You Are What You Eat

Advances in Marine Predator Diet Estimation via Fatty Acids

Jennifer McNichol

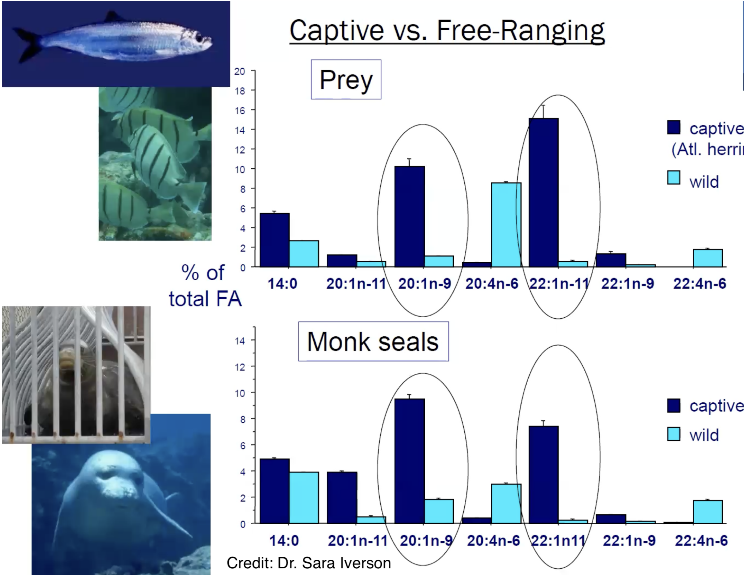
Ecological motivation

- Dietary estimation is a research hotspot of quantitative ecology, providing key insights into predator–prey relationships (Zhang et al., 2020).
- Example: Are polar bear diets changing to land-based resources due to melting sea ice, which has traditionally allowed them to forage on seals? (Bourque et al., 2020)
- For many species, we do not have all of the information needed to estimate diet and it may be difficult to obtain.

Marine diet estimation

- Stomach content analysis has been used to identify diet composition but has many disadvantages.
- Fatty acid signature analysis (FASA) can estimate the diet composition of predators. *FASA methods are non-invasive and provide information on the longer-term diet.*
- Other methods such as stable isotope analysis are limited in resolution.

Fatty acid (FA) signature similarities



Credit: Dr. Sara Iverson

Quantitative fatty acid signature analysis (QFASA)

- Quantitative fatty acid signature analysis (Iverson et al., 2004) estimates the proportion α of prey type i in the diet by minimizing

$$\text{dist}(\boldsymbol{Y}, \sum_{i=1}^{I} \alpha_i \bar{\boldsymbol{X}}_i)$$

where $\boldsymbol{Y}$ = predator FA signature
$\bar{\boldsymbol{X}}_i$ = mean FA signature of prey type i

- QFASA is widely used, particularly in the context of marine mammals, where the majority of long-term energy storage occurs in the form of fat in the adipocytes situated between the muscle and the skin, making it accessible for biopsy.
- R package *QFASA* (Stewart et al., 2021)

Compositional data analysis

- FA signatures and diet estimates are compositional vectors.
- Log-ratio transformations are commonly used to transform compositional data to multivariate normality.
- The isometric log-ratio (ilr) transformation is recommended:

$$z(x) = Hw(x), \quad w(x) = \log\left(\frac{x_i}{\prod_{i=1}^{D} x_i^{1/D}}\right), \quad \text{for} \quad i = 1, \ldots, D.$$

where H is the Helmert matrix after deletion of the first row.

Measures of distance

- A choice of distance measure is needed in QFASA and also some analyses carried out on the diet estimates.
- Aitchison's Distance: Euclidean distance between ilr transformed compositions is the recommended distance measure for compositional data.
- Aitchison's distance satisfies properties considered to be fundamental to compositional data analysis, but *zeros are problematic* due to logarithm.
- Chisquare distance (Stewart 2017) is a nice alternative that allows for zeros.

Maximum likelihood approach to FASA

Maximum unified fatty acid signature analysis (MUFASA) assumes

$$\boldsymbol{Y} = \left(\sum_{i=1}^{I} \alpha_i \boldsymbol{Z} \right) \circ \boldsymbol{\epsilon}$$

where $\boldsymbol{Z}$ is a random effect representing the unobserved FA signatures of they prey.

- $\boldsymbol{Y}$, $\boldsymbol{Z}$ and ϵ are ilr transformed and assumed to be multivariate normal.
- A marginal likelihood was obtained by integrating the joint likelihood with respect to the random effects using the R package *TMB*.

