Understanding the effects of climate warming on food webs via individual-level physiology

Max Lindmark, Swedish University of Agricultural Sciences,
Department of Aquatic Resources

maxlindmark.netlify.com | @max_lindmark

GMRI May 2021 Seminar

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- Anna Gårdmark (SLU)
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Students

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Coauthors:

- Asta Audzijonyte (UTAS)
- Julia Blanchard (UTAS)
- Michele Casini (SLU)
- Sean Anderson (DFO)
- Viktor Thunell (SLU)
- Romain Forrester (UTAS)
- Jonatan Reum (NOAA)

… And others!

Impacts of warming on individuals and food webs

Predicted responses of animal communities to climate change:

- Altered phenology
- Changes in spatial distribution
- **“Shrinking”**

Daufresne et al., (2009) PNAS

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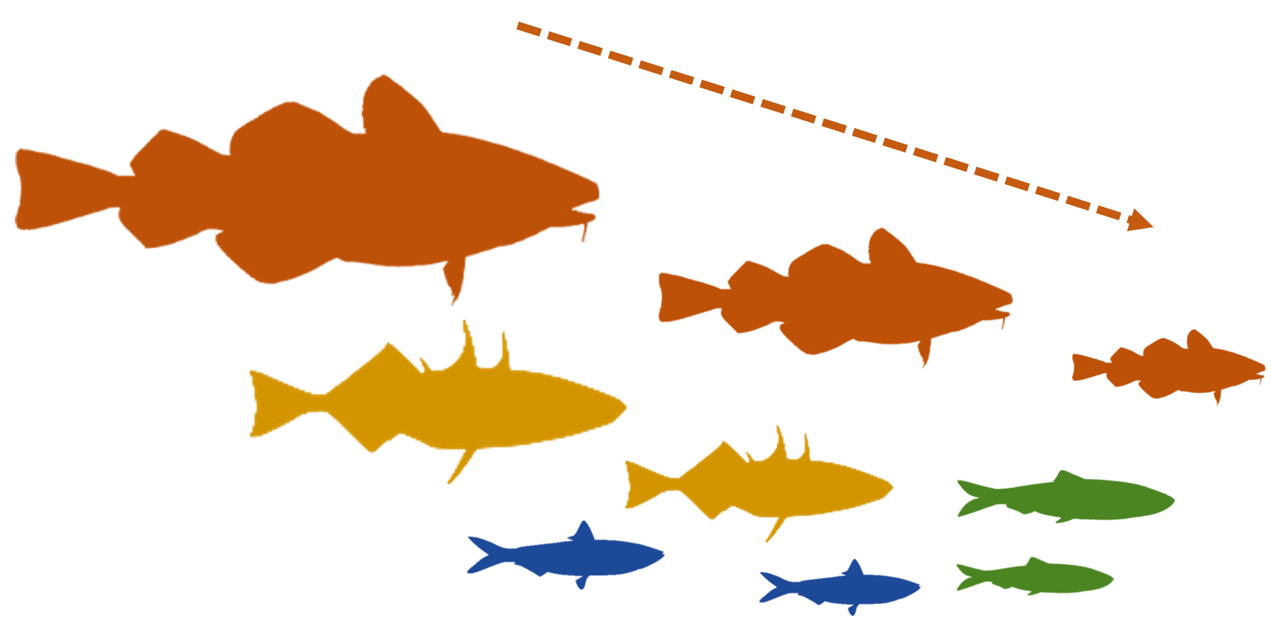

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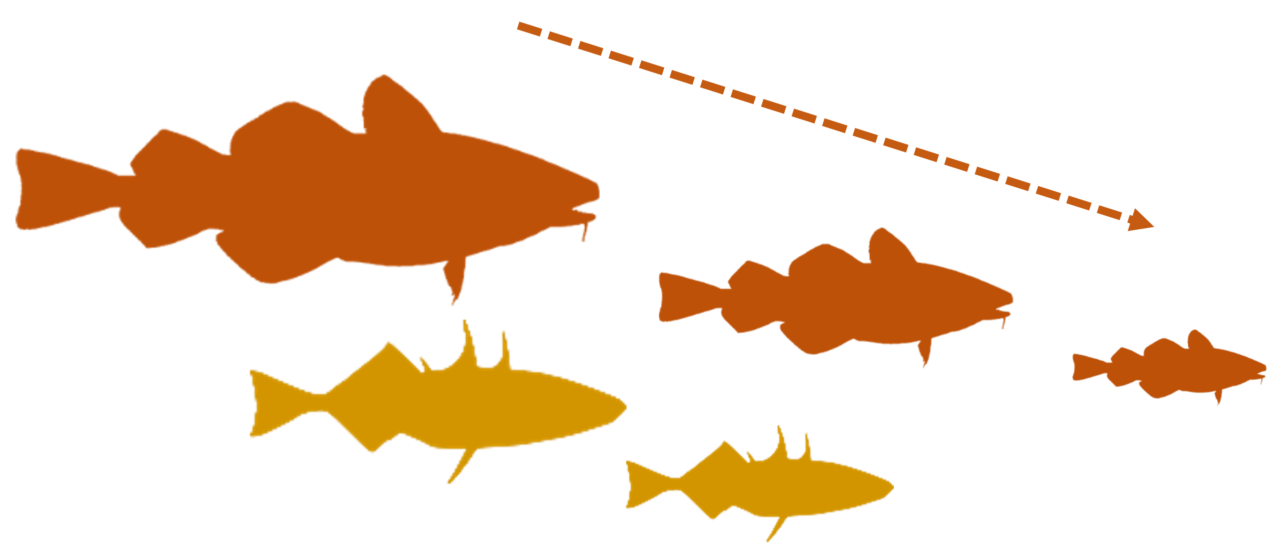

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Impacts of warming on individuals and food webs

Predicted responses of animal communities to climate change:

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Global Change Biology (2014) 20, 1023–1031, doi: 10.1111/gcb.12514

OPINION

Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes

ALAN R. BAUDRON[1], COBY L. NEEDLE[2], ADRIAAN D. RIJNSDORP[3] and C. TARA MARSHALL[1]

[1]*Institute of Biological and Environmental Sciences, University of Aberdeen, Tillydrone Avenue, Aberdeen, AB24 2TZ, Scotland UK,* [2]*Marine Laboratory, Marine Scotland - Science, PO Box 101 375 Victoria Road, Aberdeen, AB11 9DB, Scotland UK,* [3]*Institute of Marine Resources, and Ecosystem Studies and Aquaculture and Fisheries Group, IMARES, Haringkade 1, IJmuiden, 1976 CP, The Netherlands*

Daufresne et al., (2009) PNAS

Impacts of warming on individuals and food webs

1. Climate warming increases the metabolism and resource demands of ectotherm organisms

Impacts of warming on individuals and food webs

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2. Effects of temperature depend on body size and food levels

Impacts of warming on individuals and food webs

1. Climate warming increases the metabolism and resource demands of ectotherm organisms

2. Effects of temperature depend on body size and food levels

3. Need to account for physiological and food web effects

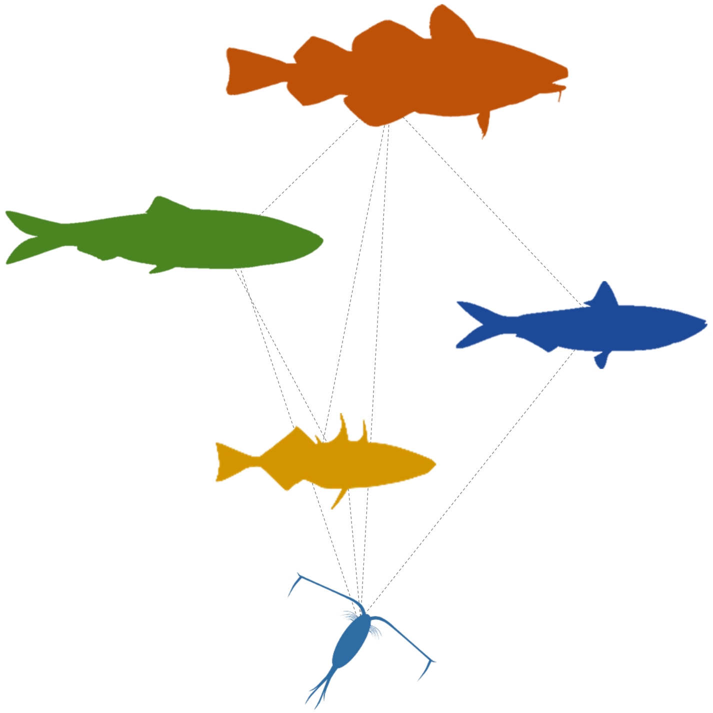
Impacts of warming on individuals and food webs

Contents

Body size & food webs

- Species-level energetics from average size of a species

- Body size is a trait of a species

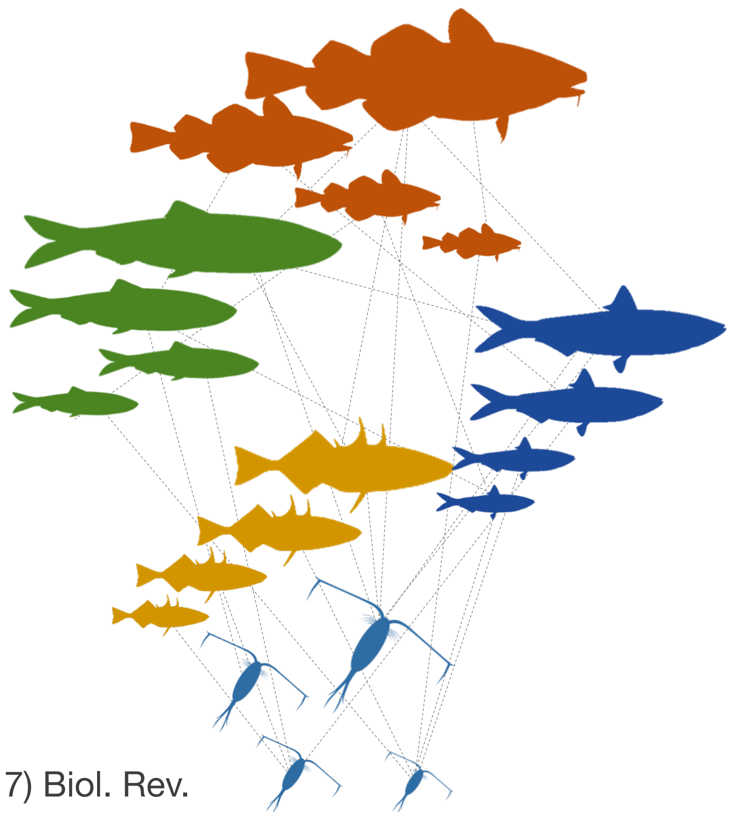


Yodzis & Innes (1992) AmNat; De Roos & Persson (2013) Ecology; Vasseur & McCann (2015) AmNat; Brose et al (2017) Biol. Rev.

Body size & food webs

- Body size is also a trait of an individual

- Temperature affects life stages differently!



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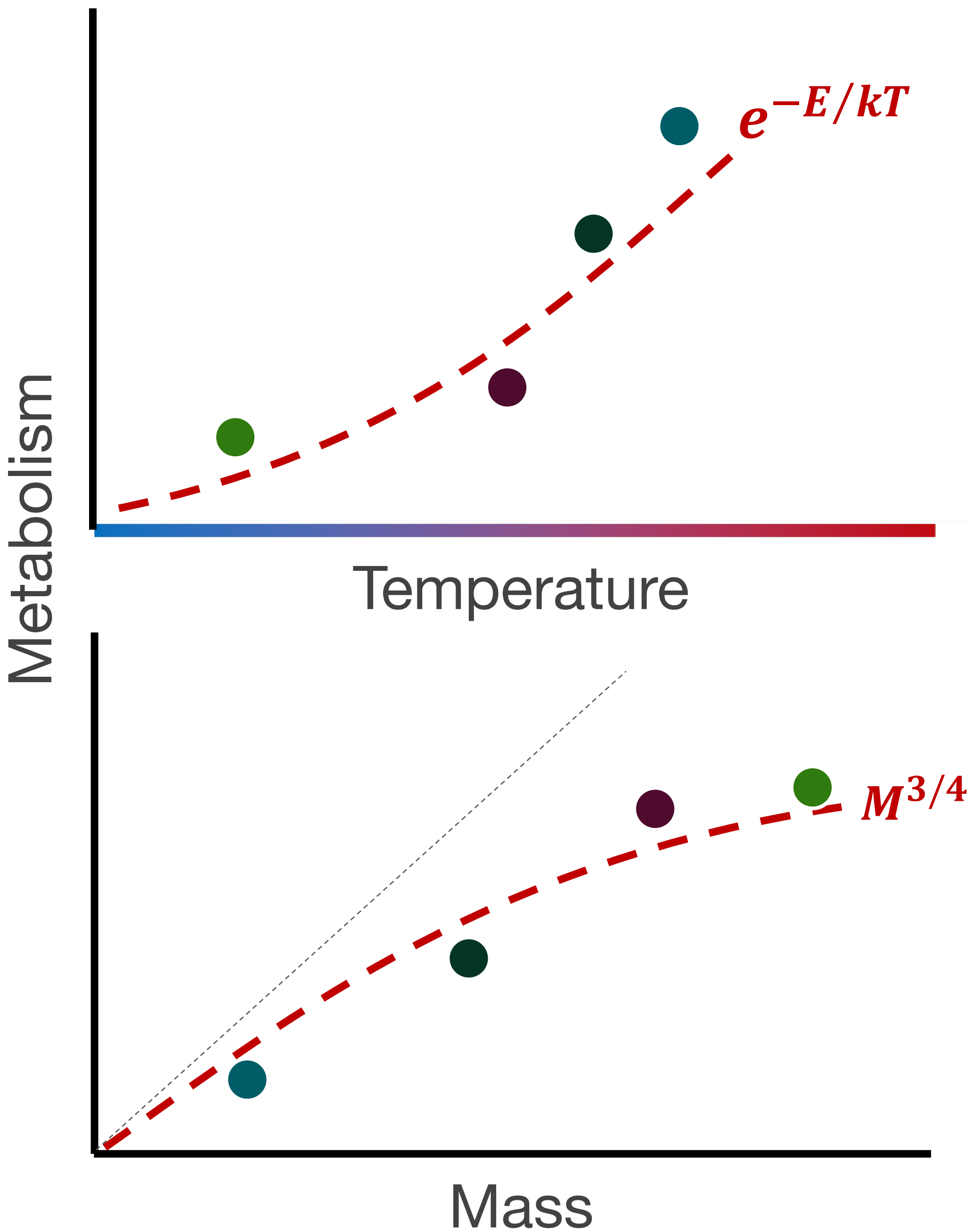
4. Outlook & future work

