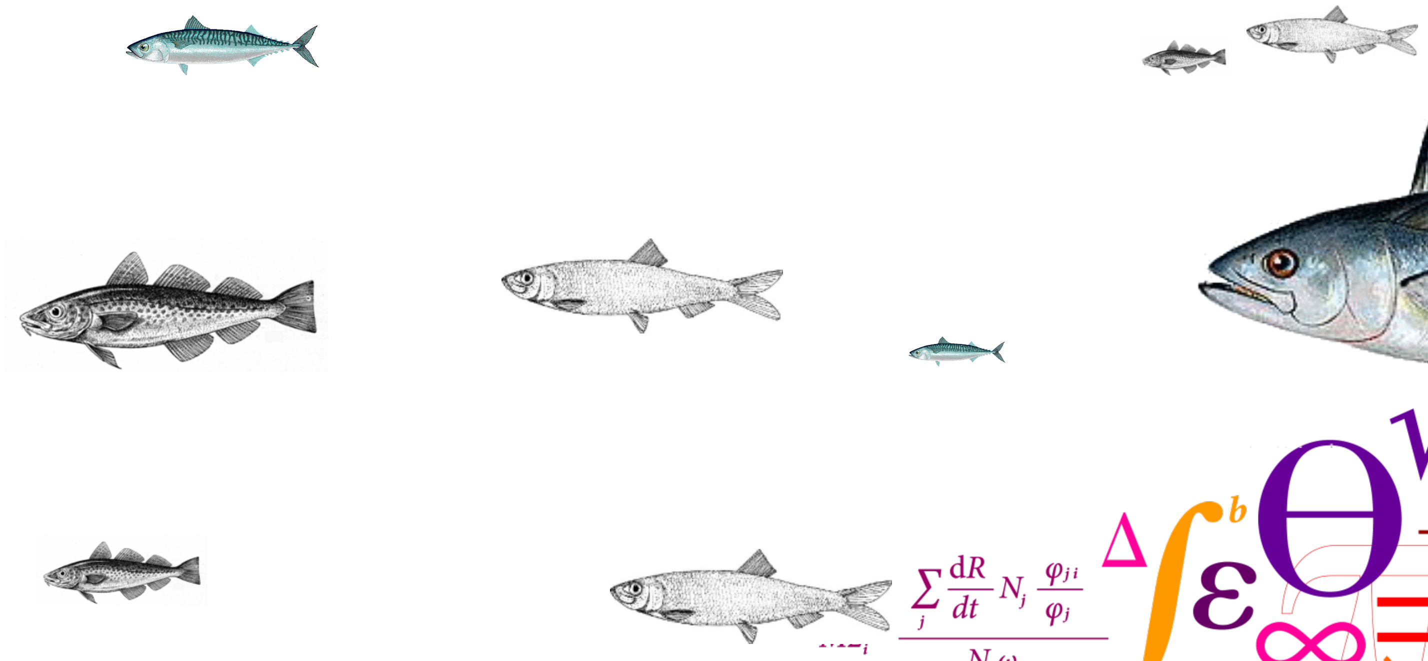
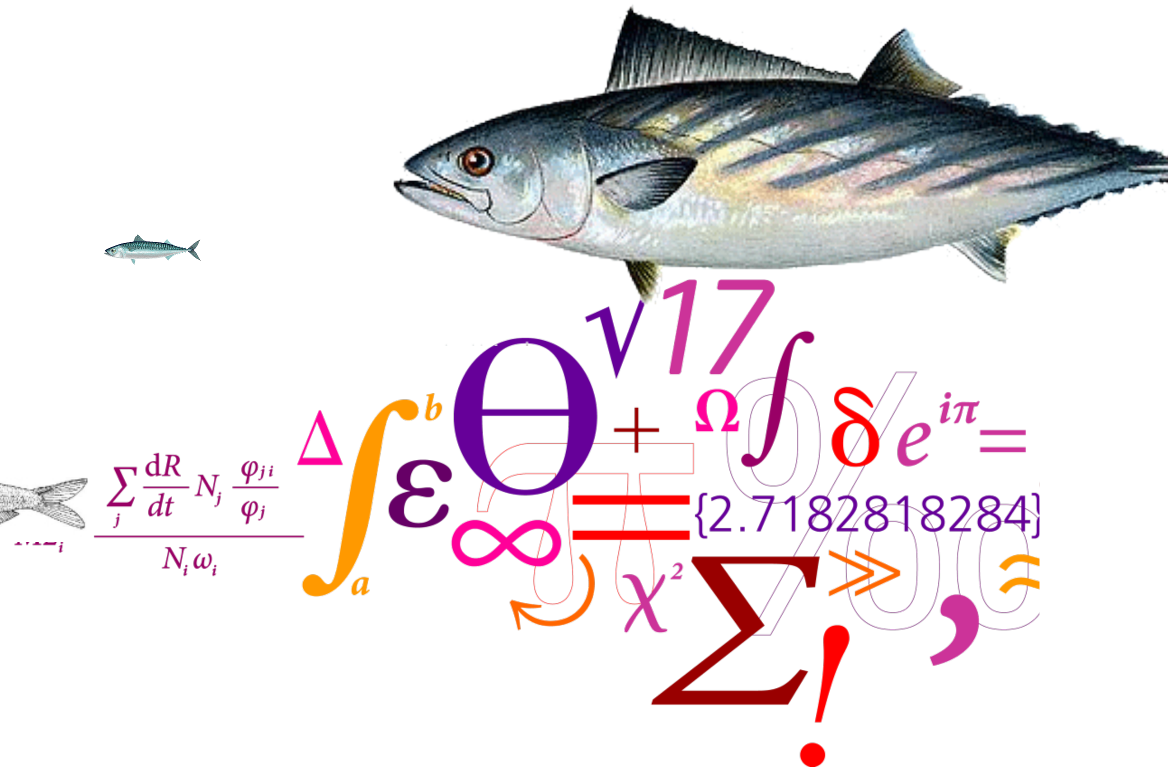
Structure and dynamics of the fish community