Joint work with H. Steeves, C. Stewart, C. Field, A. MacNeil, S. Lang

MUFASA

- Results of a simulation study and real-life data suggest that overall, MUFASA is comparable to QFASA in terms of yielding accurate diet estimates.
- We developed an algorithm for obtaining confidence intervals for the true diet as well as methodology for integrating covariates into MUFASA.

- Advantages of MUFASA:
  - Random effect provides a more realistic model.
  - Predator and within prey type variability are taken into account.
  - Potential to resolve other fatty signature analysis problems through the likelihood.
- Disadvantage of MUFASA:
  - Large computational burden

Calibration coefficients

- CCs are used to account for the potential metabolization of FAs.
- May be obtained from long-term controlled diet feeding studies.
- We should have a set of CCs for every species of predator.
- Simultaneous QFASA (SQFASA; Bromaghin et al., 2017) is an extension of QFASA which estimates CCs alongside diet.

Simultaneous maximum unified fatty acid signature analysis (SMUFASA)

- SMUFASA extends MUFASA to estimate CCs and diet.
- Predator FAs are modelled by

$$\boldsymbol{Y} = \boldsymbol{C} \circ \left(\sum_{i=1}^{I} \alpha_i \boldsymbol{Z} \right) \circ \boldsymbol{\epsilon}$$

  where $\boldsymbol{Z}$ is a random effect representing the unobserved FA signatures of they prey.
- $\boldsymbol{\alpha}$ and $\boldsymbol{C}$ are parameters to be estimated in the optimization.

$$\mathcal{L} \propto \prod_{j=1}^{n.pred} f(\boldsymbol{Y}_j^{ilr} | \boldsymbol{Z}_j^{ilr}, \boldsymbol{\alpha}, \boldsymbol{C}, \Sigma_\epsilon, \hat{\Sigma}, \boldsymbol{X}^{ilr}) f(\boldsymbol{Z}_j^{ilr})$$

$$= \prod_{j=1}^{n.pred} \left(\frac{1}{(2\pi)^{\frac{K-1}{2}} |\boldsymbol{\Sigma}_\epsilon|^{\frac{1}{2}}} \exp\left\{ -\frac{1}{2} \left(\boldsymbol{Y}_j^{ilr} - \boldsymbol{\eta}_j^{ilr} \right)' \boldsymbol{\Sigma}_\epsilon^{-1} \left(\boldsymbol{Y}_j^{ilr} - \boldsymbol{\eta}_j^{ilr} \right) \right\} \times \right.$$

$$\left. \prod_{i=1}^{I} \frac{1}{(2\pi)^{\frac{K-1}{2}} |\hat{\boldsymbol{\Sigma}}|^{\frac{1}{2}}} \exp\left\{ -\frac{1}{2} \left(\boldsymbol{Z}_{ji}^{ilr} - \hat{\boldsymbol{\mu}}_i \right)' \hat{\boldsymbol{\Sigma}}^{-1} \left(\boldsymbol{Z}_{ji}^{ilr} - \hat{\boldsymbol{\mu}}_i \right) \right\} \right)$$

St. Lawrence Estuary Beluga

SLE Beluga

- Steady decline at a rate of about 1% per year led to a change in conservation status from Threatened to Endangered in 2016.
- 2022 census estimated between 1,530 and 2,180 belugas.
- Threats to the population: contaminants, noise, and reduced prey availability.

What do we know about the diet of the SLE Beluga?

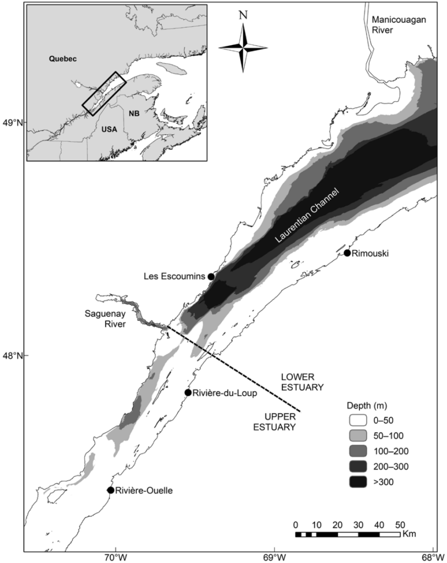
Stomach content analysis: Vladykov 1946

- Banc de Manicouagan, 1938 – 1939
- Mostly sand lance and capelin.

Stomach content analysis: Lesage et al. 2020

- St. Lawrence estuary, 1989 – 2019
- Mostly demersal fish such as cod, hake, and redfish.