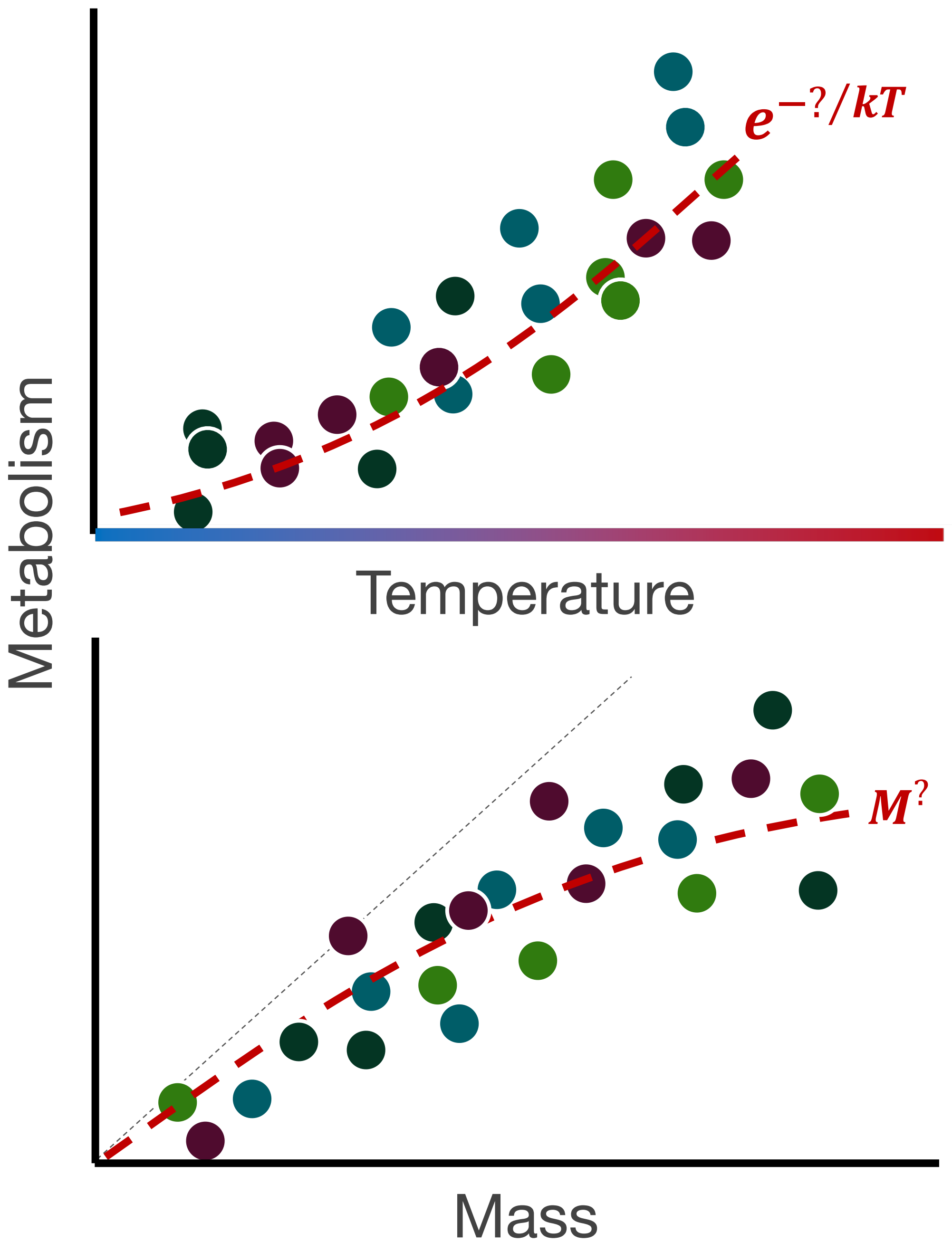
Metabolism increases with temperature and size



$$B = B_0 M^{3/4} e^{-E/kT}$$

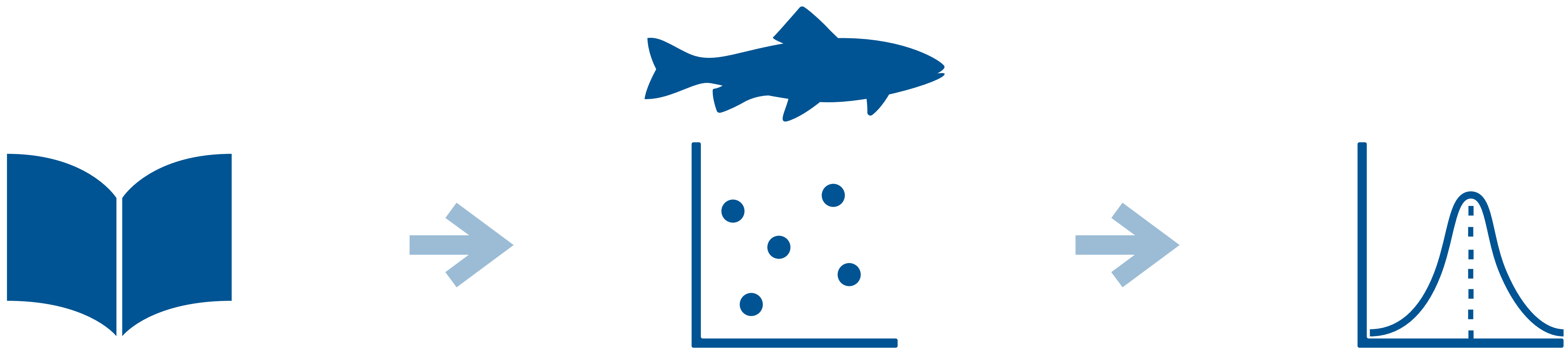
Kleiber (1932) Hilgardia; Brown et al. (2004) Ecology

Metabolism increases with temperature and size



Kleiber (1932) Hilgardia; Brown et al. (2004) Ecology

Literature search



>4500 studies

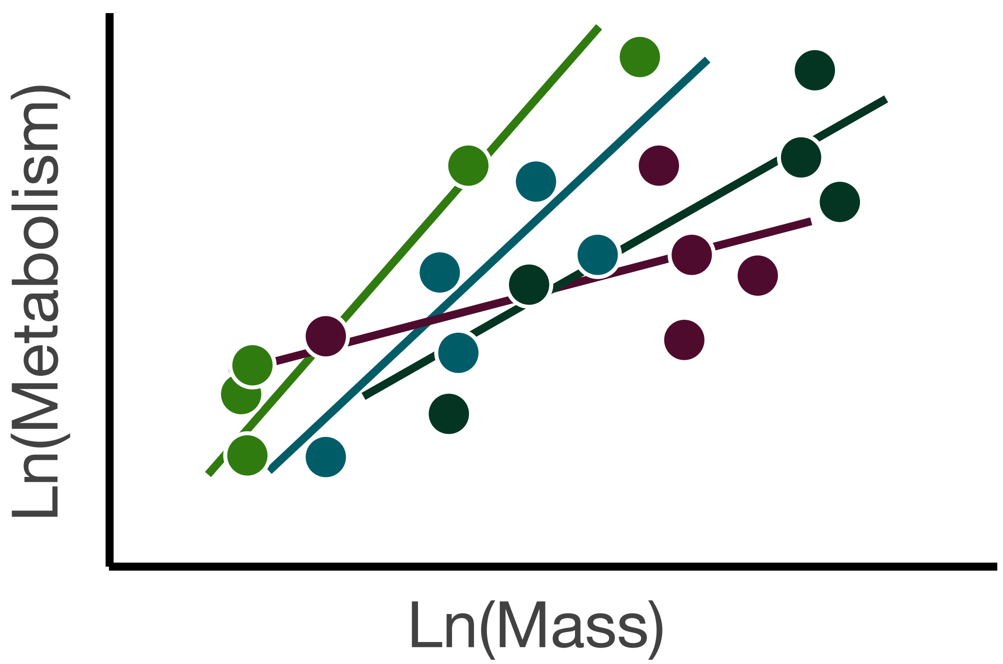
- Metabolism
- Feeding rates
- Growth

3570 data points

>60 species

Lindmark et al., (2020) BioRxiv

Size and temperature dependence of rates

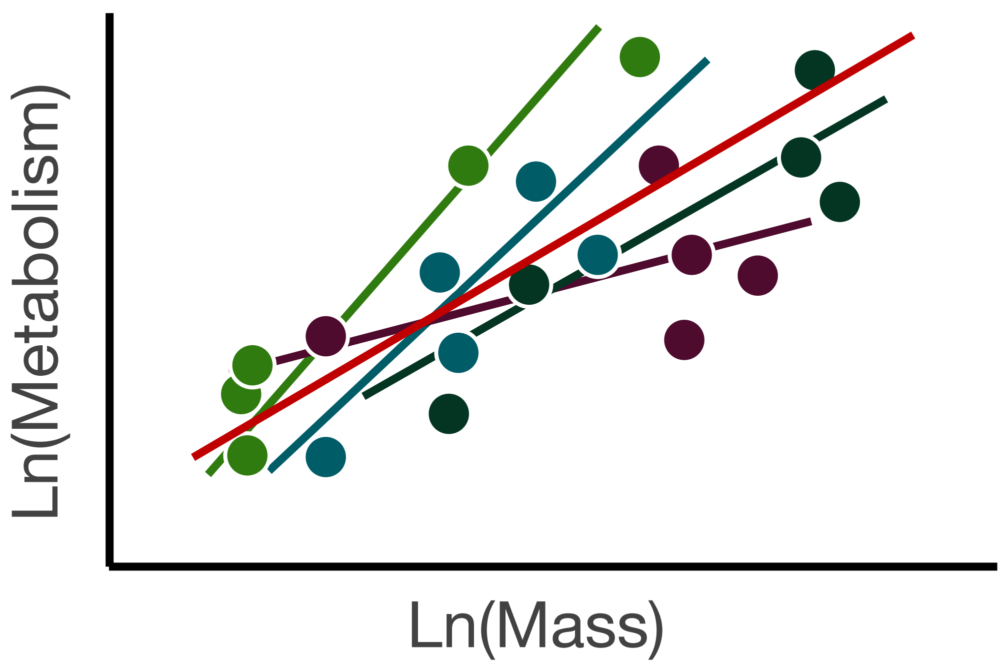


Hierarchical Bayesian models

- Variation within and between species
- Estimate parameters with shrinkage: find general relationships
- “Borrow” from data-rich species

Lindmark et al., (2020) BioRxiv

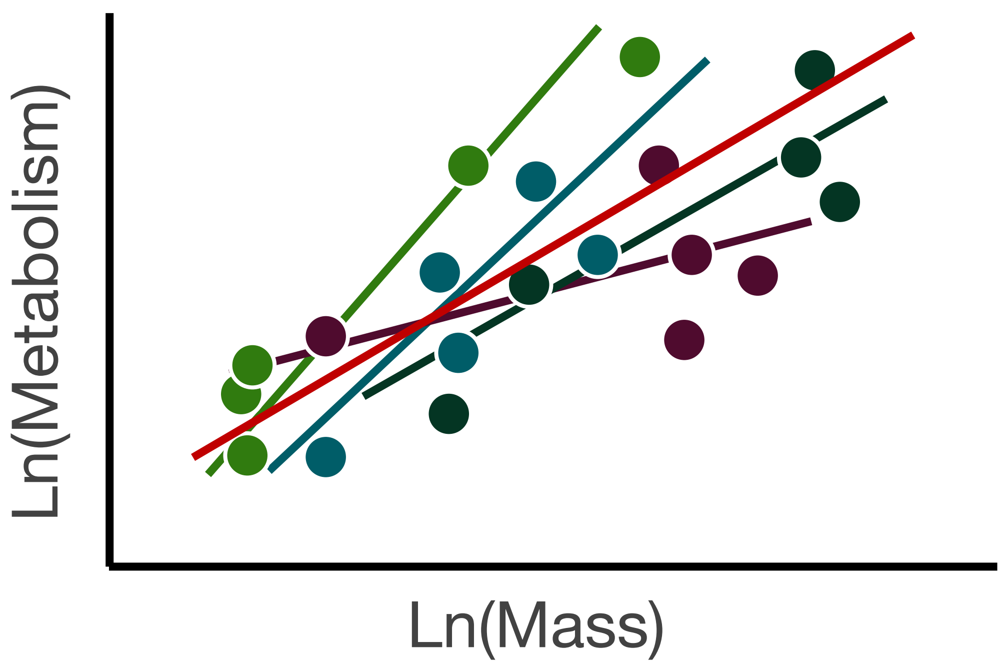
Size and temperature dependence of rates



$$y_{ij} \sim N(\mu_{ij}, \sigma^2)$$
$$\mu_{ij} = \beta_{0j} + \beta_1 m_i + \beta_2 t_{A,i} + \beta_3 t_{A,i} m_i$$
$$\beta_{1:3j} \sim N(\mu_{\beta_{1:3}}, \sigma_{\beta_{1:3}})$$