-- from individuals to ecosystems

Ken H. Andersen





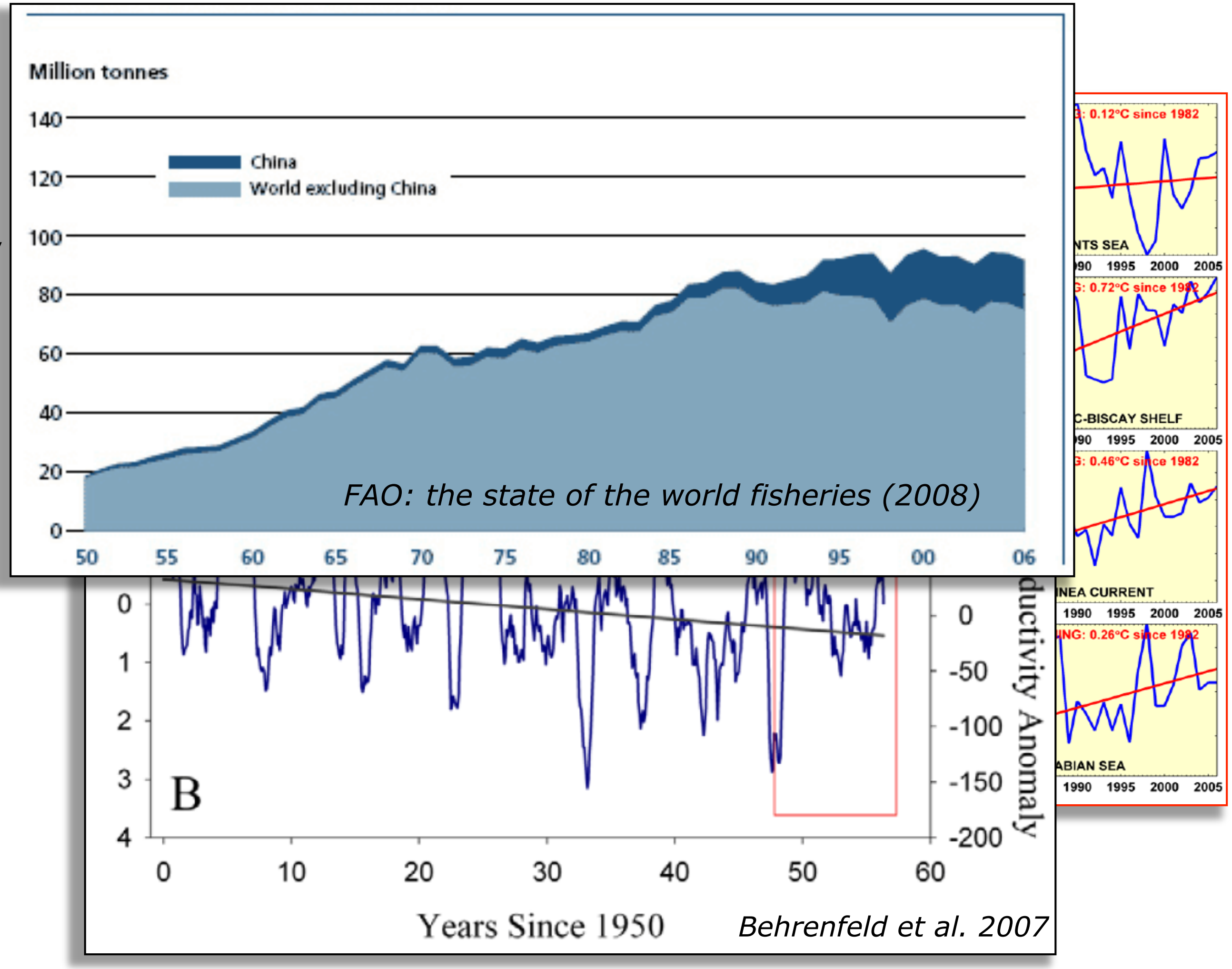
DTU Aqua
National Institute of Aquatic Resources

