Supplemental Information for Limburg and Casini, "Effect of Marine Hypoxia on Baltic Sea Cod *Gadus morhua*: Evidence from Otolith Chemical Proxies"

Figure S-1. Diagram showing A. the location of otoliths and the semicircular canals in a typical fish skull; B. a whole cod sagittal otolith, showing the V-notch (arrow) where the core is located; C. distal view of a cod otolith, showing how a transverse section is cut (lines); D. a polished transverse section of a cod otolith, showing the core (arrow) and annual sequences of opaque and translucent growth zones.

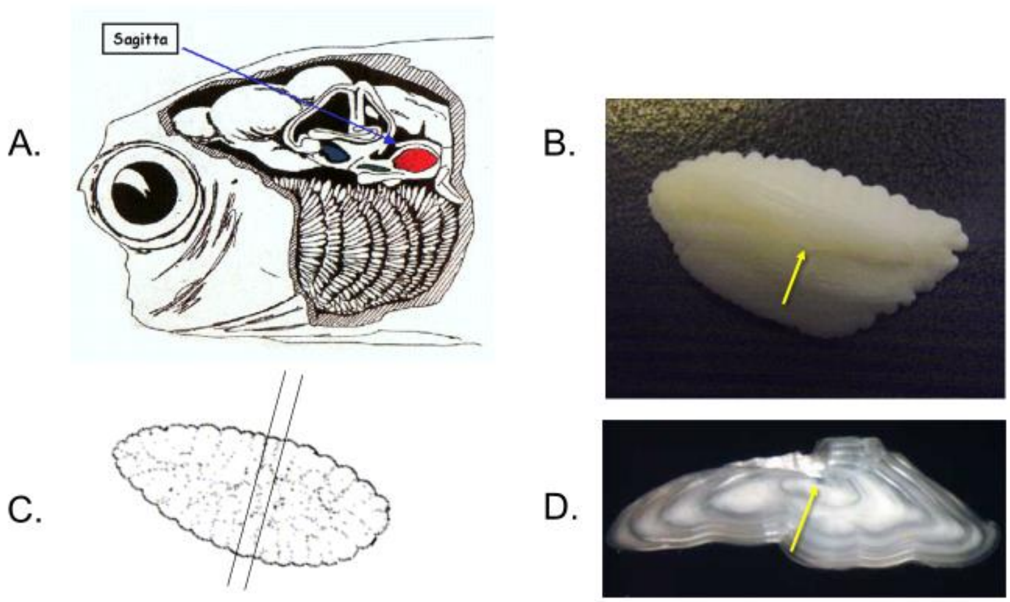


Figure S-1.

Figure S-2. Boxplots of lifetime mean element:calcium ratios, by time period; includes 10 Neolithic otoliths, aged approximately 4500 YBP.

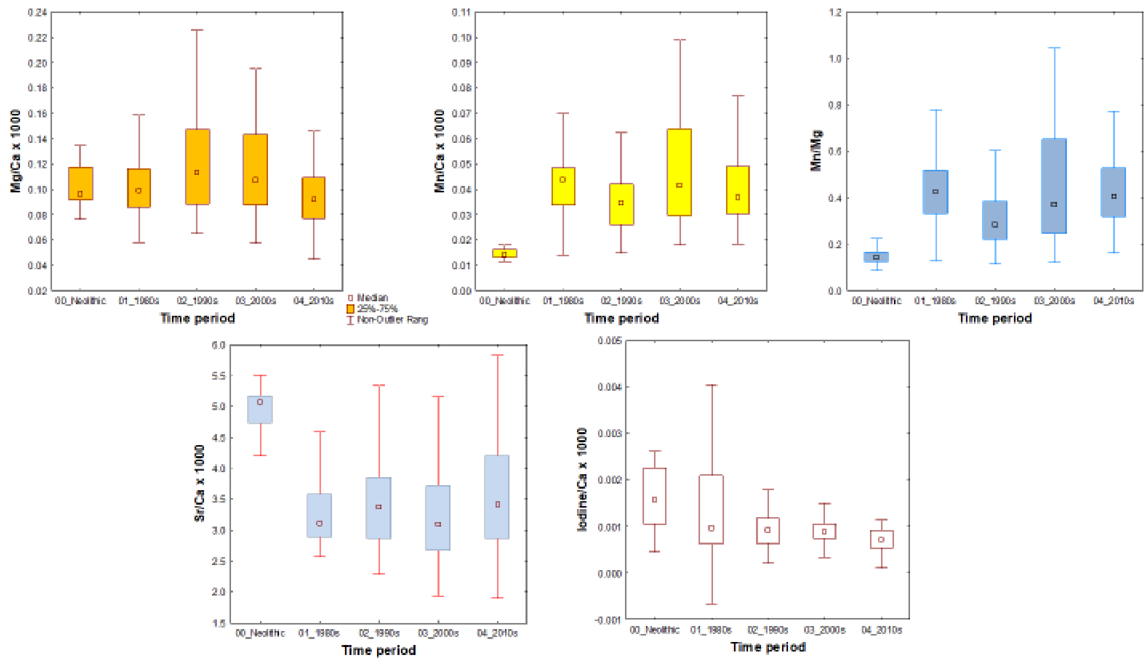


Figure S-2.