Lindmark et al., (2020) BioRxiv

Size and temperature dependence of rates



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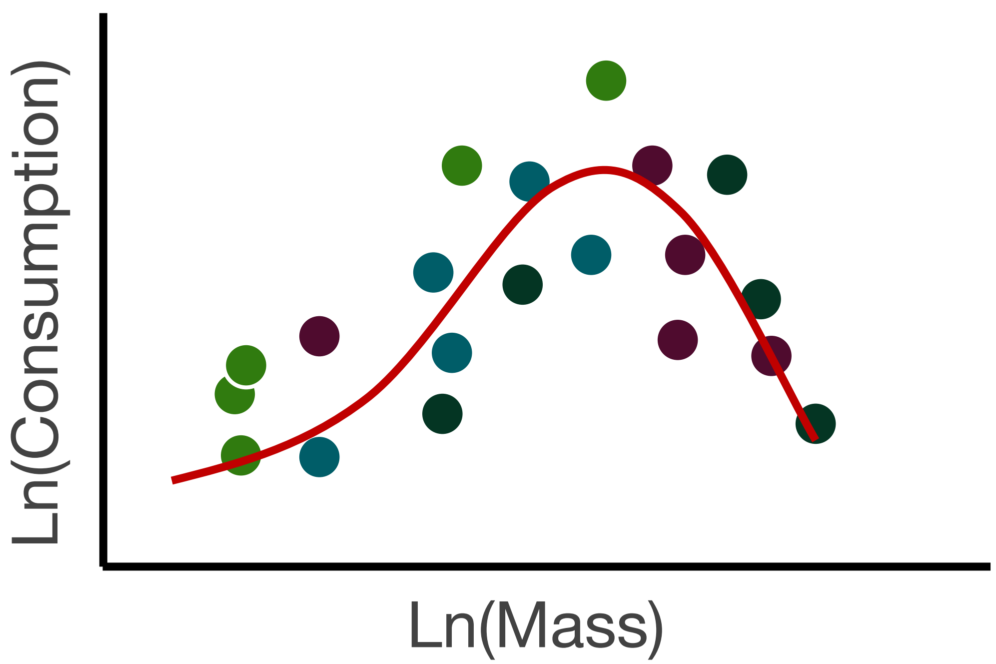
Size and temperature dependence of rates



$$y_{ij} \sim N(\mu_{ij}, \sigma^2)$$

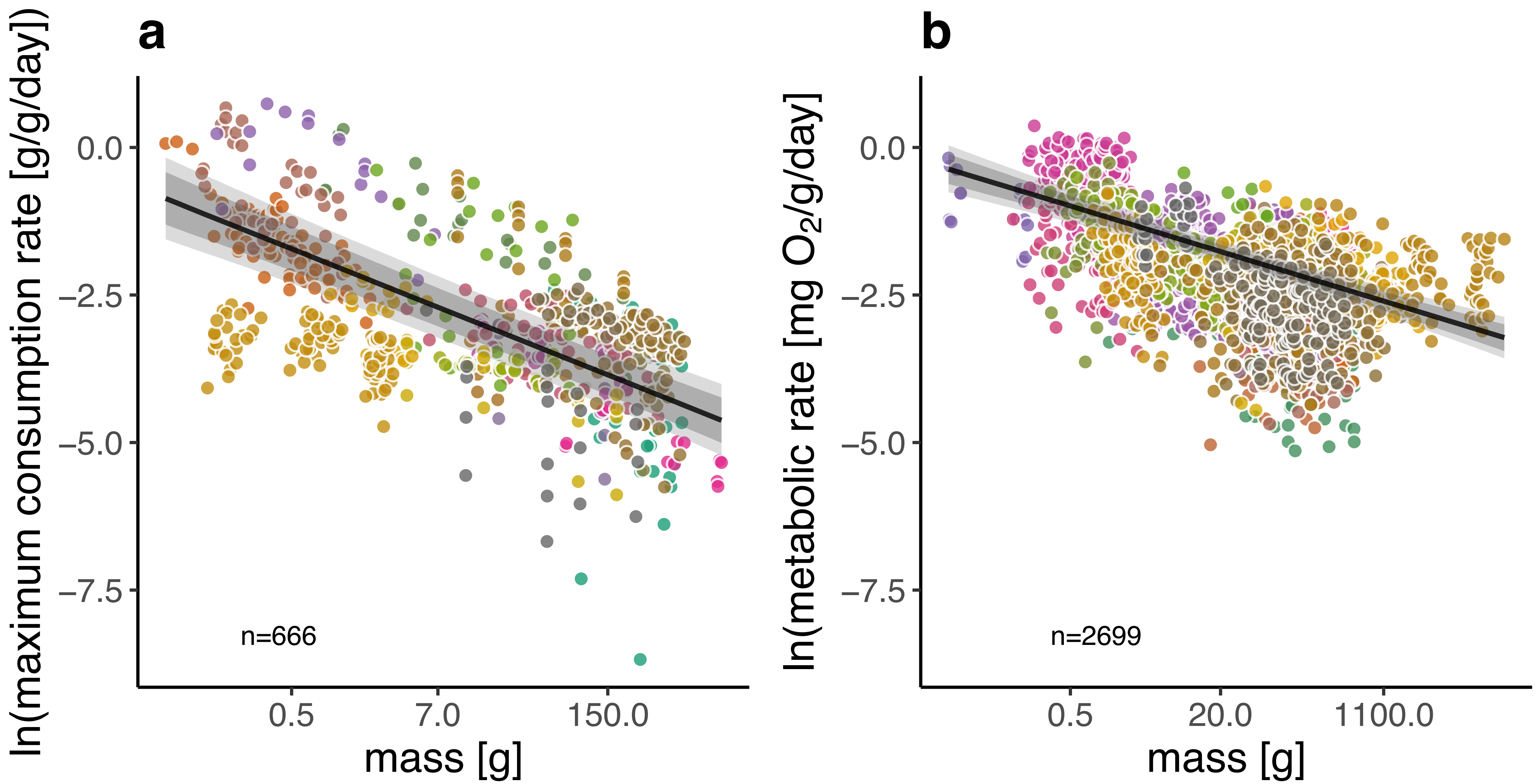
$$\mu_{ij} = \frac{C_{0j}(T_c)e^{E_j(1/kT_c - 1/kT)}}{1 + e^{E_h(1/kT_h - 1/kT)}}$$

$$C_{0j} \sim N(\mu_{C_0}, \sigma_{C_0})$$

$$E_j \sim N(\mu_E, \sigma_E)$$

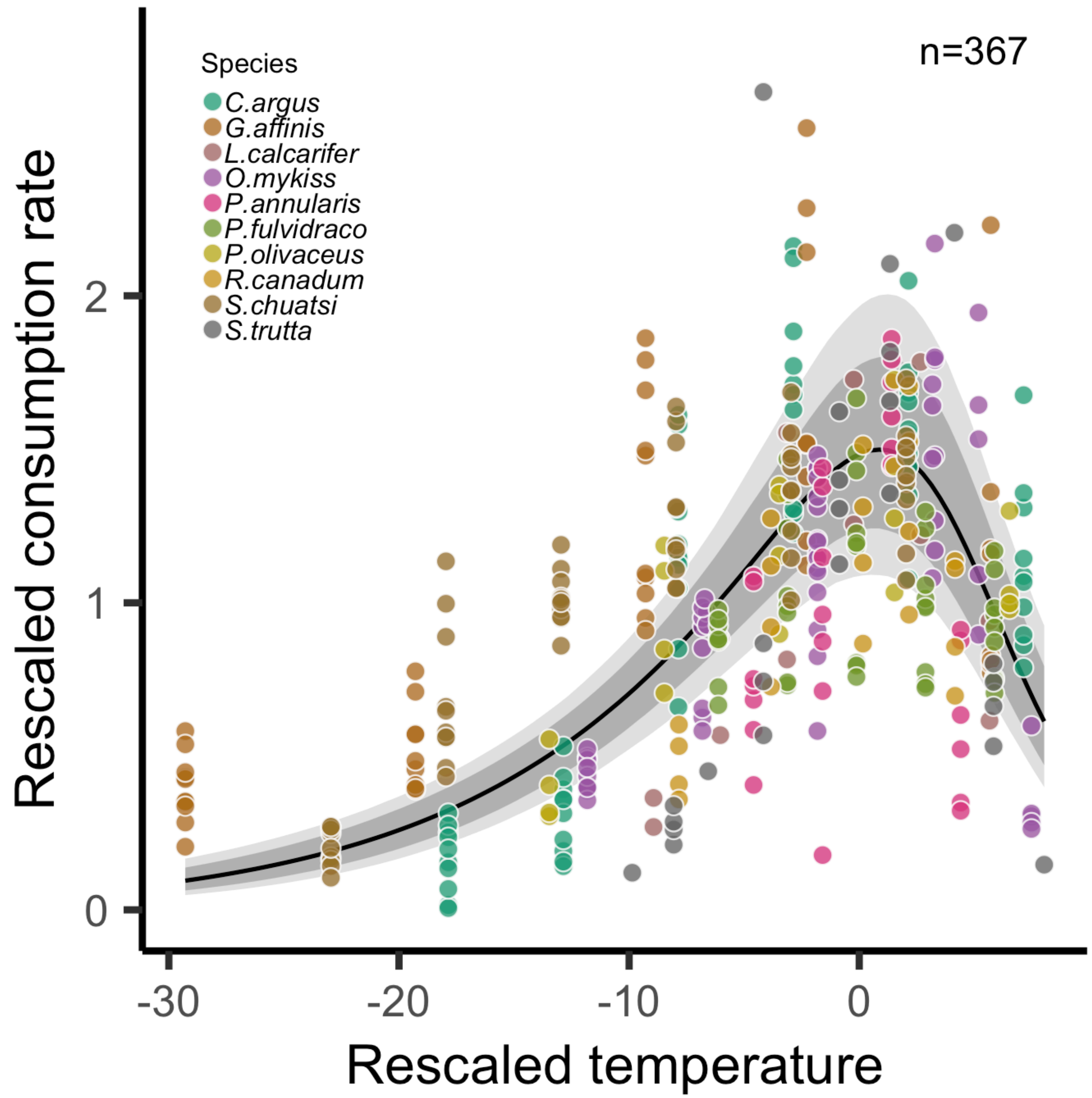
Lindmark et al., (2020) BioRxiv

Smaller exponent for metabolism than consumption



Lindmark et al., (2020) BioRxiv

Consumption rates decline if too warm



Lindmark et al., (2020) BioRxiv

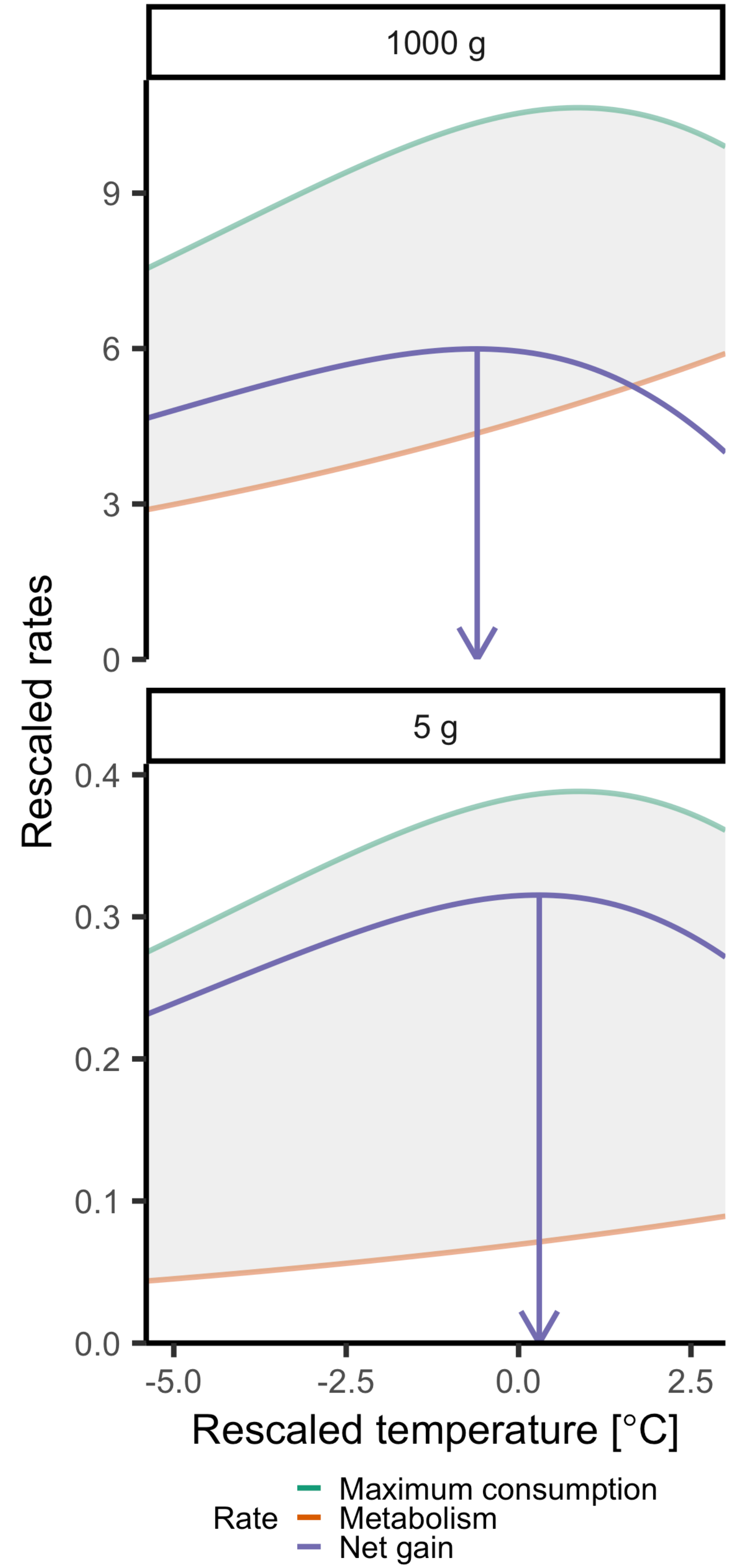
Simple growth model

- Metabolism catches up with consumption as fish growth
- Consumption rate increases first and then declines with warming
- Put this in simple growth model