- No reliable CCs for belugas so QFASA has never been applied.



Choy et al. (2019) captive study

- Two unrelated female beluga whales (an adult and a juvenile) housed at the Vancouver Aquarium were fed a consistent diet of capelin, opalescent inshore squid and Pacific herring, with daily dietary intake (mass and calories) recorded from August 5th, 2011 to August 5th, 2012.
- Dietary estimation was carried out using QFASA with several different sets of calibration coefficients.
- CCs derived from mink fed herring were found to give the most accurate results.
- CCs specific to belugas could not be measured because the belugas died.

SLE Beluga analysis

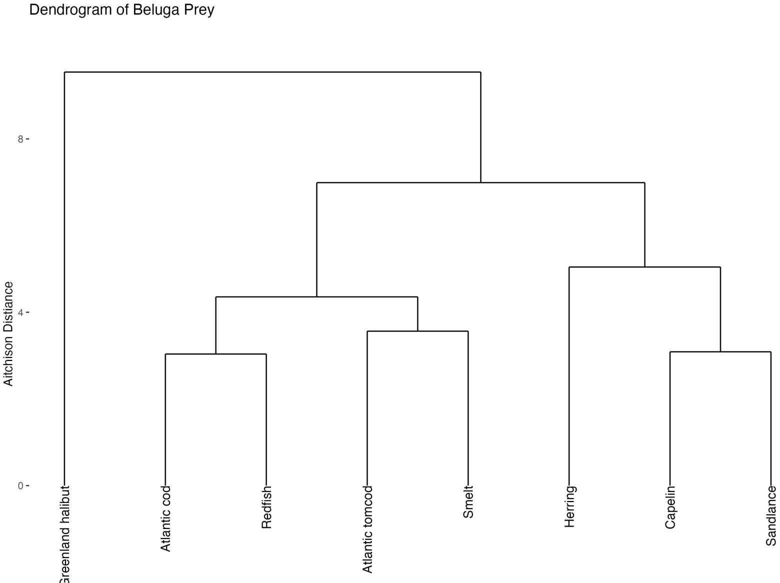
Beluga data:

- Inner blubber FA signatures and the isotopic signatures of the muscle collected as part of a long-term necropsy program led by Fisheries and Oceans Canada (Lesage et al. 2014) under permits issued in compliance with the Species at Risk Act and Fisheries Act.
- FA signatures obtained for a sample of 20 male belugas
- Prey items chosen from the likely prey found in Lesage et al. (2020) and Vladykov (1946).

Analyses:

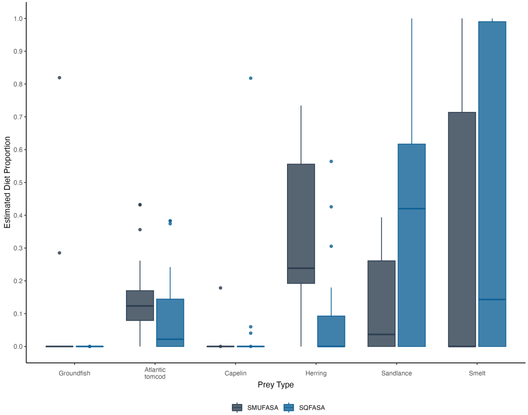
- We applied SMUFASA (and SQFASA) to estimate diet and CCs.
- We applied MixSIAR (Stock et al. 2018) on stable isotope samples.