Marine Global Change

1) Climate change

2) Changing productivity

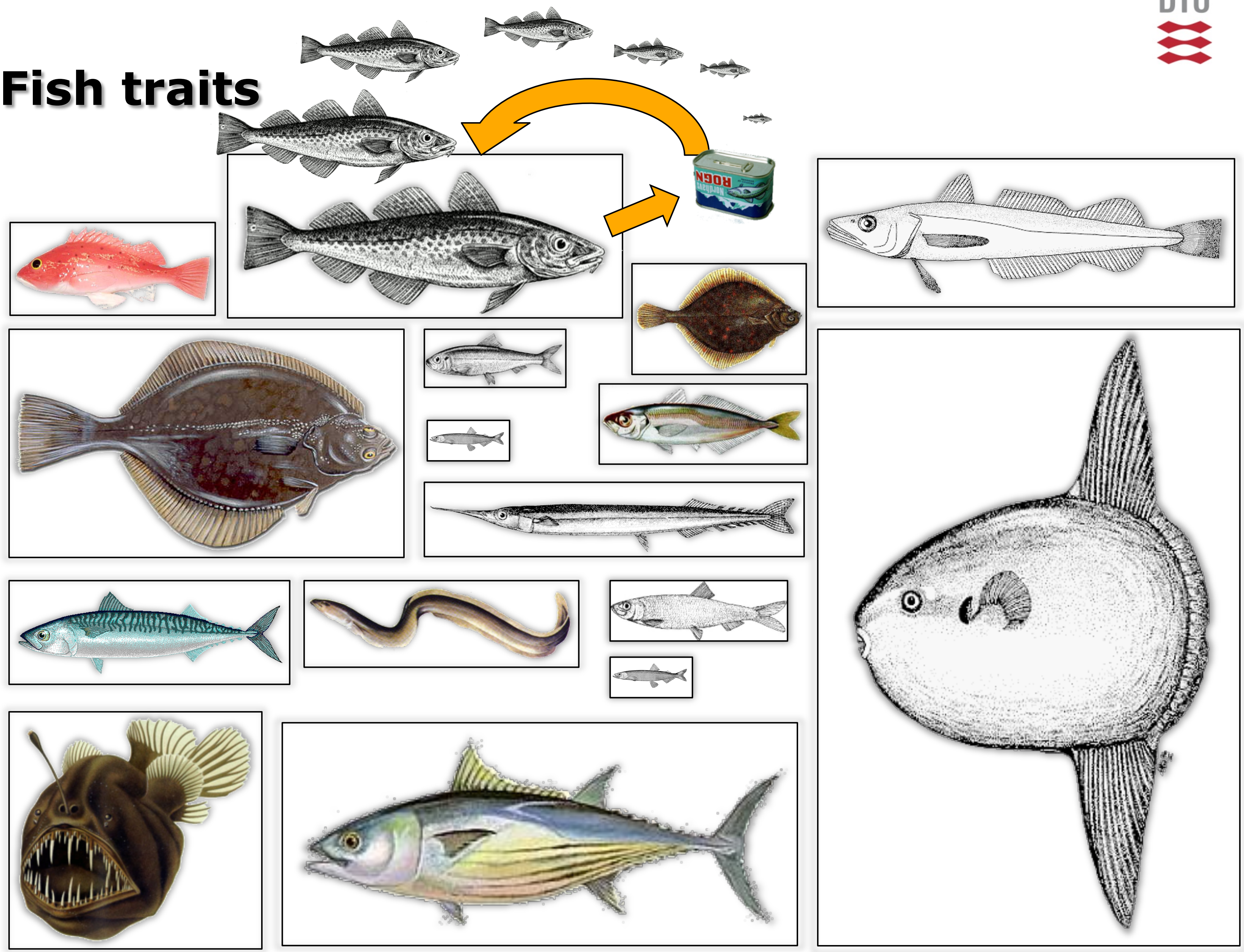
3) Fishing



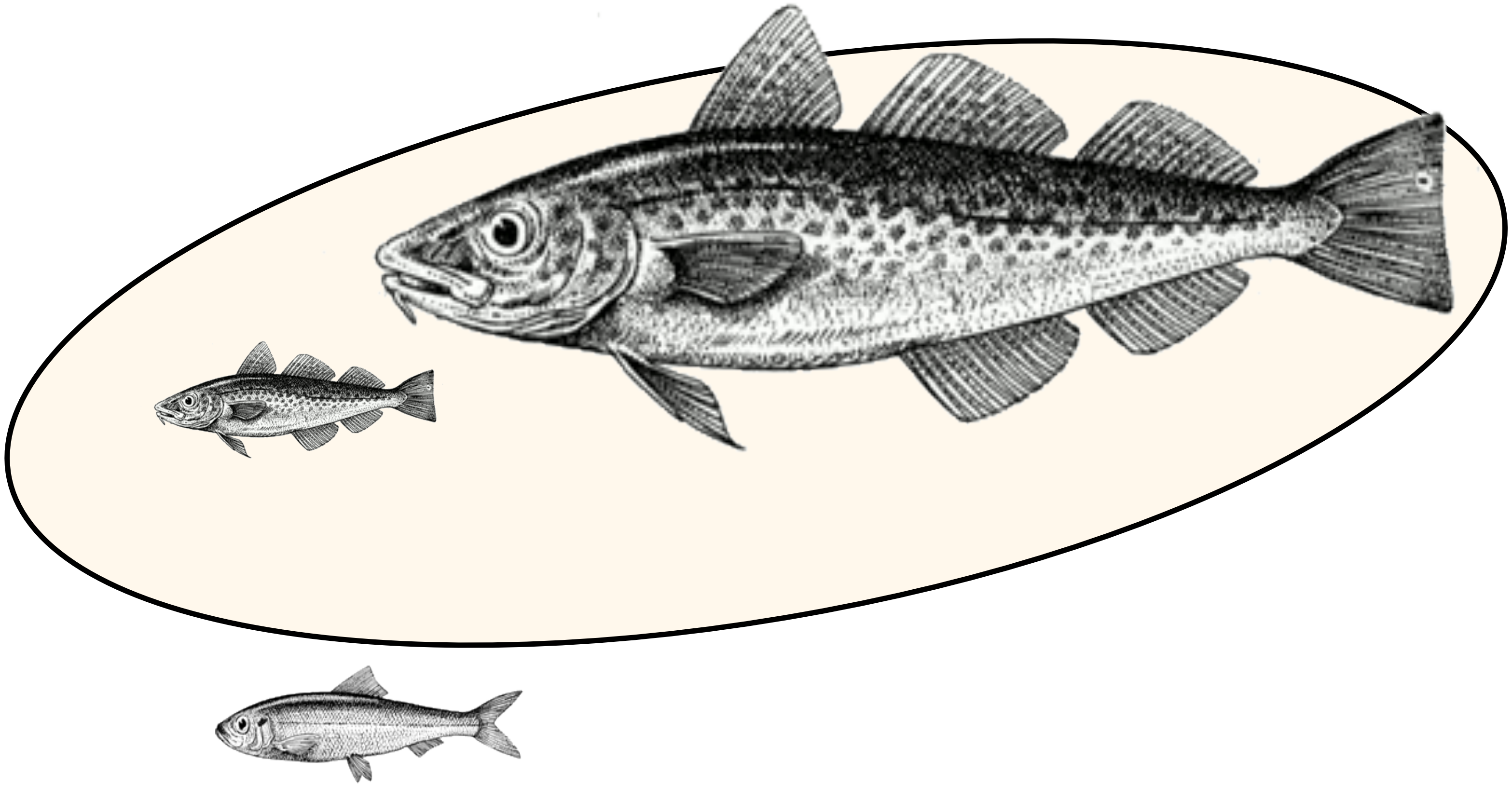
Outline

1) Structure of the fish community (+ some more)
2) Response of the fish community to fishing