$$\frac{dM}{dt} = aM^b - cM^d$$

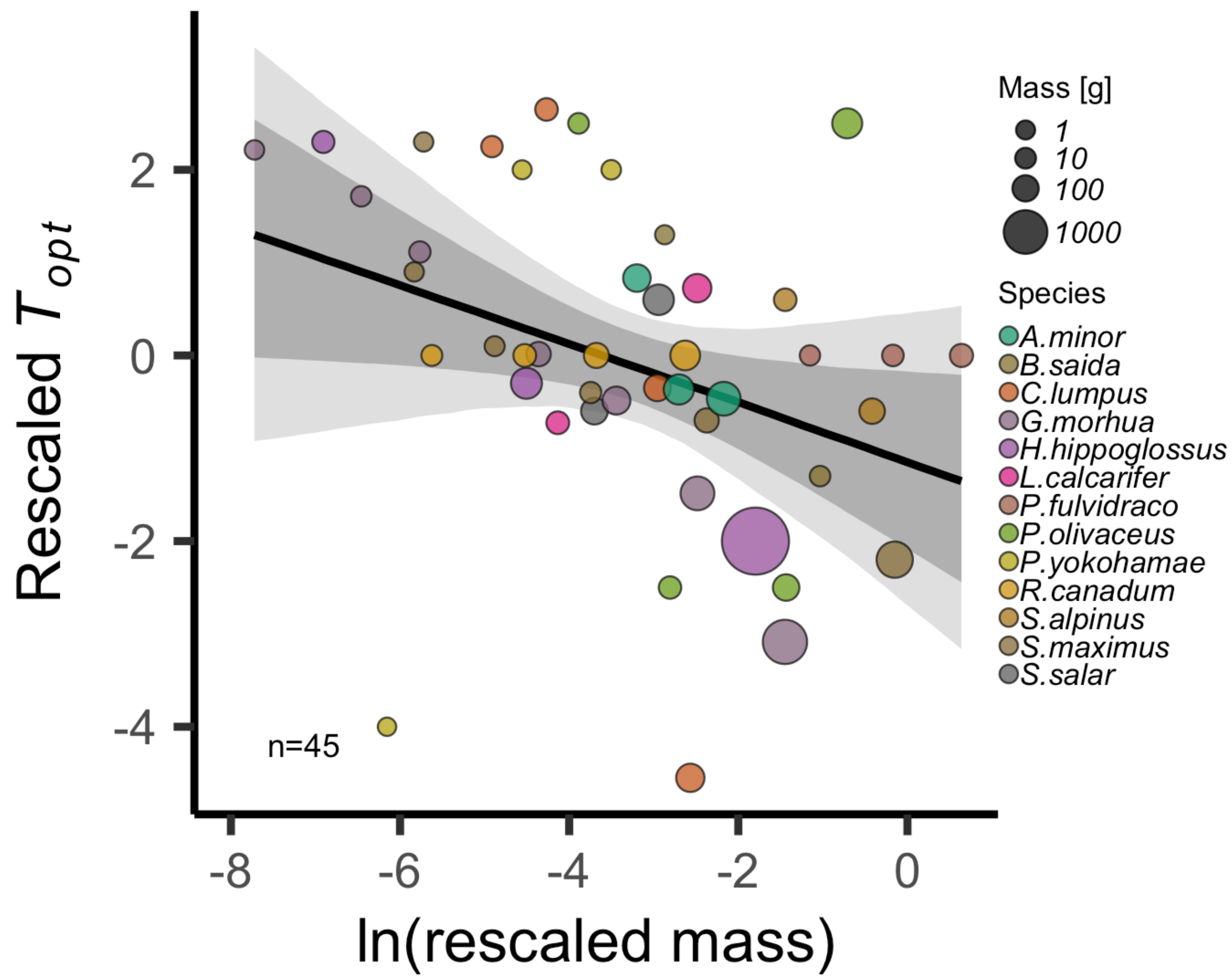
Lindmark et al., (2020) BioRxiv; Morita et al., (2010) OIKOS

$$\frac{dM}{dt} = aM^b - cM^d$$



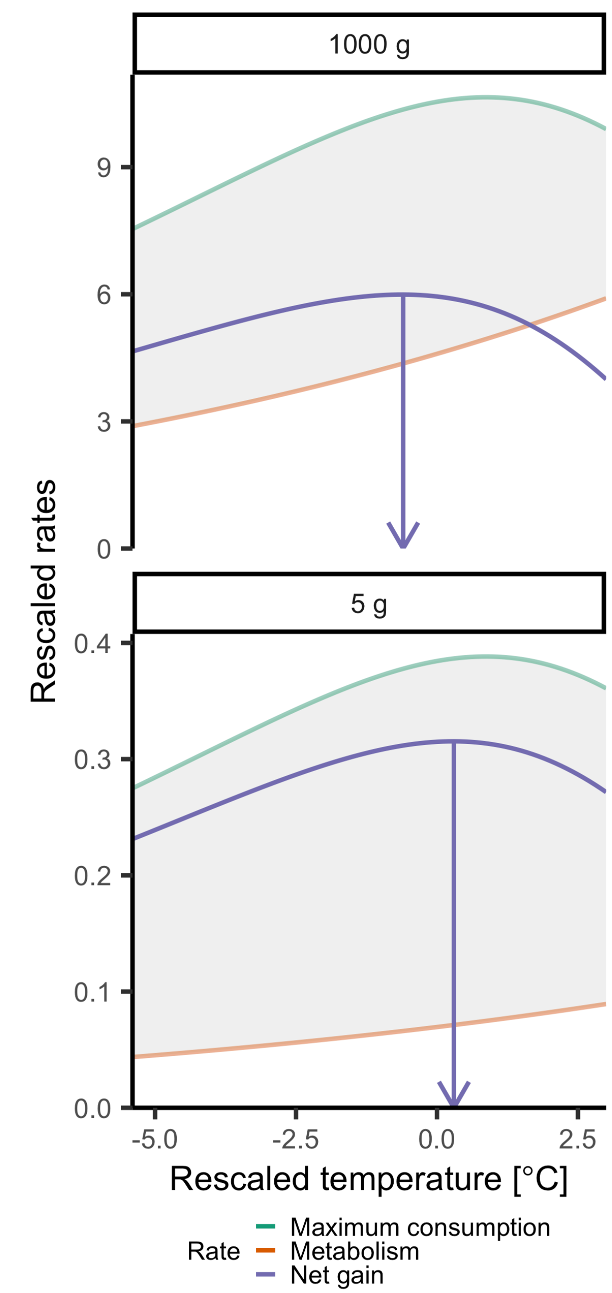
Lindmark et al., (2020) BioRxiv

Optimum growth temperature declines with size



Lindmark et al., (2020) BioRxiv

- Metabolism catches up with consumption as fish growth
- Consumption rate increases first and then declines with warming
- Simple mechanism causing TSR?



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Mechanistic food web models

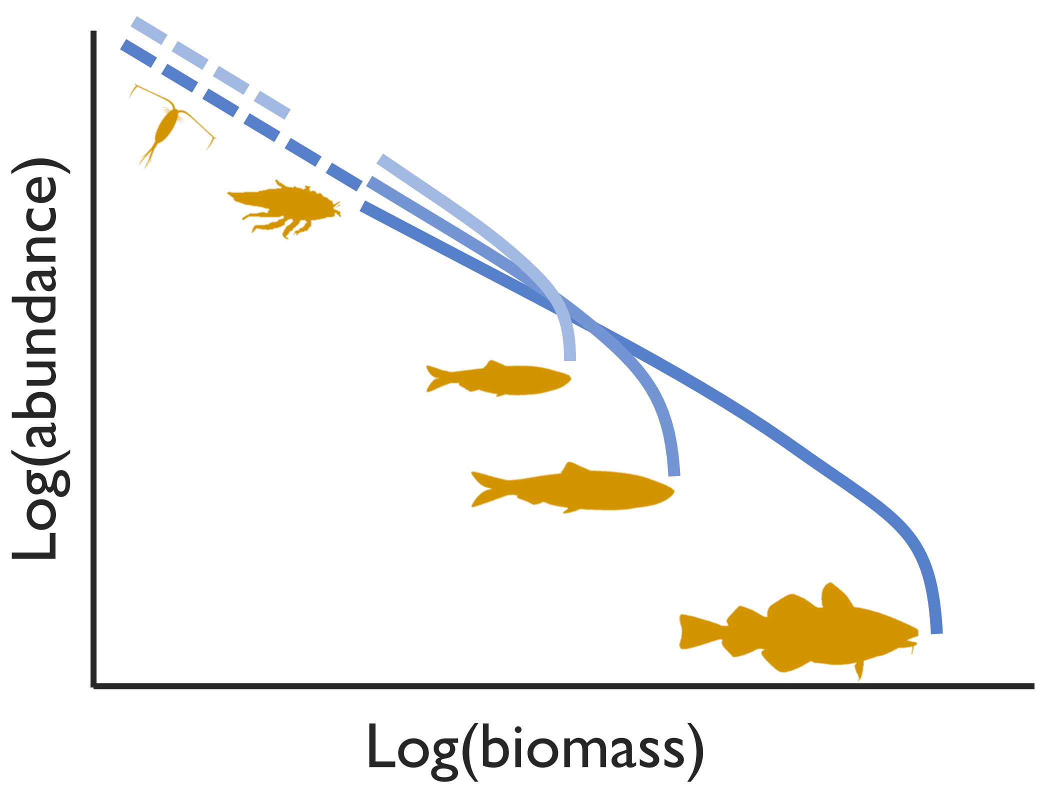
- How do growth rates, size-at-age and size-structure change with warming in food webs?

- What is the role of physiological (top down) effects vs changes in resources (bottom up) for the effect of warming on size-structure?

- How does that affect fisheries reference points and targets?

R:mizer; Hartvig et al. (2011) Journal of Theoretical Biology; Scott et al. (2014) Methods in Ecology & Evolution ; Lindmark et al (in prep)

Size-spectrum model



McKendrick von Foerster equation

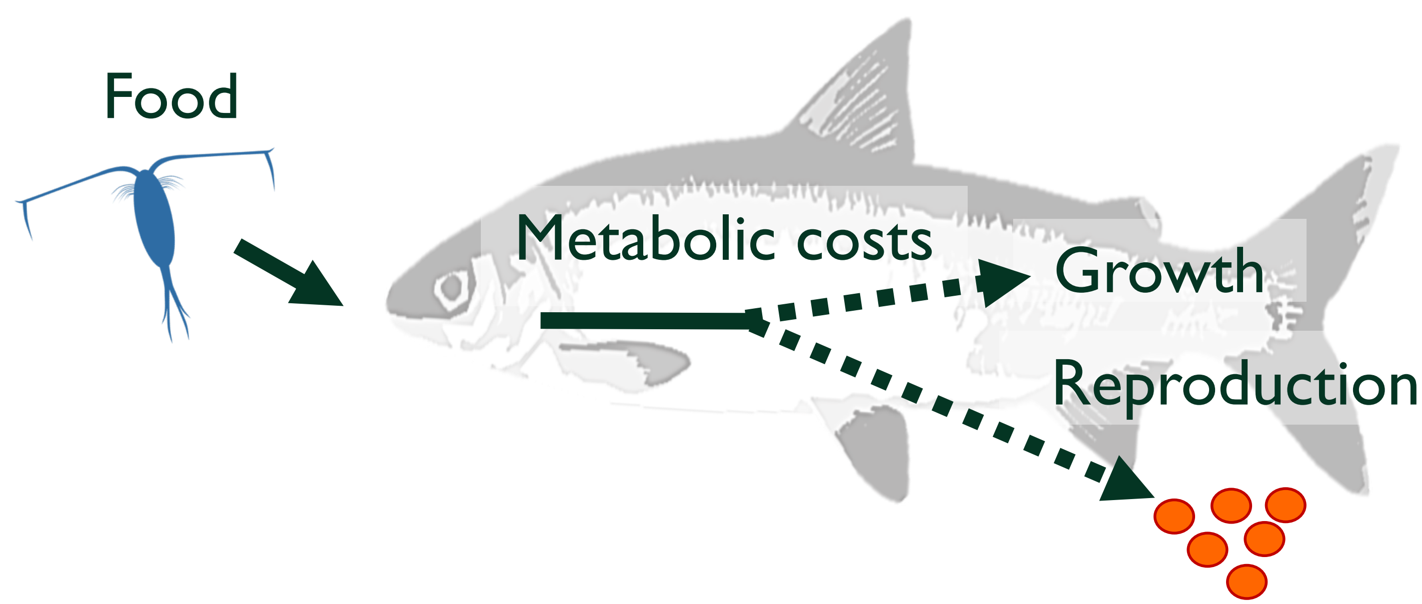
- General model inspired by the Baltic Sea
- Cod, Sprat, Herring, Benthos, Plankton

$$\frac{\partial N_i(w)}{\partial t} + \frac{\partial g_i(w) N_i(w)}{\partial w} = -\mu_i(w) N_i(w)$$