Table S-1. Mean, median, minimum, maximum, and percentile data for Mn/Ca and Mn/Mg, calculated by year for modern Baltic cod. Median values were used to set thresholds for hypoxia.

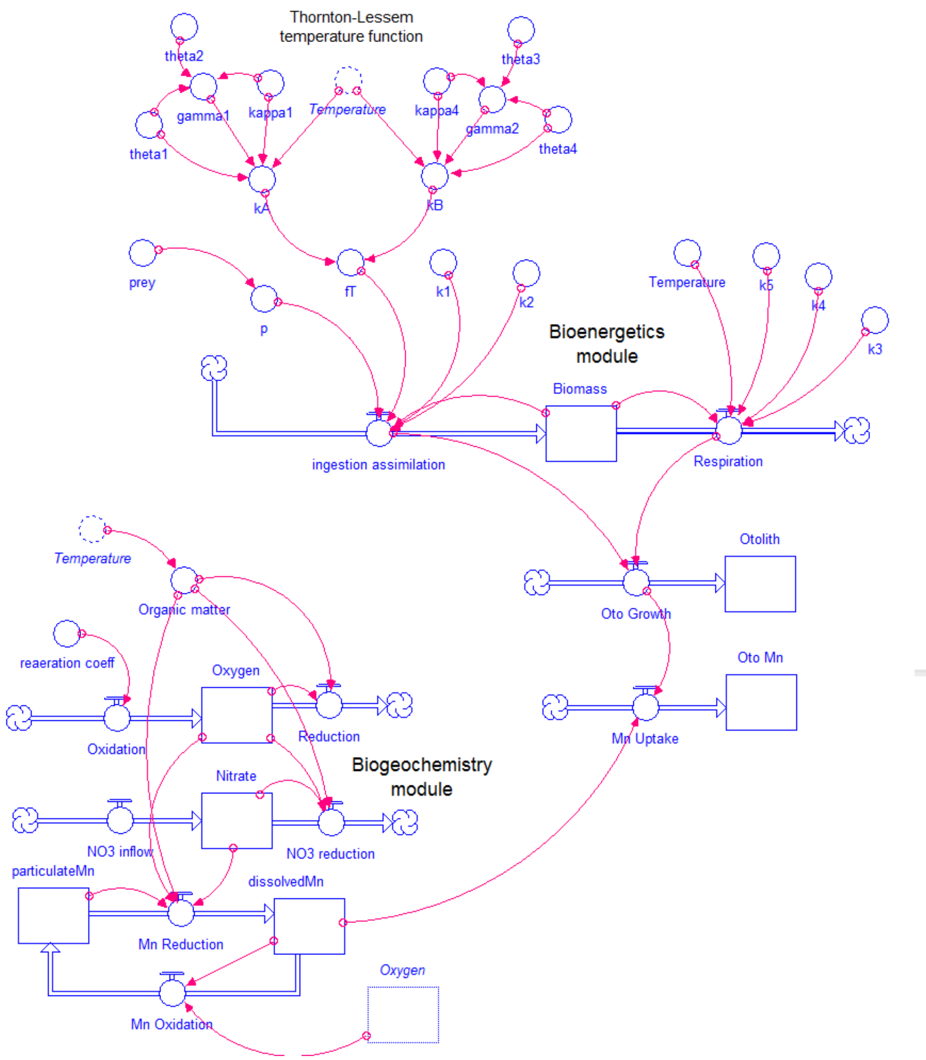
Mn/Ca	Valid N	Mean	**Median**	Min	Max	10th perc.	90th perc	s.d.
Age 0	322	0.056	0.0532	0.017	0.148	0.033	0.081	0.020
Age 1	291	0.045	0.0400	0.010	0.201	0.023	0.070	0.024
Age 2	210	0.026	0.0214	0.004	0.185	0.009	0.045	0.023
Age 3	173	0.017	0.0132	0.002	0.087	0.005	0.034	0.014
Age 4	106	0.014	0.0090	0.001	0.069	0.003	0.031	0.013
Age 5	54	0.013	0.0084	0.001	0.077	0.002	0.030	0.016
Age 6+	25	0.016	0.0067	0.001	0.060	0.003	0.035	0.015

Mn/Mg	Valid N	Mean	**Median**	Min	Max	10th perc.	90th perc	s.d.
Age 0	322	0.55	0.508	0.10	2.71	0.27	0.84	0.27
Age 1	291	0.43	0.382	0.08	3.34	0.19	0.68	0.30
Age 2	210	0.26	0.200	0.04	1.78	0.08	0.50	0.24
Age 3	173	0.19	0.132	0.02	1.35	0.05	0.43	0.19
Age 4	106	0.18	0.104	0.02	1.27	0.03	0.37	0.20
Age 5	54	0.19	0.105	0.01	1.10	0.03	0.42	0.23
Age 6+	25	0.27	0.161	0.02	0.97	0.05	0.57	0.24

A conceptual model of otolith uptake and incorporation of manganese.