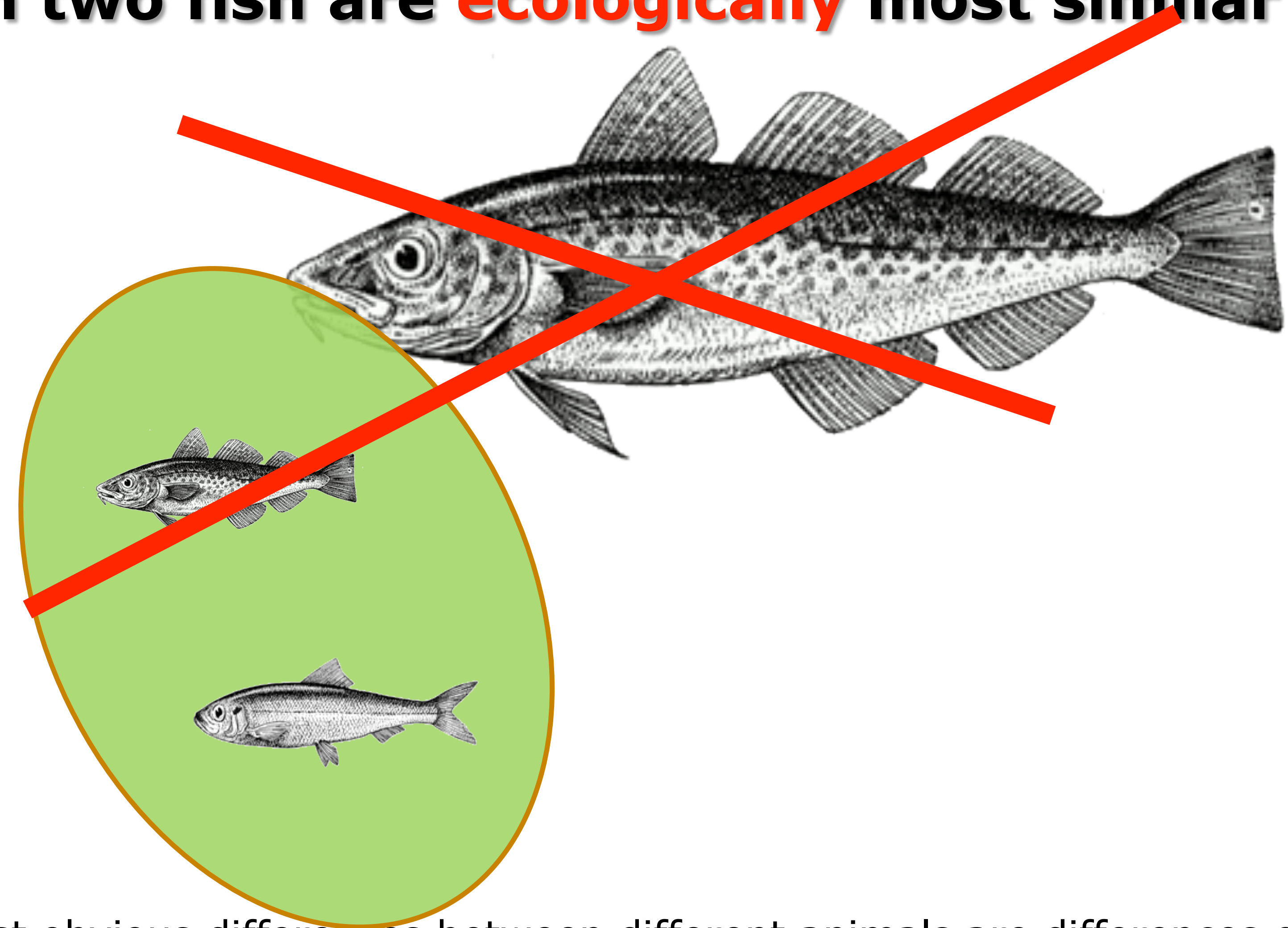
Fish traits



Which two fish are most similar?