R:mizer; Hartvig et al. (2011) Journal of Theoretical Biology; Scott et al. (2014) Methods in Ecology & Evolution ; Lindmark et al (in prep)

Size-spectrum model

- Assumptions made at the individual-level
- Food dependent growth and development
- Type II Functional response



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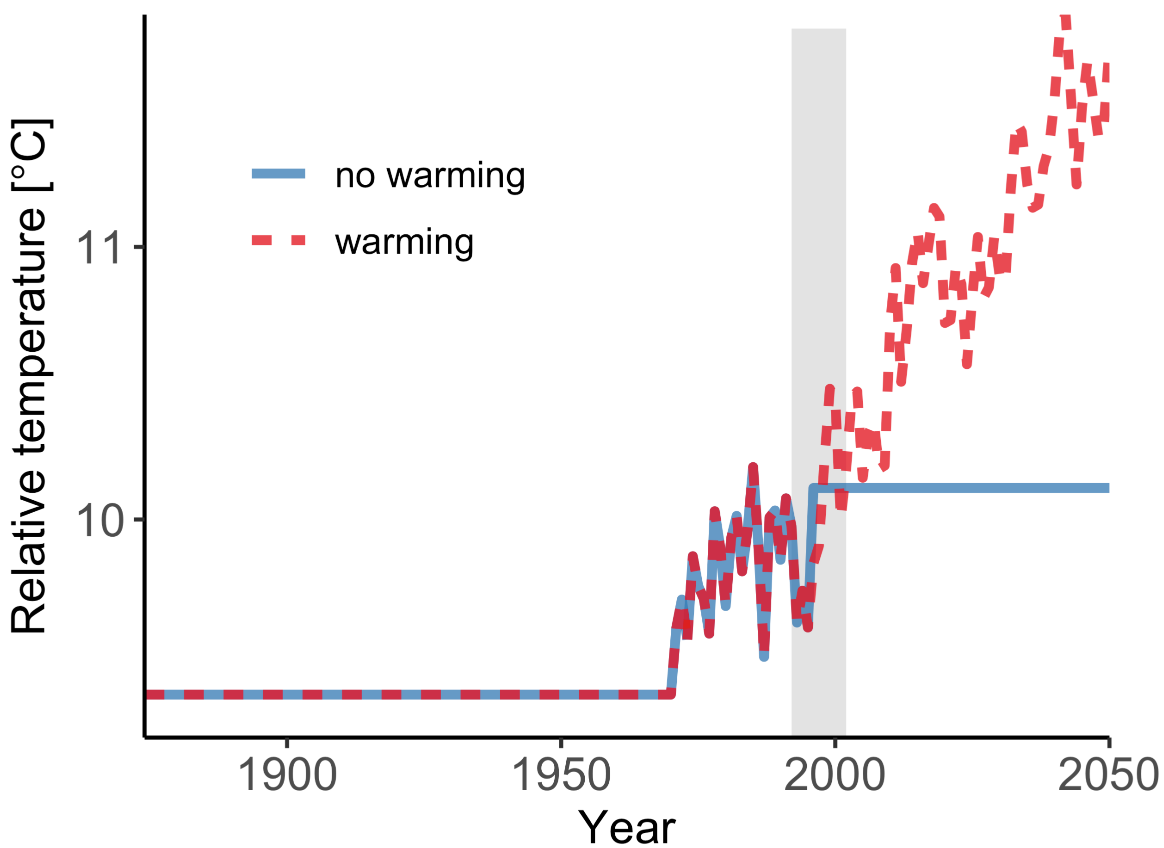
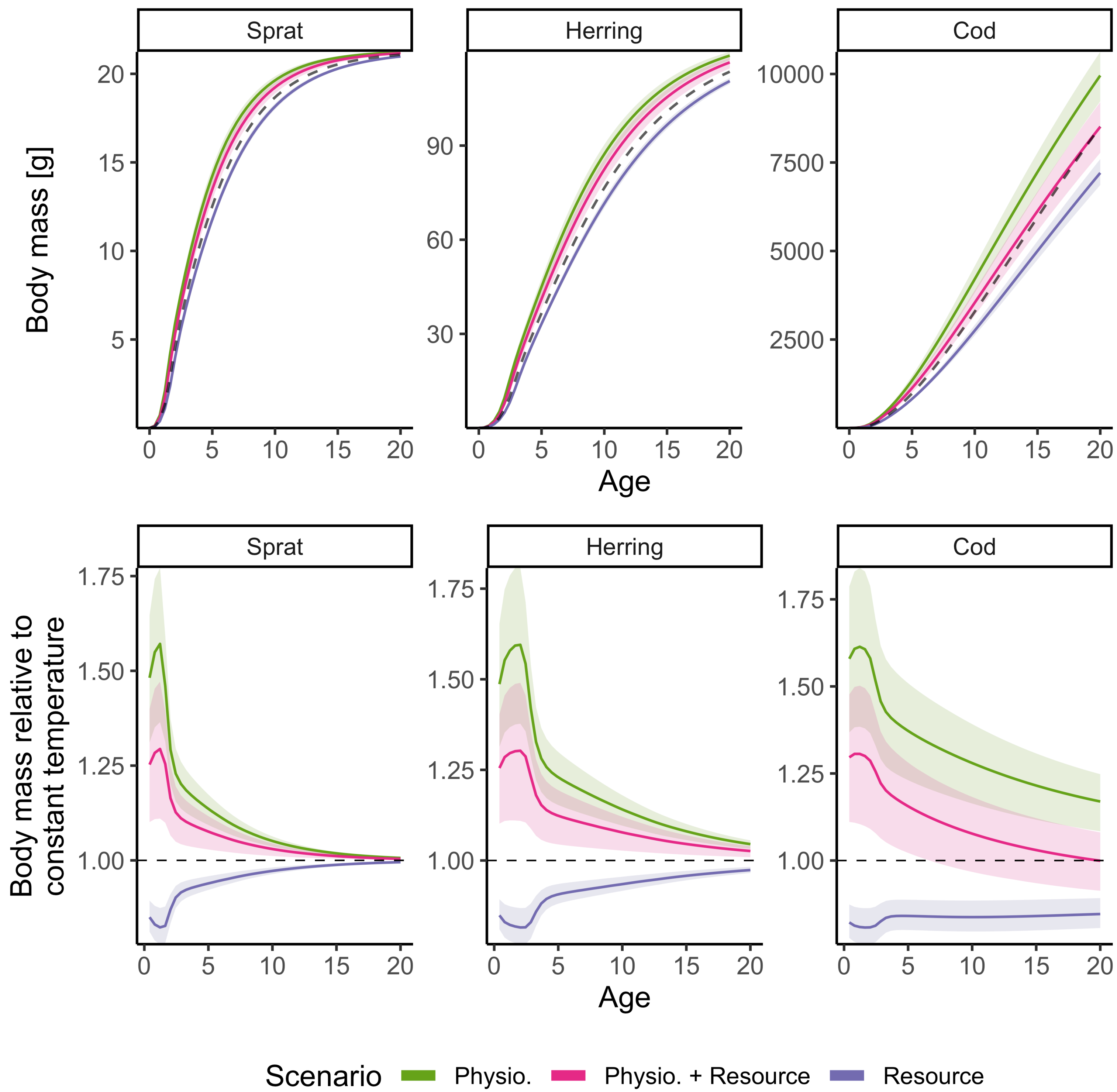
Size-spectrum model



- Simulation through time
- Time varying fishing mortality
- Time varying ocean temperatures from regional coupled model projection

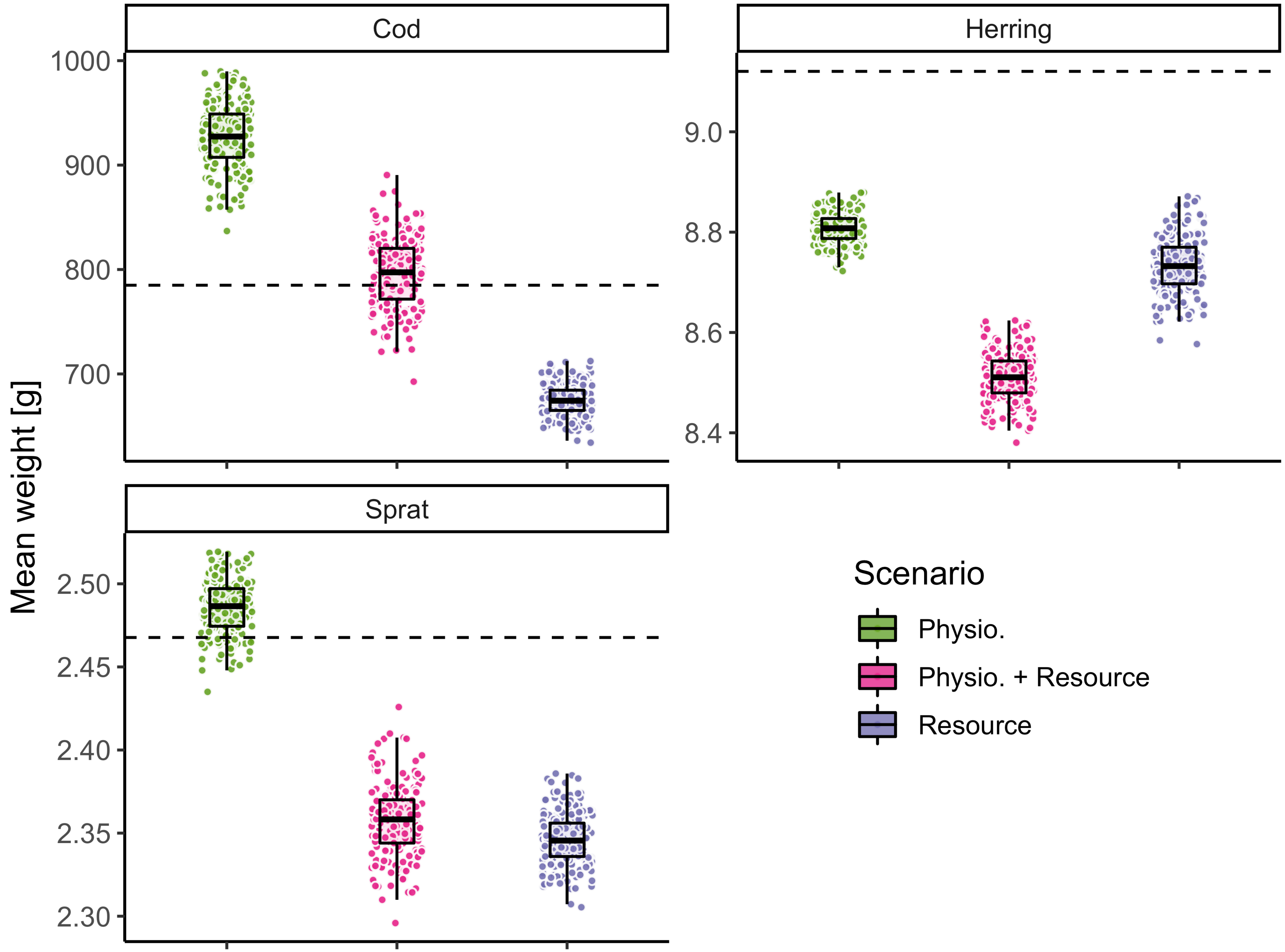
R:mizer; Hartvig et al. (2011) Journal of Theoretical Biology; Scott et al. (2014) Methods in Ecology & Evolution ; Lindmark et al (in prep)

