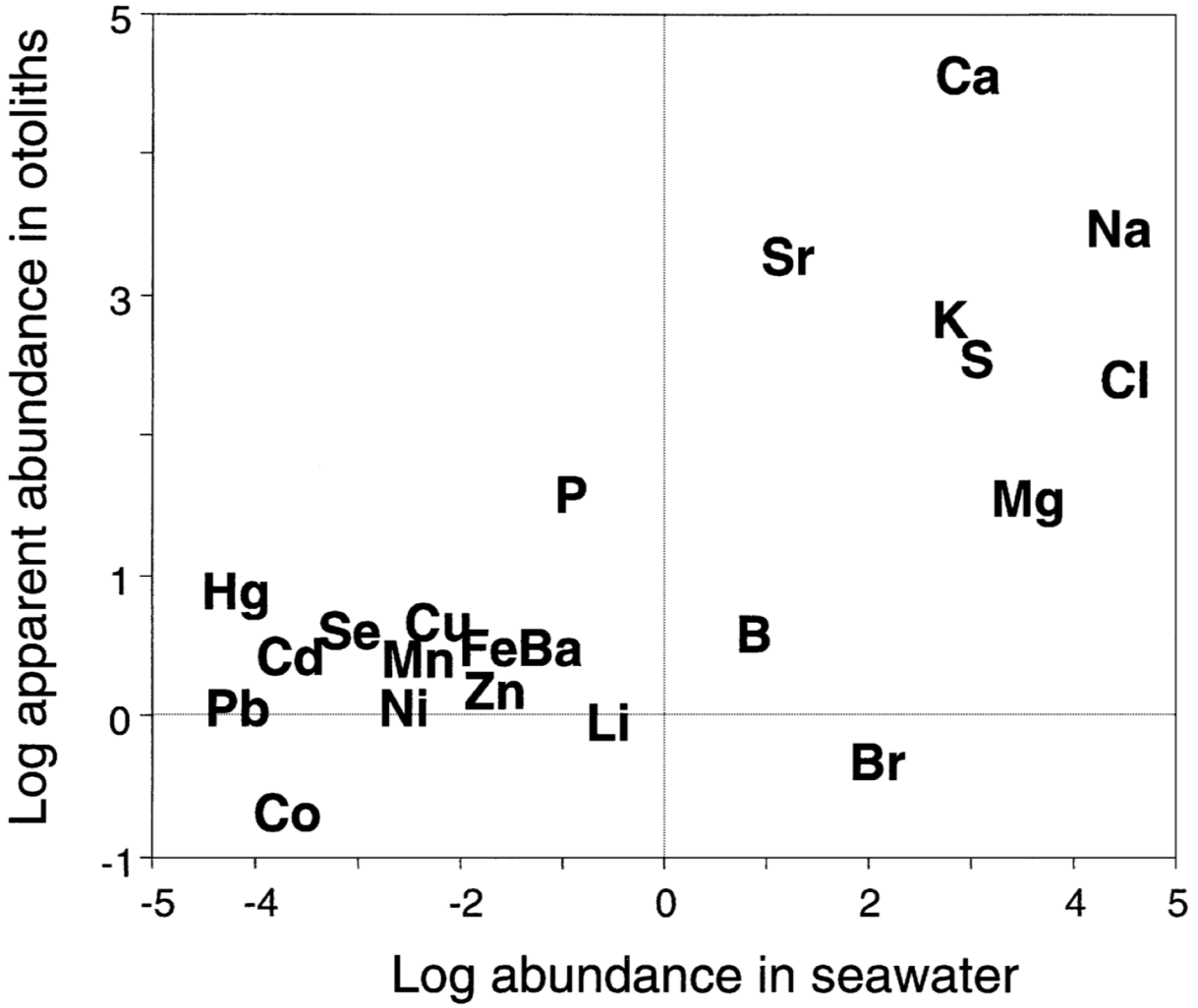

Primarily Ca, but in trace amounts, also other elements, are regularly deposited in the otolith cellular matrix, a quality which allows otoliths to be used to age fish.

Local water conditions (temperature, salinity, nutrient profile), as well as physiology (activity, feeding), influence the extent to which elements are substituted for Ca in the otolith.

Trace element profiles from the otolith nucleus are indicative of early life exposure, while profiles from the otolith edge reflect exposure just prior to capture.

Thorrold SR, Swearer SE (2009) Otolith Chemistry. In: Green BS, Mapstone BD, Carlos G, Begg GA (eds) Tropical Fish Otoliths: Information for Assessment, Management and Ecology. Springer Netherlands, Dordrecht, p 249-295, pp 249-295. doi:10.1007/978-1-4020-5775-5_8