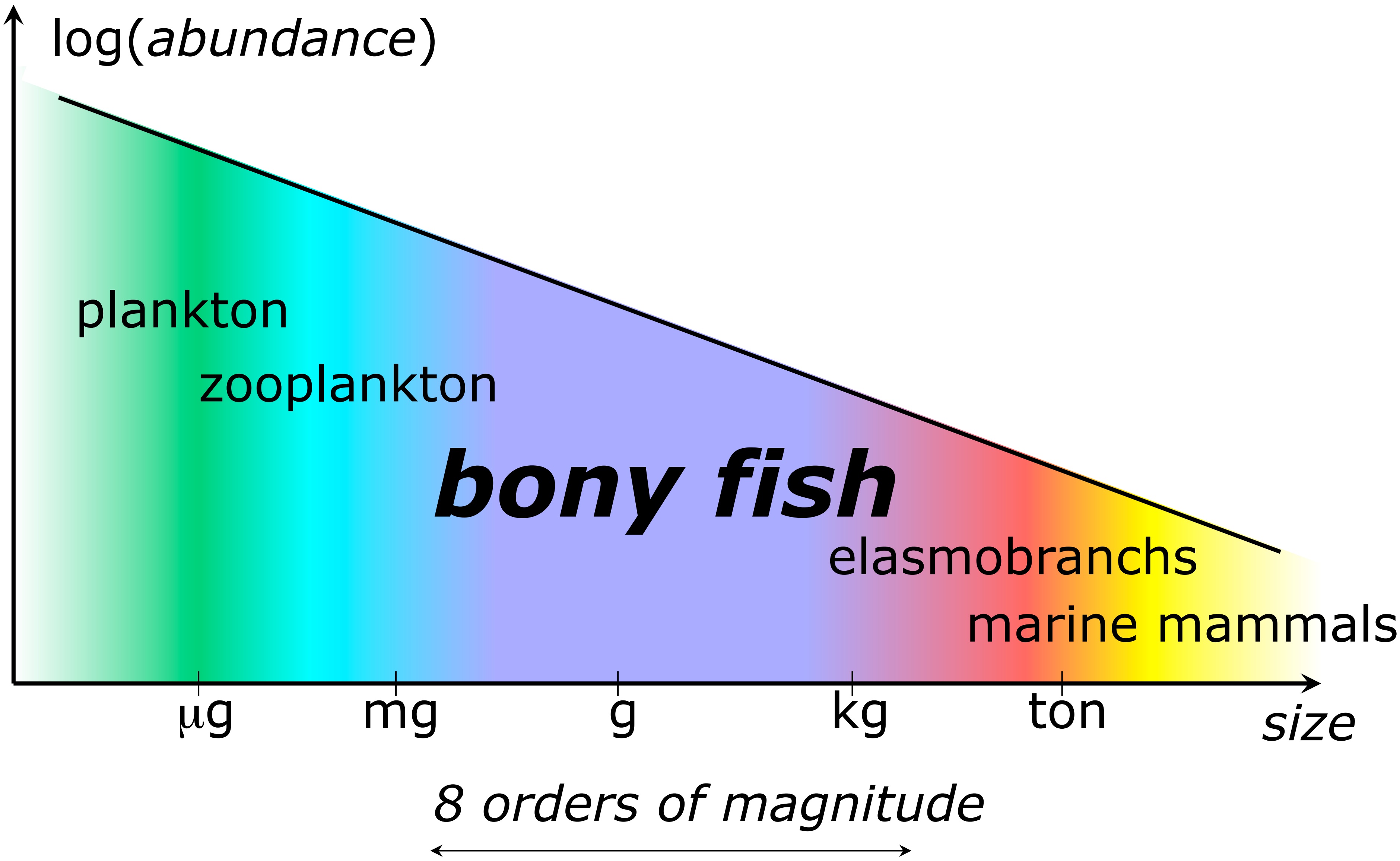


Which two fish are **ecologically** most similar?



"The most obvious differences between different animals are differences of size..." (Haldane, 1928)

The Marine Size Spectrum



Sheldon conjecture

Sheldon & Parsons (1967): Sheldon et al (1972):

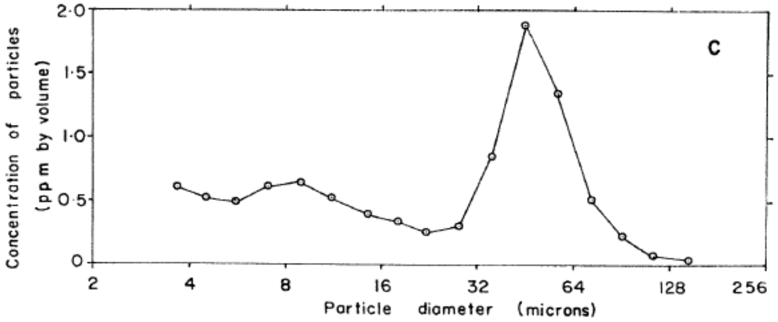


FIG. 1. Particulate matter in a single sample of seawater taken during a bloom of the diatom *Skeletonema costatum*. A, numbers of particles versus particle volume; B, numbers of particles versus particle diameter; C, concentration of particles versus particle diameter on a logarithmic scale.

PARTICLES IN THE OCEAN 337

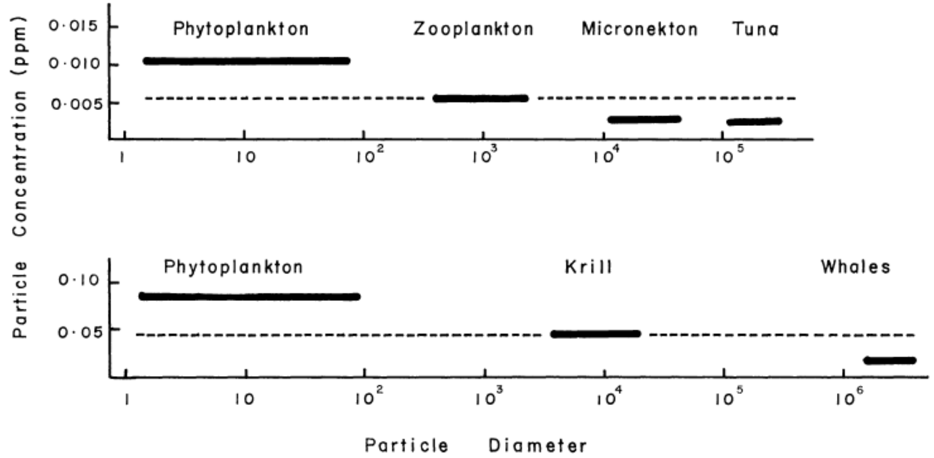
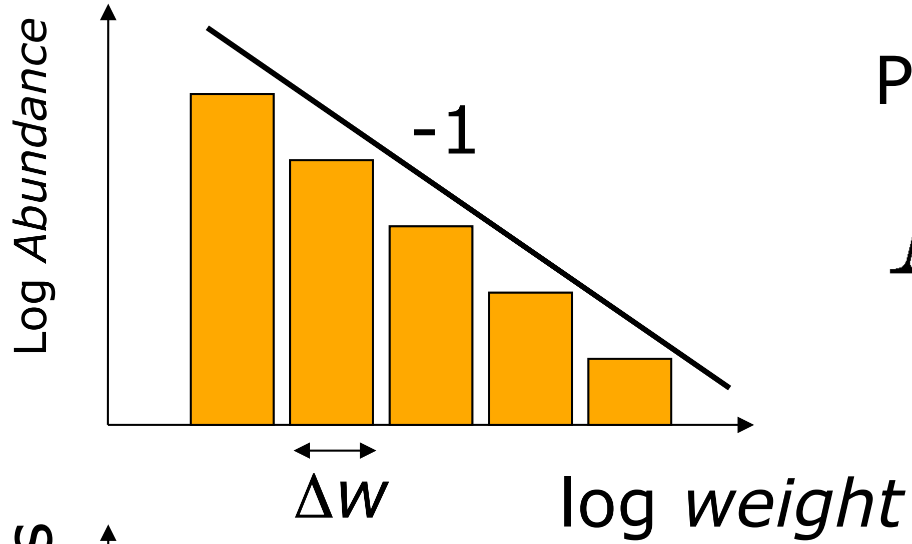