Size-spectrum model: growth rates



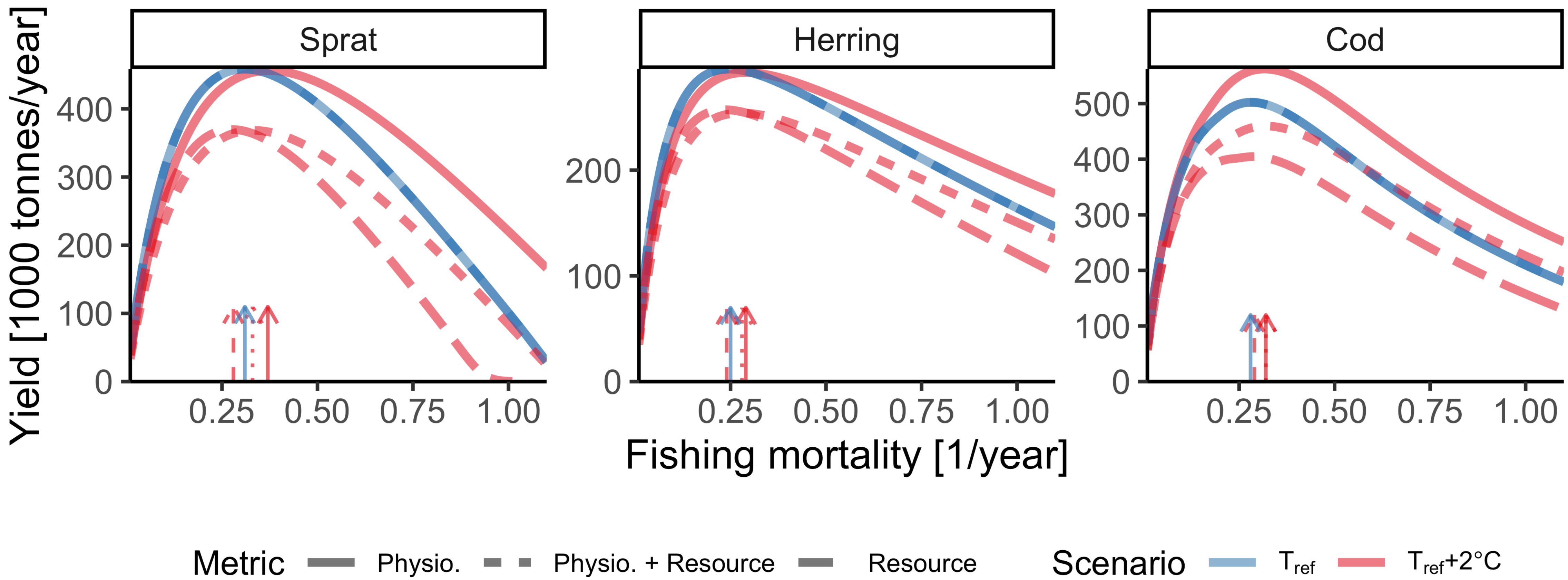
Lindmark et al (in prep)

Size-spectrum model: mean weight



Lindmark et al (in prep)

Size-spectrum model: reference points & targets



Lindmark et al (in prep)

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Large scale natural experiment

- Biotest Lake: enclosed lagoon on the Baltic coast
- 1980- : heated with cooling water from nuclear power plant
- +8°C above surrounding sea
- Scientific sampling only source of mortality

Lindmark et al., (in prep); Huss et al., (2019) Global Change Biology

Large scale natural experiment

- Eurasian perch
- > 22 000 back-calculated lengths (operculum bone & otoliths)
- > 8 000 individuals
- 1980-2003 (grid removed in 2004)

Linda Nyman/ArtDatabanken

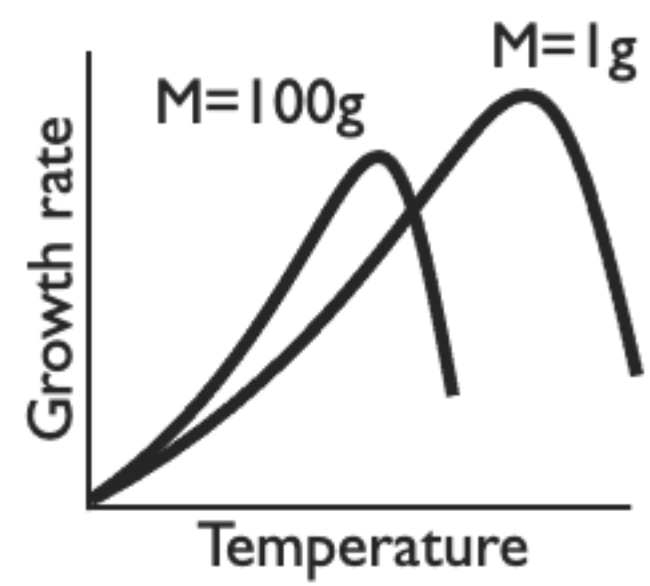
photo: https://www.slu.se/institutioner/akvatiska-resurser/miljoanalys/individnival/Aldersanalys-av-fisk/

Lindmark et al., (in prep); Huss et al., (2019) Global Change Biology

Large scale natural experiment

- Growth exponentially increasing at sub-peak temperatures

- Peak temperature declining function of size



Lindmark et al., (in prep); Huss et al., (2019) Global Change Biology

Large scale natural experiment

- VBGE
- Support for shared or unique parameters?
- Dummy variable for area ([w]arm, [c]old)
- Length-at-age data
- Cohort-varying (j) K and L∞
- Informative priors

Hierarchical VB model with dummy

$$L_i \sim N(\mu_i, \sigma_i^2)$$

$$\mu_i = A_c[L_{\inf_{c,j}}](1 - e^{(-K_{c,j}(age_{j[i]} - t_0))} + A_w[L_{inf_{w,j}} \ldots$$

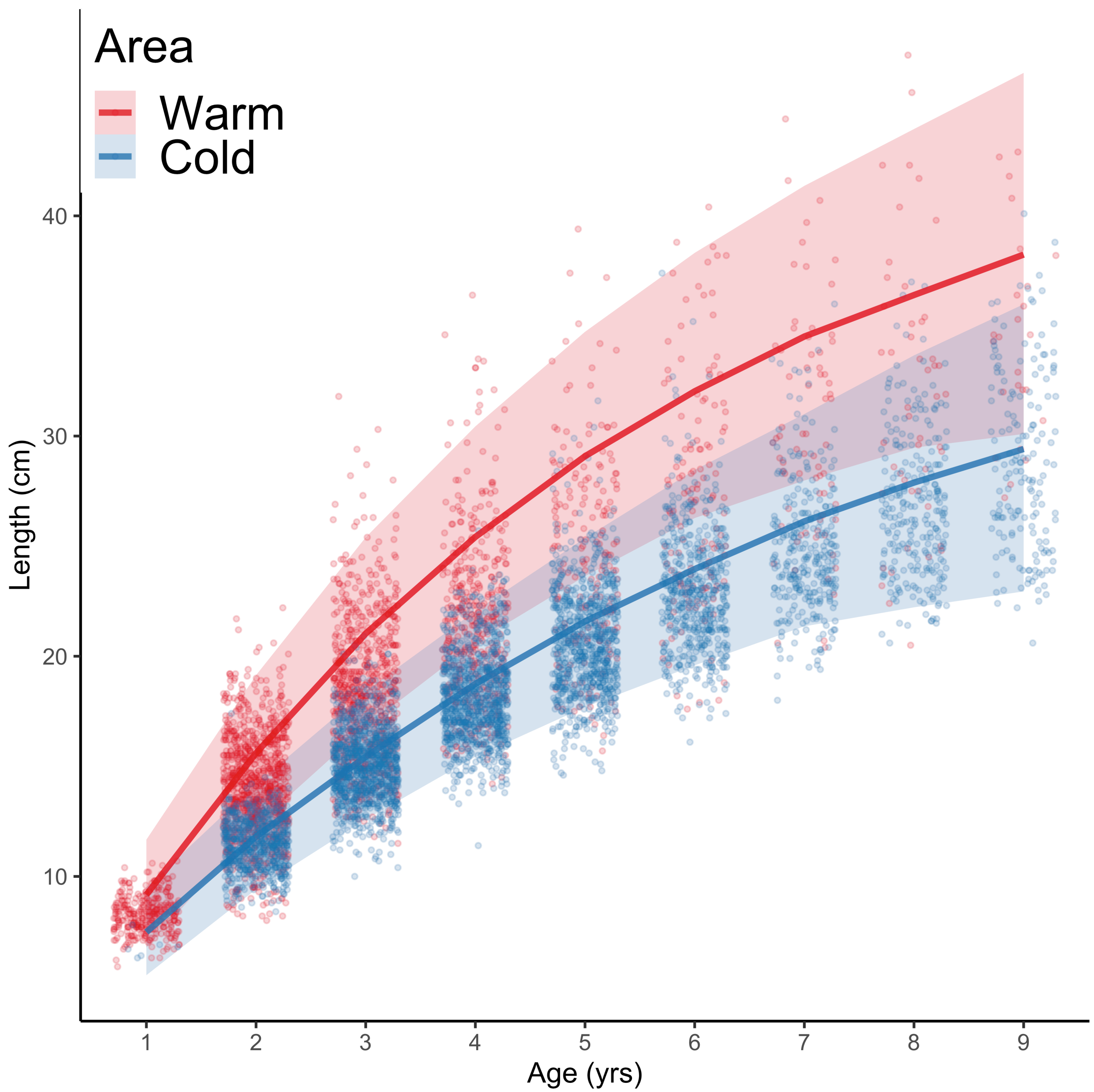
$$\sigma_i^2 = \beta_{0,\sigma} + \beta_{1,\sigma} age_i$$

$$L_{inf,c,w,j} \sim N(\mu_{\beta_{L_{inf}}}, \sigma_{\beta_{L_{inf}}})$$

$$K_{c,w,j} \sim N(\mu_{\beta_K}, \sigma_{\beta_K})$$

Lindmark et al., (in prep); brms, Bürkner (2017)

Large scale natural experiment



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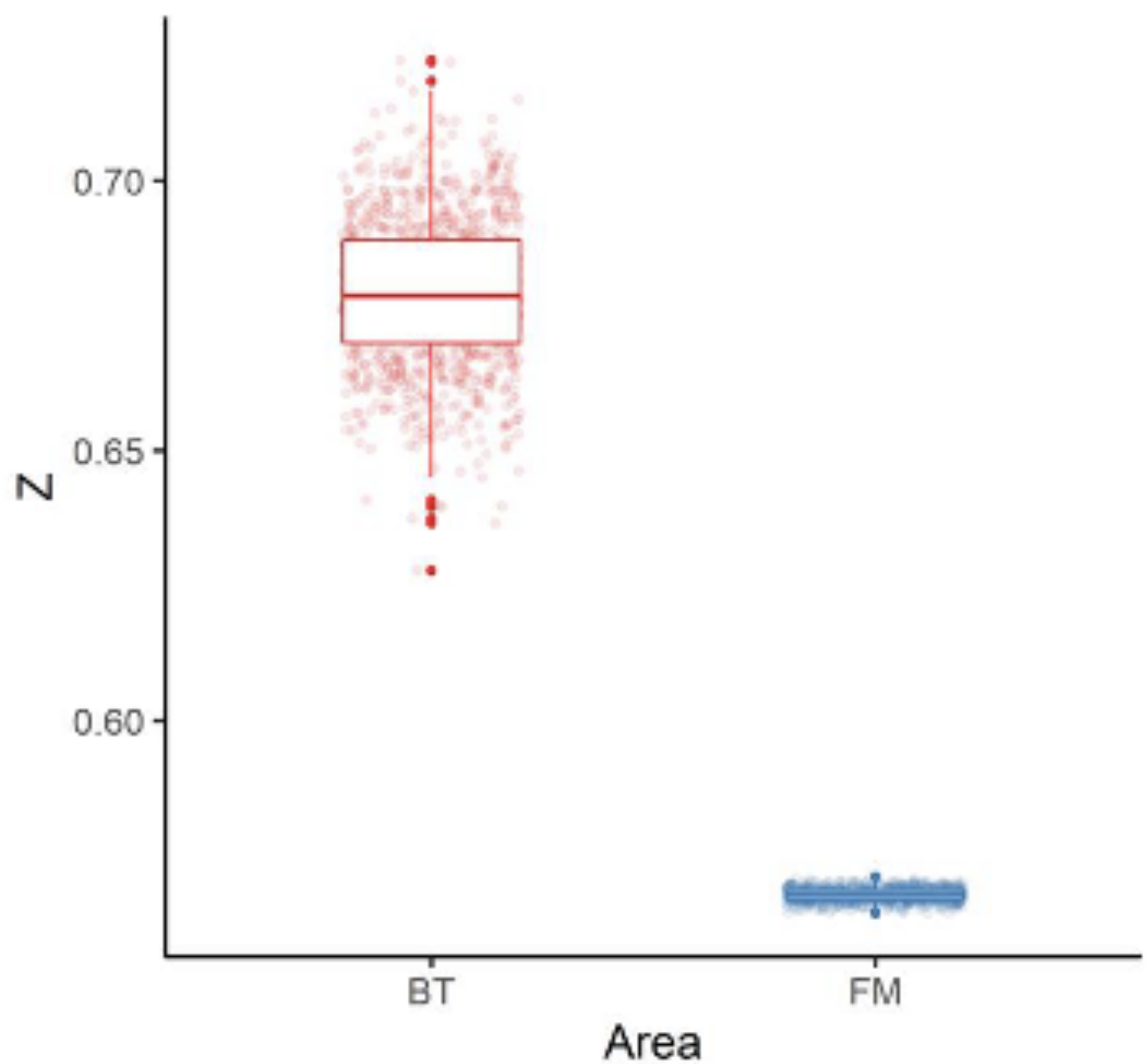

Lindmark et al., (in prep); brms, Bürkner (2017)

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Outlook & Future Work

- Other environmental stressors?
- Challenges & opportunities with size-spectrum models
- Open questions in physiology

Thank you for listening!