Antarctic toothfish
Combined approach

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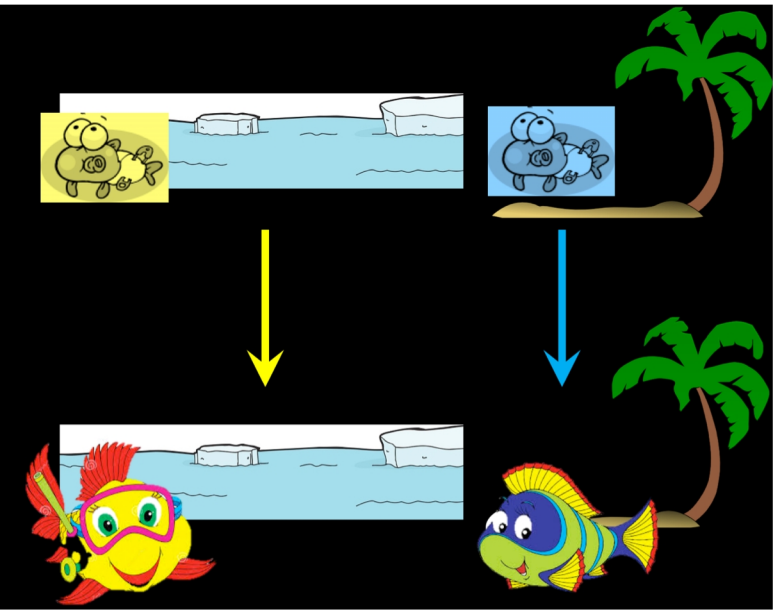
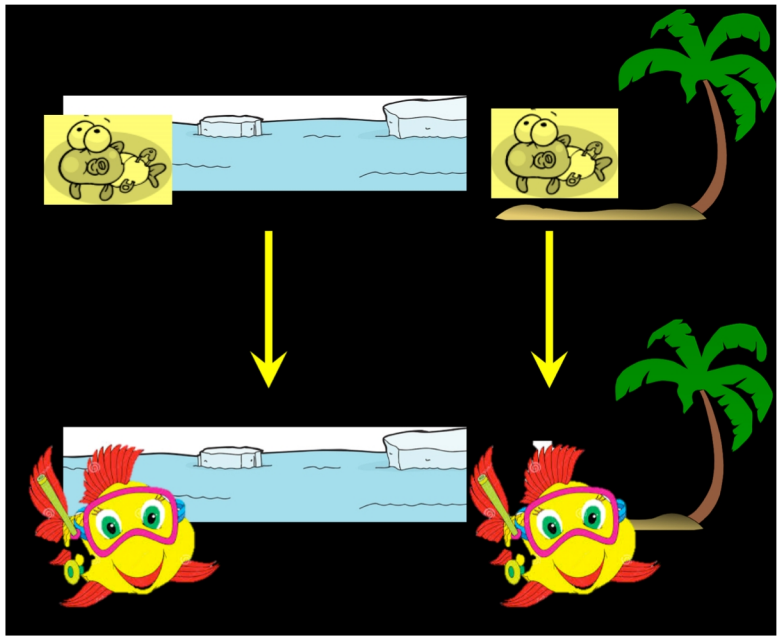
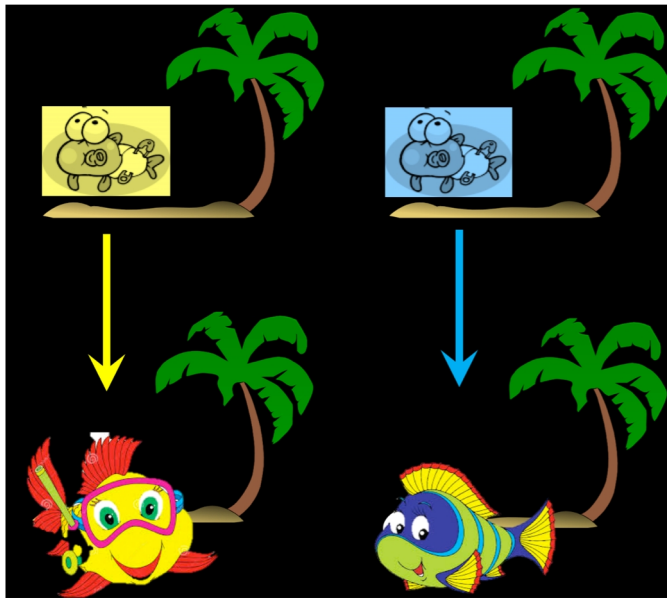


Where populations are **sufficiently isolated** and **environments differ**, genetics and otolith nucleus chemistry will yield the **same population structure**



Where small amounts of **gene flow** are enough to homogenize otherwise dynamically different populations, only **element analysis** would elucidate structure



Where spawning environments of otherwise **separately breeding populations** are similar enough, only **genetics** would elucidate structure