FIG. 12. Estimates of standing stock (thick lines). Above: equatorial Pacific. Below: Antarctic. The thin broken line is an estimate of the true or potential standing stock of living material. Some of the estimates were derived from data of Blackburn (1968), Blackburn et al. (1970), Mackintosh (1970), Mackintosh and Brown (1956), Marr (1962), and Riley (1963).

Sheldons conjecture:

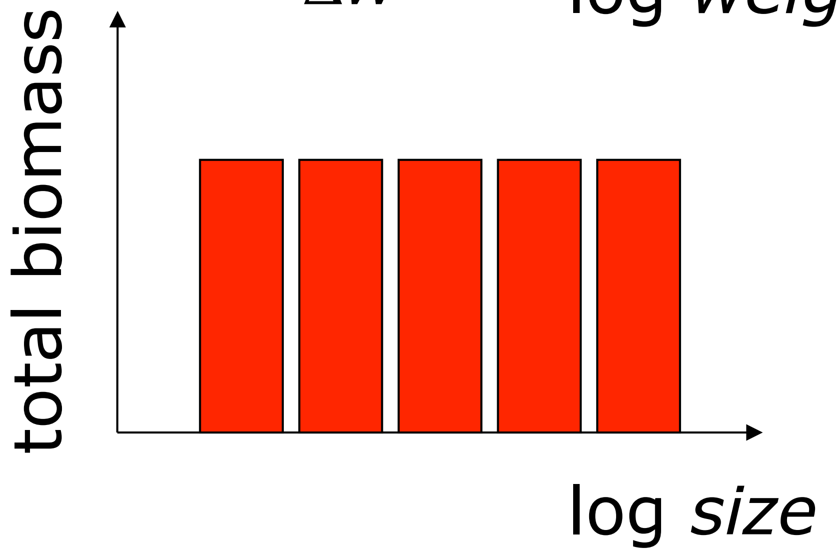
The biomass in logarithmically spaced size groups is constant

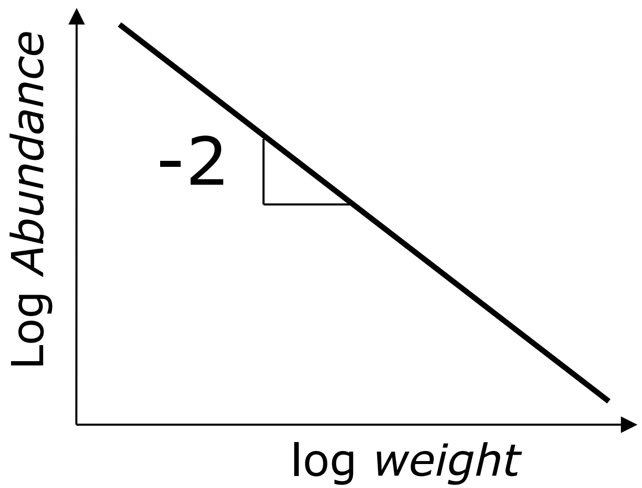
What is a size spectrum really?



Power law scaling:

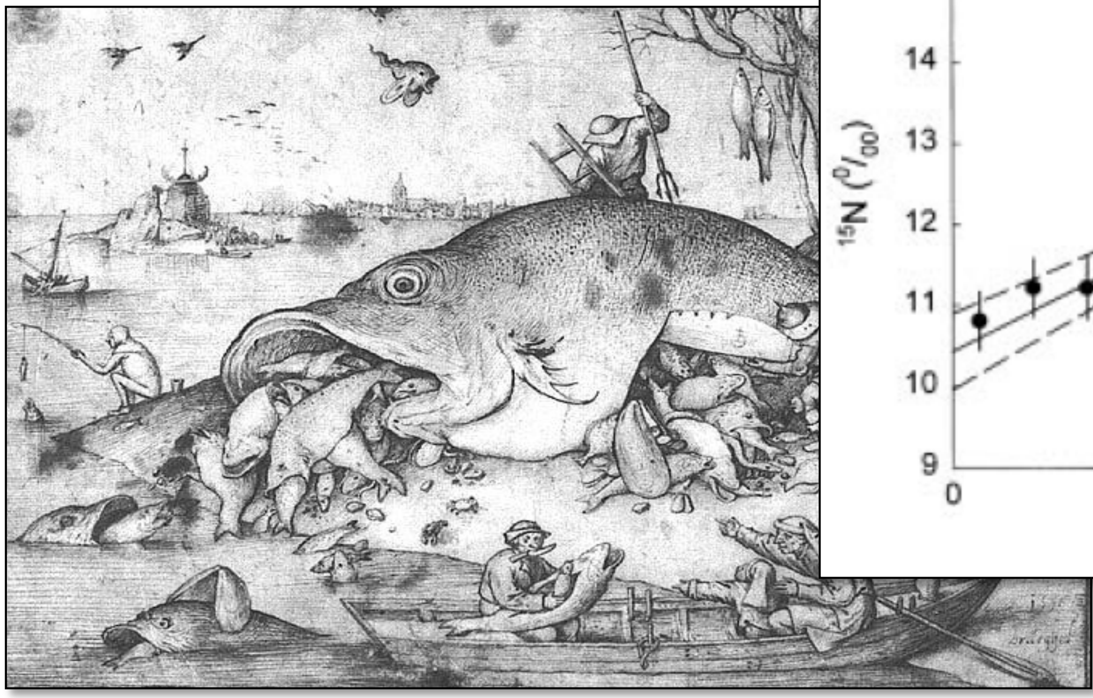
$$N = \kappa w^{-\lambda}$$



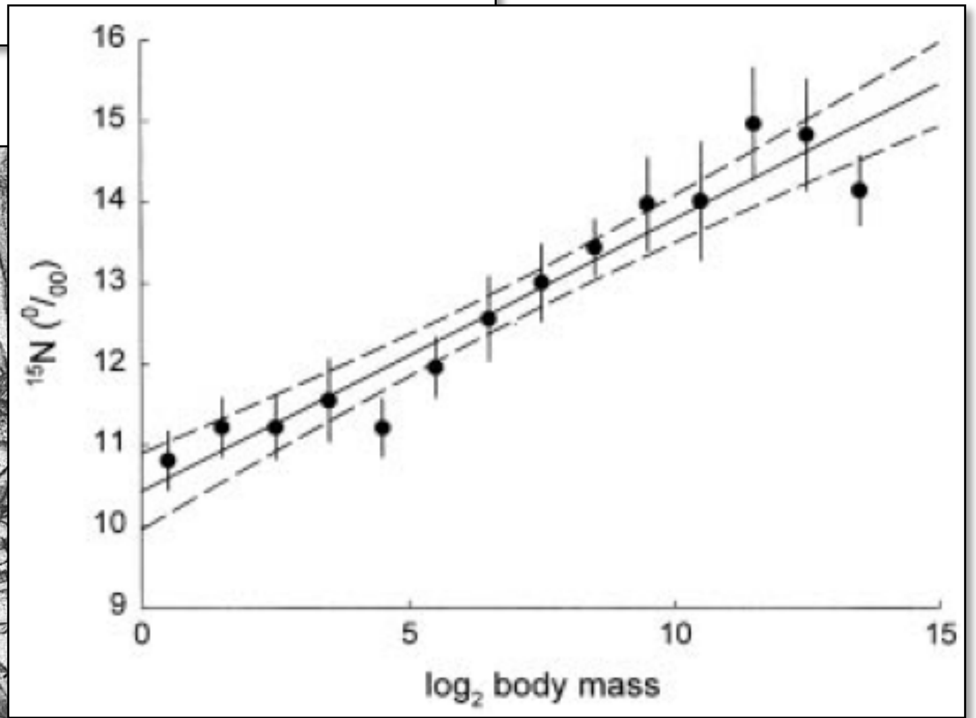


Big fish eat smaller fish

Third Fisherman: Master, I marvel how the fishes live in the sea.
First Fisherman: Why, as men do a-land; the great ones eat up the little ones.
Shakespeare, Pericles 2.1.69-70