Max Lindmark, Swedish University of Agricultural Sciences,
Department of Aquatic Resources

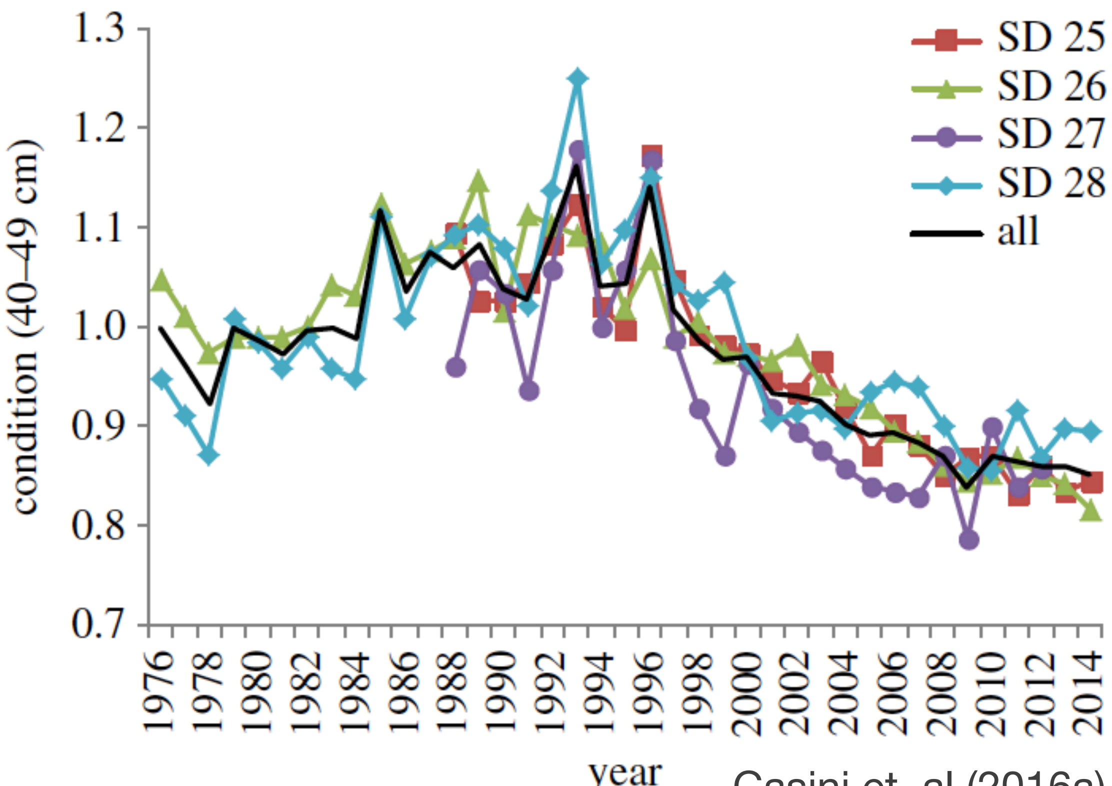
maxlindmark.netlify.com | @max_lindmark

GMRI May 2021 Seminar

Baltic cod condition

- Steady decline since the collapse in the early 1990's

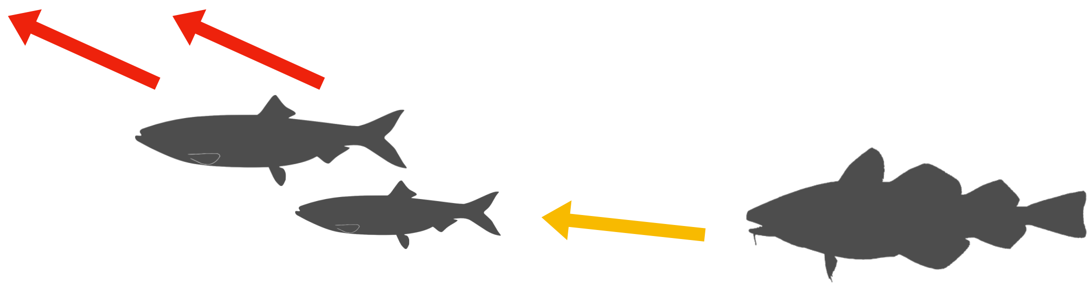
- Poor growth + increased natural mortality = low biomass production



Casini et. al (2016a)

Gårdmark et al. (2015); Neuenfeldt et al. (2020); Svedäng & Hornborg (2014); Casini et al. (2016b) phylopic.org

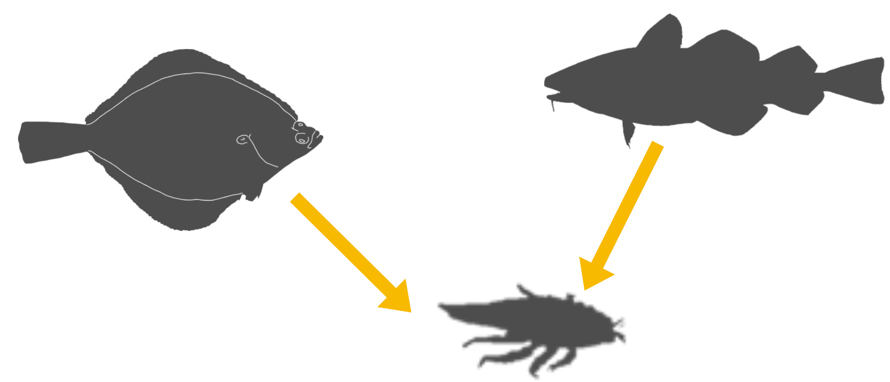
Hypothesised drivers



- Spatial mismatch with pelagic prey

- Lack of right-sized pelagic prey

- Intraspecific + interspecific competition for benthic resources



- (direct effects of oxygen)

Casini et al. (2016b); Gårdmark et al. (2015); Orio et al. (2019, 2020); Neuenfeldt et al. (2020); Svedäng & Hornborg (2014); Limburg and Casini (2019); Svedäng et al. 2020)

Spatiotemporal GLMMs

- Account for correlations using random effects! (package `sdmTMB`)

- BITS 1991-2019 Q4

Condition model

- Weight of individual i at spatial location s at time t

- Student-t distribution

- No model selection - include all and check for overfitting

CPUE model

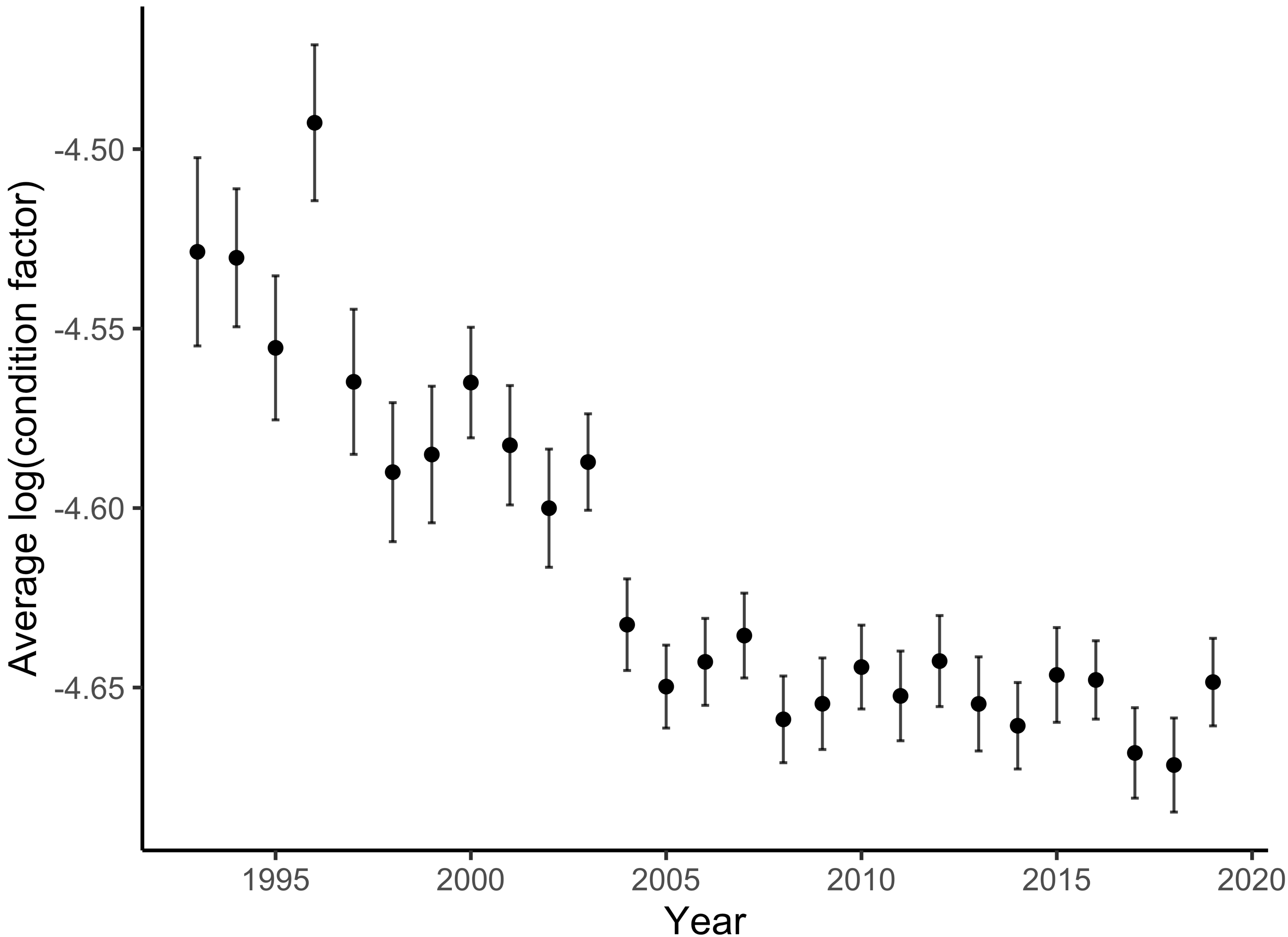
- CPUE at spatial location s at time t

- Tweedie-distribution

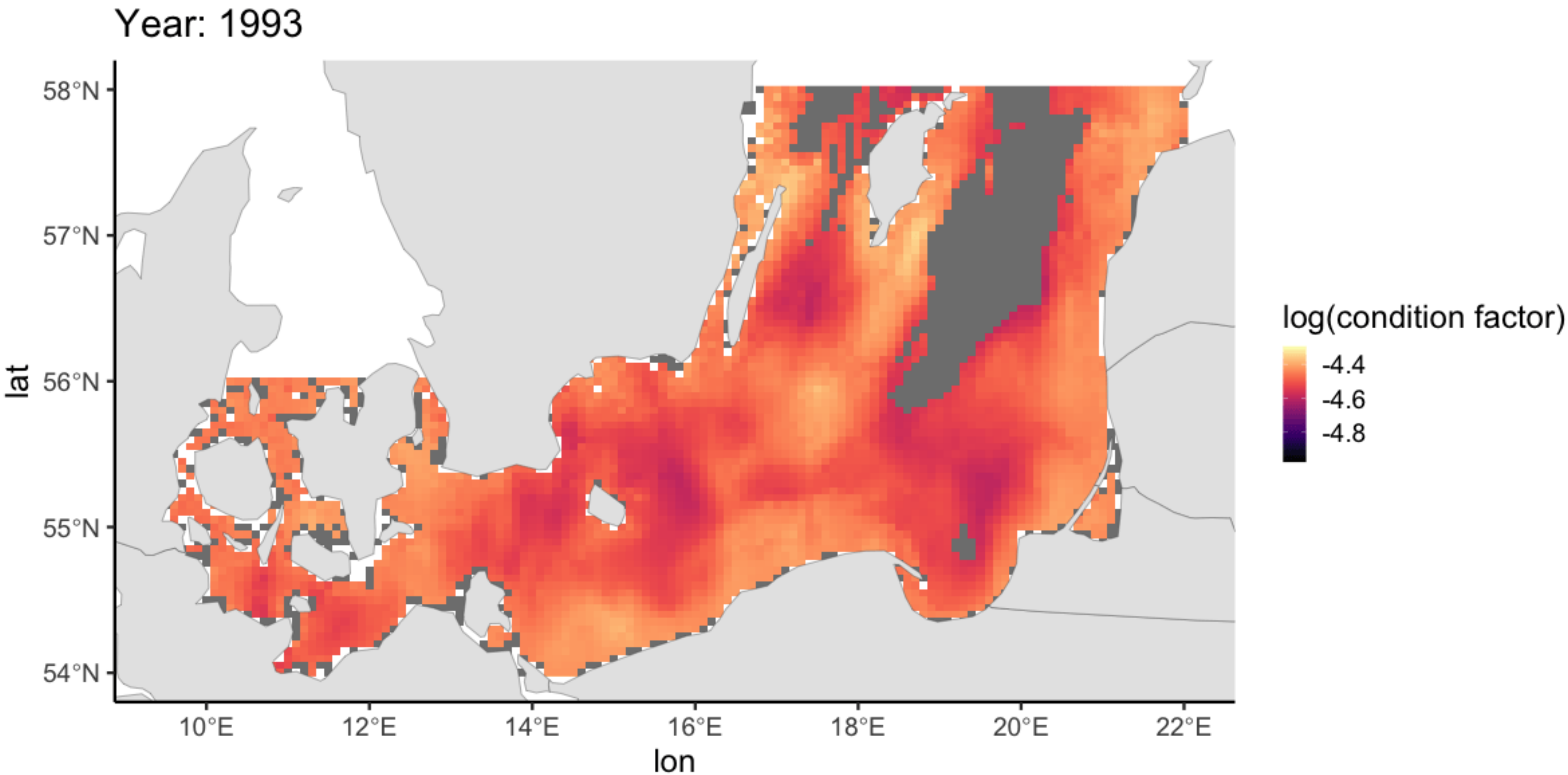
- Depth, oxygen and temperature as covariates (splines)