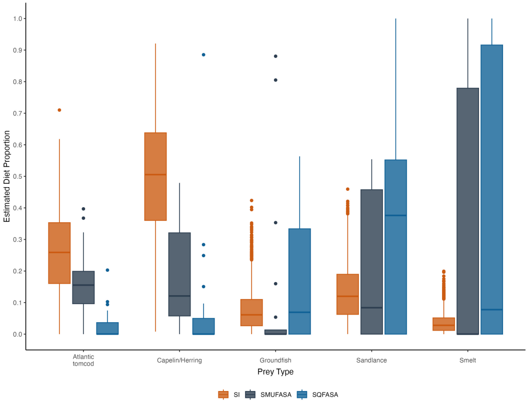
Prey



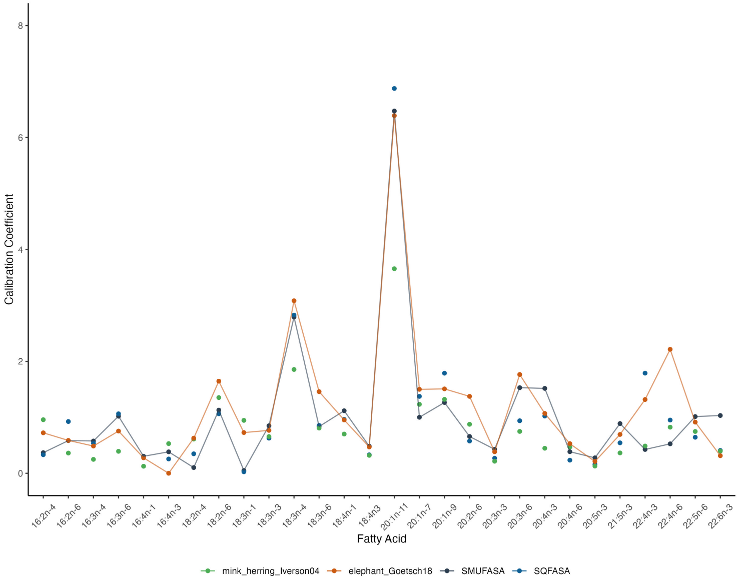
Dendrogram of Beluga Prey
Aitchison Distiance
8
4
0
Greenland halibut
Atlantic cod
Redfish
Atlantic tomcod
Smelt
Herring
Capelin
Sandlance

Beluga diet estimates





Calibration coefficient estimates



Conclusions and future work

- All FASA models are sensitive to the selection of FA set. We could benefit from a statistical way to choose these.
- Highly sensitive to choice of FA set used and confounding between prey types.

SMUFASA benefits:

- (Sort of) accessible to apply $\rightarrow$ QFASA R package.
- More reliable than SQFASA.
- Model accounts for sources of variability.
- Can obtain confidence intervals and include covariates.

SMUFASA trade-offs:

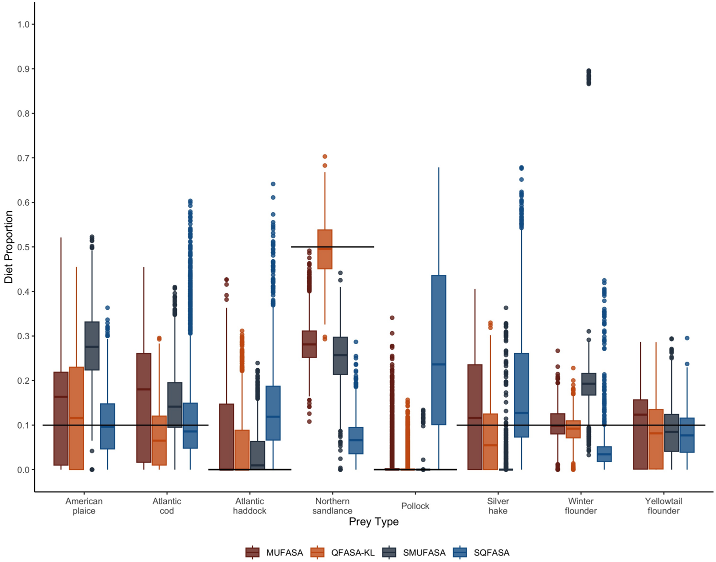
- Computationally intensive.
- May not be as accurate as QFASA with *known*, *species specific* CCs.

Thank you!

- Jory Cabrol, Fisheries and Oceans Canada
- Veronique Lesage, Fisheries and Oceans Canada
- Connie Stewart, UNB
- Holly Steeves, Western
- Shelley Lang, Northwest Atlantic Fisheries Centre
- Chris Field, Dalhousie

Simulations

Create "pseudo-predators" (seals, n=20) based on real-life prey data set (fish) and realistic diet. Number of simulations = 100



Chukchi Sea polar bears

- Samples were collected from polar bears of all age and sex classes during mark-recapture studies throughout the springs of 2008 to 2011 in the Chukchi Sea.
- 48 adult ($\geq$ 5 years) females, 50 adult males, 13 sub-adult (2-4 years) females, and 25 sub-adult males.

Table 1: Species included in the marine mammal prey database.

Prey Species	Scientific name	*n*
Bearded seal	*Erignathus barbatus*	83
Beluga whale	*Delphinapterus leucas*	29
Bowhead whale	*Balaena mysticetus*	64
Ribbon seal	*Histriophoca fasciata*	32
Ringed seal	*Pusa hispida*	23
Spotted seal	*Phoca largha*	24
Walrus	*Odobenus rosmarus*	102

Note: fat content among above species are similar.

Polar bear results