Summary

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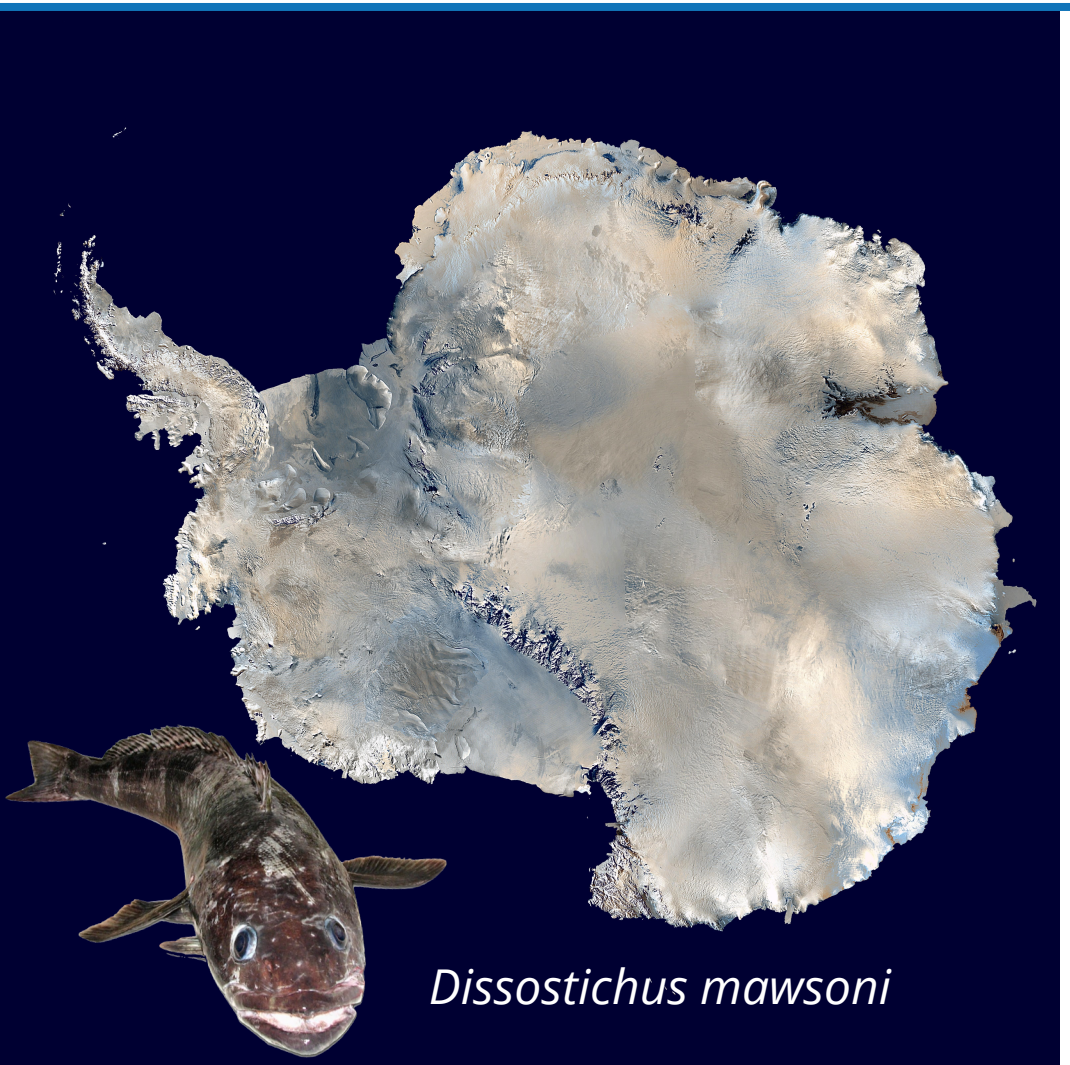

- Antarctic toothfish are commercially exploited top predators in the Southern Ocean ecosystem
- CCAMLR manages their fishery and is working to implement a network of MPAs that protect habitat critical to Antarctic toothfish life history
- The Weddell Sea is a critical region for which little is known of Antarctic toothfish population structure and for which an MPA has been in development
- The Antarctic toothfish life history hypothesis asserts that fish spawn on offshore sea mounts, prior to dispersal and retention via currents
- This project combines next-generation sequencing methods with trace element analysis to test population hypotheses based on hydrography

Thank you for your attention

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website jildacaccavo.com

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Photo of Weddell Seal with captured Antarctic toothfish © Jessica Meir, provided by Thomas Brey

Jilda Alicia Caccavo is supported by an Alexander von Humboldt Research Fellowship for Postdoctoral Researchers

For more information

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3. Lack M (2008) Continuing CCAMLR's Fight against IUU Fishing for Toothfish WWF Australia and TRAFFIC International
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5. Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung (2016) Weddell Sea - 8 Reasons for a Marine Protected Area. https://www.awi.de/nc/en/about-us/service/press/press-release/germany-is-proposing-a-marine-protected-area-in-antartica.html.
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8. Ryan S, Schröder M, Huhn O, Timmermann R (2016) On the warm inflow at the eastern boundary of the Weddell Gyre Deep-Sea Research Part I: Oceanographic Research Papers 107:70-81 doi:10.1016/j.dsr.2015.11.002
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Useful links

- Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) https://www.ccamlr.org/
- Weddell Sea Marine Protected Area https://www.awi.de/nc/en/about-us/service/press/press-release/germany-is-proposing-a-marine-protected-area-in-antartica.html
- AWI Department of Functional Ecology https://www.awi.de/en/science/biosciences/functional-ecology.html
- BeGenDiv Team https://begendiv.de/people/
- IZW Department of Evolutionary Genetics http://www.izw-berlin.de/about-us-160.html