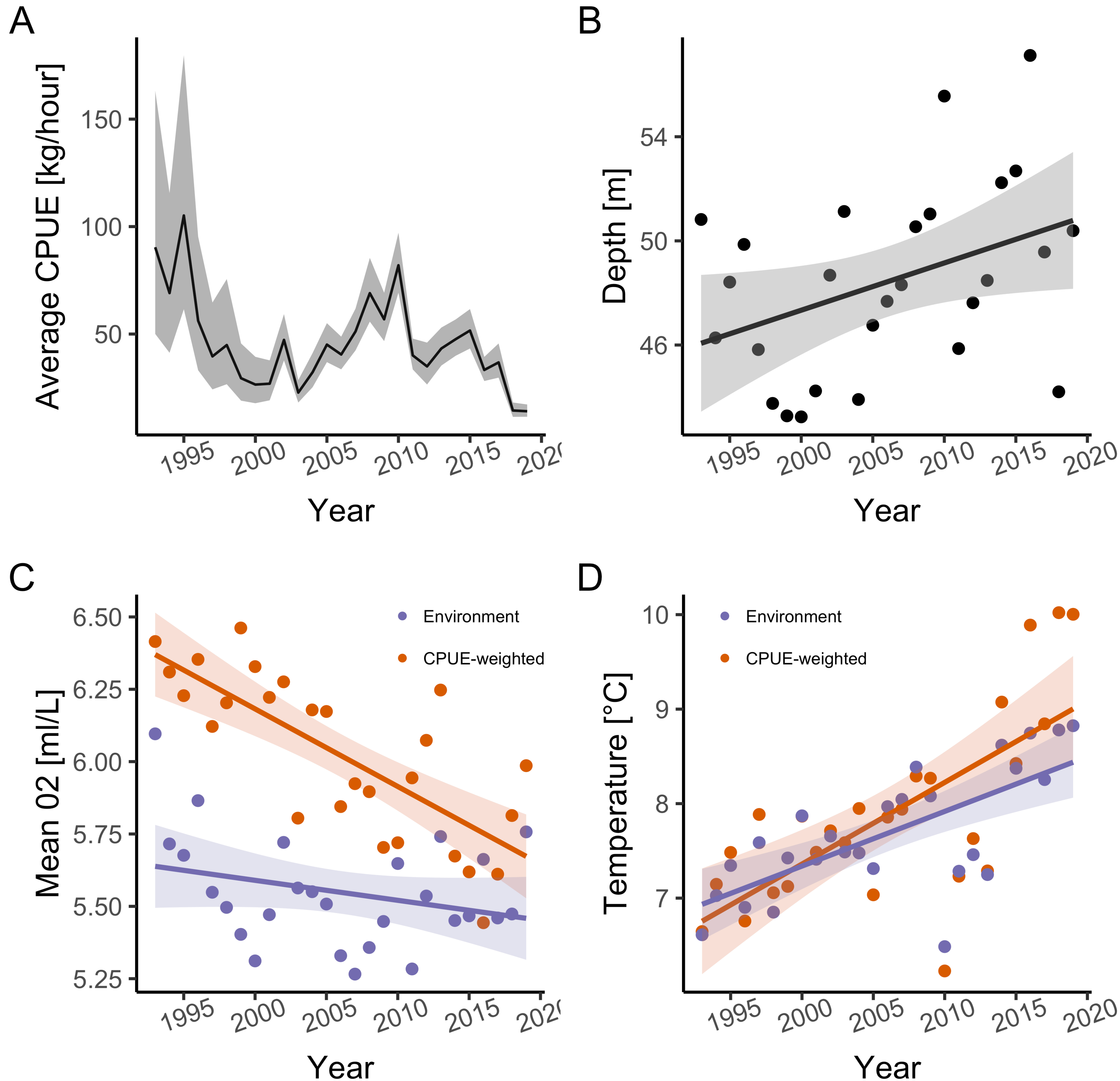
Le Cren (1951); Thorson & Minto (2015); Andersen *et al.*, (2019); Anderson *et al.*, (2021)

Decline over time



Decline over time




A
Average CPUE [kg/hour]
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Mean 02 [ml/L]
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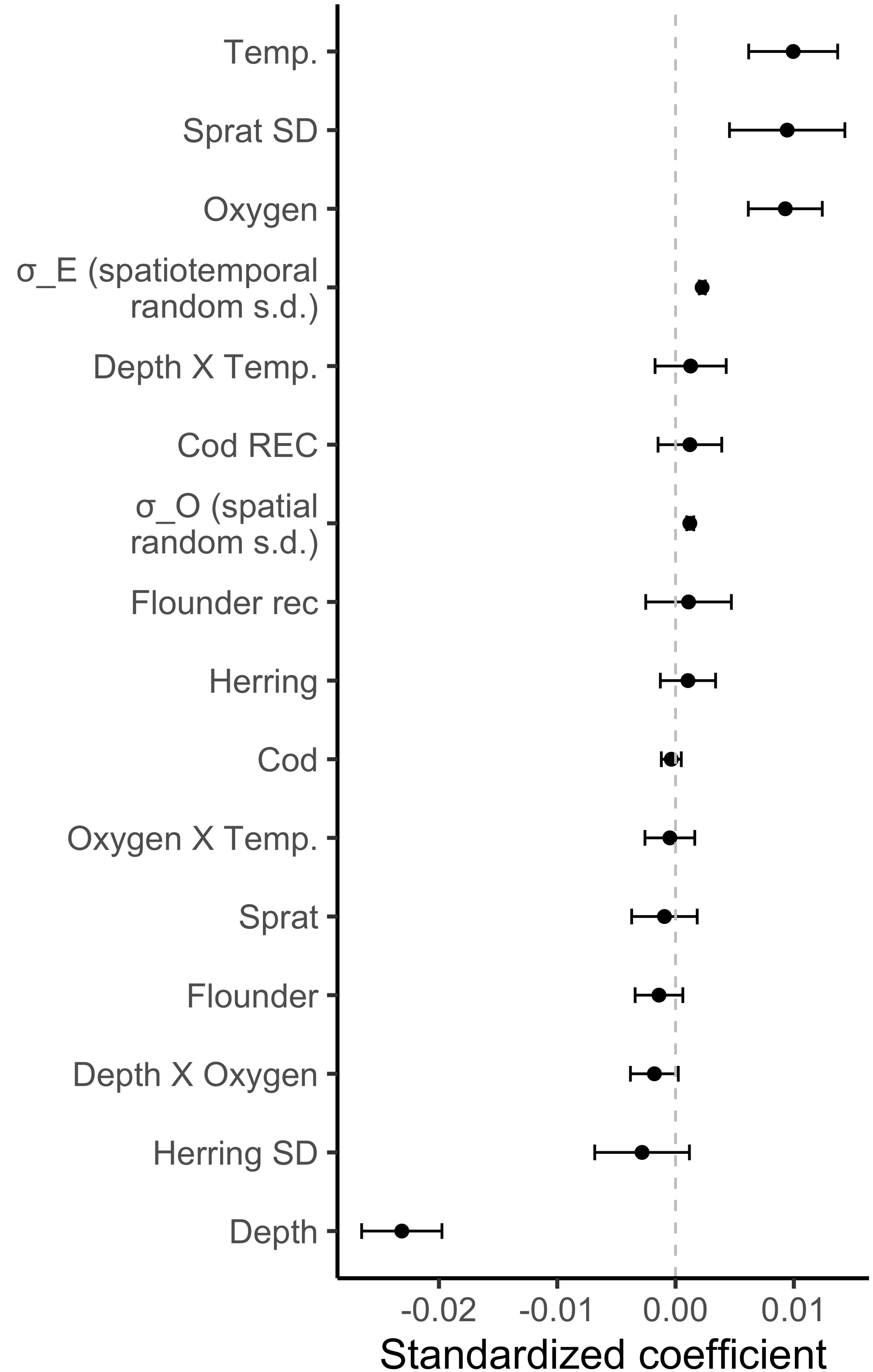
Covariates



Temp.
Sprat SD
Oxygen
σ_E (spatiotemporal random s.d.)
Depth X Temp.
Cod REC
σ_O (spatial random s.d.)
Flounder rec
Herring
Cod
Oxygen X Temp.
Sprat
Flounder
Depth X Oxygen
Herring SD
Depth
-0.02
-0.01
0.00
0.01
Standardized coefficient

Conclusions

- Why did condition decline between 1993-2005?
  - Feeding levels where normal (Neuenfeldt et al 2020)
  - Condition declined for all sizes (not a single food source limiting)
  - Flounder going down in SD 24-25 (Orio et al 2017)

Outlook

- Still unclear as to what lead to the decline in condition, which preceded the decline in growth
  - Vague ecosystem changes? Food quality?
- Unlikely that the same mechanisms keep cod in poor physiological condition now
- What can explain spatial variation in condition in more recent, “post physiological collapse”-years?

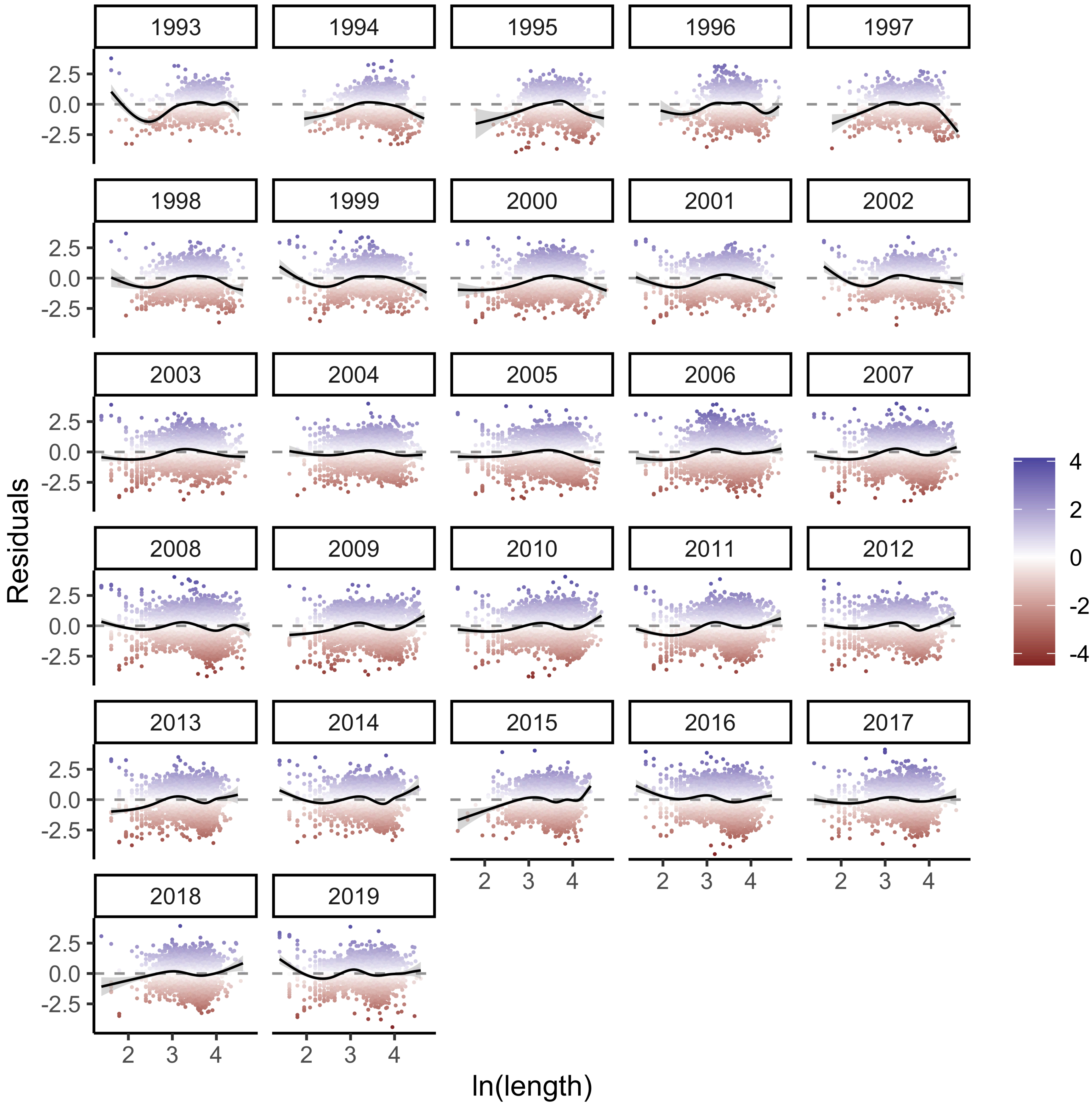
Thank you for listening!

A spatiotemporal condition model

$$\mu_{s,t} = \alpha_t + d_{depth} + \boldsymbol{\omega}_s + \boldsymbol{\epsilon}_{s,t} + \sum_{k=1}^{n_k} \boldsymbol{\gamma}_k \boldsymbol{X_k} + \beta \log(l)$$

- Fit in package `sdmTMB`
- BITS 1991-2019 Q4
- Fit full model with all covariates; Compare out-of-sample-predictive performance with minimal model

Thorson (2015); Grüss et al. (2020); **`sdmTMB`**; **`TMB`**; **`INLA`**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ln(length)
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-4
-2
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4