This exercise was conducted to explore how both fish growth (an endogenous process) and the presence of dissolved manganese in a fish's ambient environment (due to exogenous, biogeochemical processes) contribute to the observed patterns of Mn in otoliths. A simulation model was constructed in STELLA, using differential equations (Figure S-3). The model consists of a bioenergetics module that keeps track of ingestion/assimilation, respiration, and growth based on Limburg (1996). A biogeochemistry module oxidizes organic matter by sequential reduction of oxygen, nitrate, and manganese. A simpler version of the model uses a statistical relationship between bottom water dissolved oxygen concentration and dissolved Mn (data from C. Slomp): ln(Mn^{2+}, uMol) = -0.6315(dissolved O_2, mL/L) + 2.3167, R^2 = 0.48.

Figure S-3. STELLA diagram of the otolith manganese model. Rectangles are state variables; thick arrows are process flows; circles are coefficients or functions; red arrows indicate inputs to model variables.



The parameterized model equations follow.

Biomass(t) = Biomass(t - dt) + (ingestion_assimilation - Respiration) * dt
INIT Biomass = 1
INFLOWS:
ingestion_assimilation = p * k1 * Biomass^k2 * fT
OUTFLOWS:
Respiration = k3 * Biomass^k4 * exp(k5 * Temperature)

dissolvedMn(t) = dissolvedMn(t - dt) + (Mn_Reduction - Mn_Oxidation) * dt
INIT dissolvedMn = 1
INFLOWS:
Mn_Reduction = if(Oxygen < 1.5 and Nitrate < 0.5) then 0.5 * particulateMn * Organic_matter else 0
OUTFLOWS:
Mn_Oxidation = If (Oxygen > 2) then .05 * dissolvedMn else 0

Nitrate(t) = Nitrate(t - dt) + (NO3_inflow - NO3_reduction) * dt
INIT Nitrate = 2
INFLOWS:
NO3_inflow = 0.1
OUTFLOWS:
NO3_reduction = if(Oxygen < 2) then 0.2 * Organic_matter * Nitrate else 0.0001 * Organic_matter * Nitrate

Otolith(t) = Otolith(t - dt) + (Oto_Growth) * dt
INIT Otolith = 1
INFLOWS:
Oto_Growth = 0.1 * (ingestion_assimilation - Respiration)

Oto_Mn(t) = Oto_Mn(t - dt) + (Mn_Uptake) * dt
INIT Oto_Mn = 0
INFLOWS:
Mn_Uptake = Oto_Growth * dissolvedMn

Oxygen(t) = Oxygen(t - dt) + (Oxidation - Reduction) * dt
INIT Oxygen = 8
INFLOWS:
Oxidation = reaeration_coeff
OUTFLOWS:
Reduction = .012 * Organic_matter * Oxygen

particulateMn(t) = particulateMn(t - dt) + (Mn_Oxidation - Mn_Reduction) * dt
INIT particulateMn = 10
INFLOWS:
Mn_Oxidation = If (Oxygen > 2) then .05 * dissolvedMn else 0
OUTFLOWS:
Mn_Reduction = if(Oxygen < 1.5 and Nitrate < 0.5) then 0.5 * particulateMn * Organic_matter else 0

fT = GRAPH(Temperature)
(0.00, 0.0311), (2.11, 0.0381), (4.21, 0.0657), (6.32, 0.232), (8.42, 0.26), (10.5, 0.377), (12.6, 0.481), (14.7, 0.612), (16.8, 0.747), (18.9, 0.841), (21.1, 0.962), (23.2, 1.00), (25.3, 0.879), (27.4, 0.723), (29.5, 0.464), (31.6, 0.0173), (33.7, 0.00346), (35.8, 0.00), (37.9, 0.00), (40.0, 0.00)

k1 = 0.15
k2 = 0.1
k3 = 0.036
k4 = 0.776

- k5 = 0.02
- Organic_matter = 10 * Temperature
- p = .2 * prey
- prey = 400 + 400 * SIN(2*pi * (TIME - 8)/52)
- reaeration_coeff = 3
- Temperature = 16 + 12 * SIN(2*PI * (TIME - 11)/52)