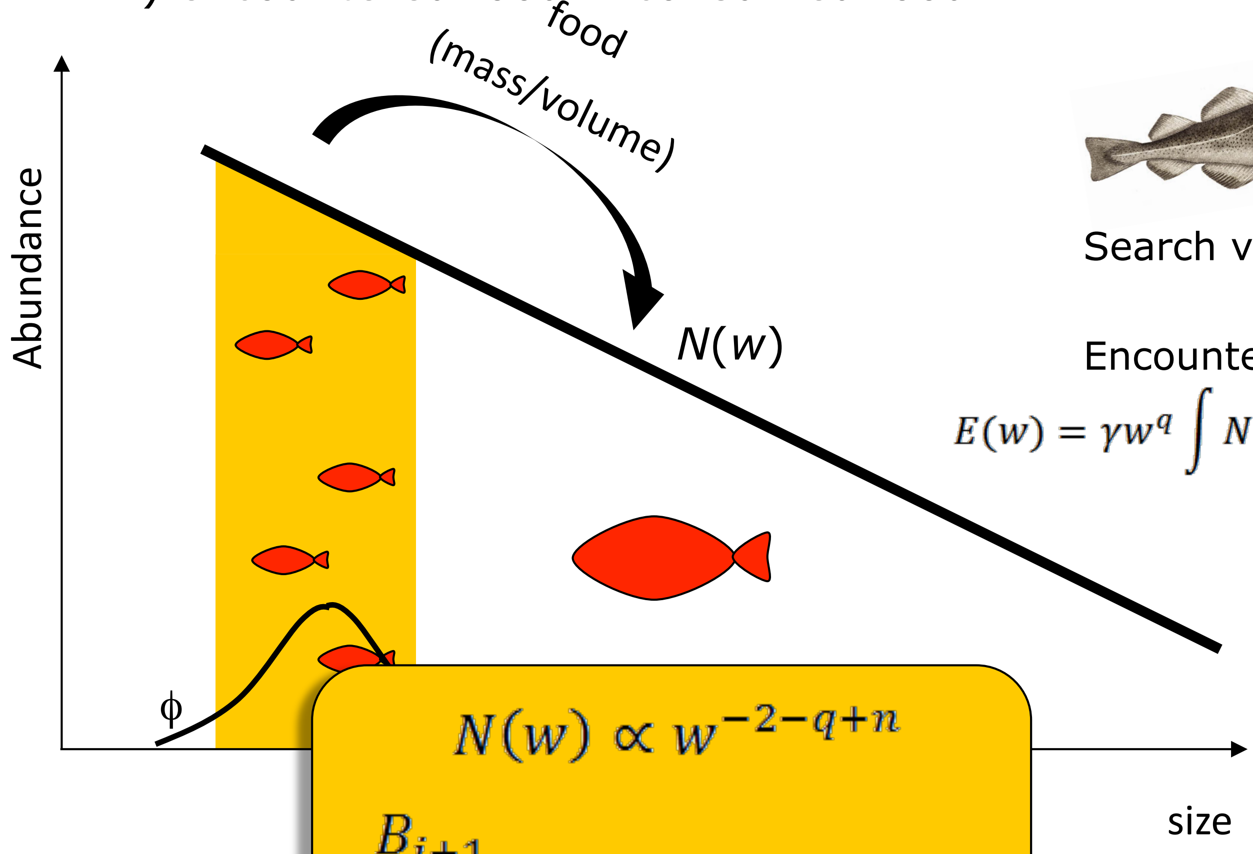
Breughel the elder, 1556

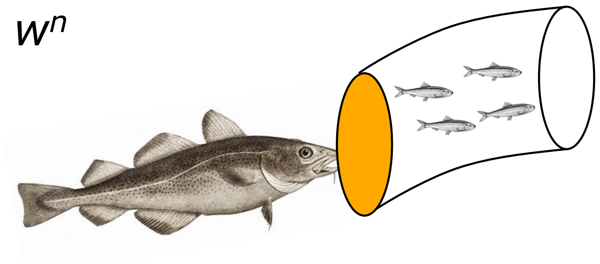


Jennings et al., JAE, 2001

Individuals -> ecosystems

1) Big fish eat smaller fish
2) Search rate proportional to size
3) Scaling size spectrum: $N = K_c w^{-\lambda}$
4) encountered food = consumed food = $h\ w^n$





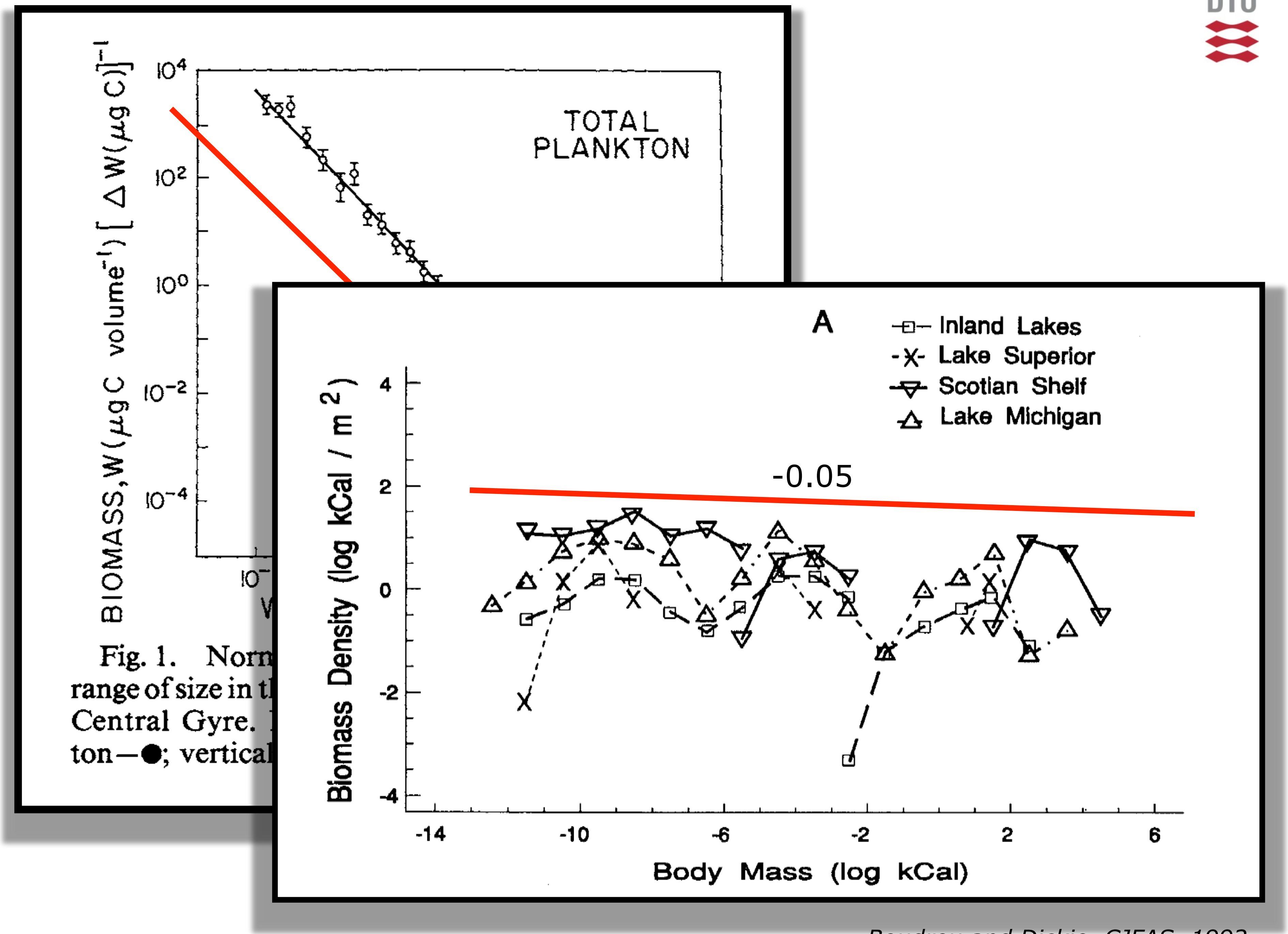
Search volume $\propto w^q$ $2/3 < q < 1$

Encountered food

$$E(w) = \gamma w^q \int N(w_p) w_p \phi\left(\frac{w_p}{w}\right) \mathrm{d}w_p \propto w^{2+q-\lambda}$$

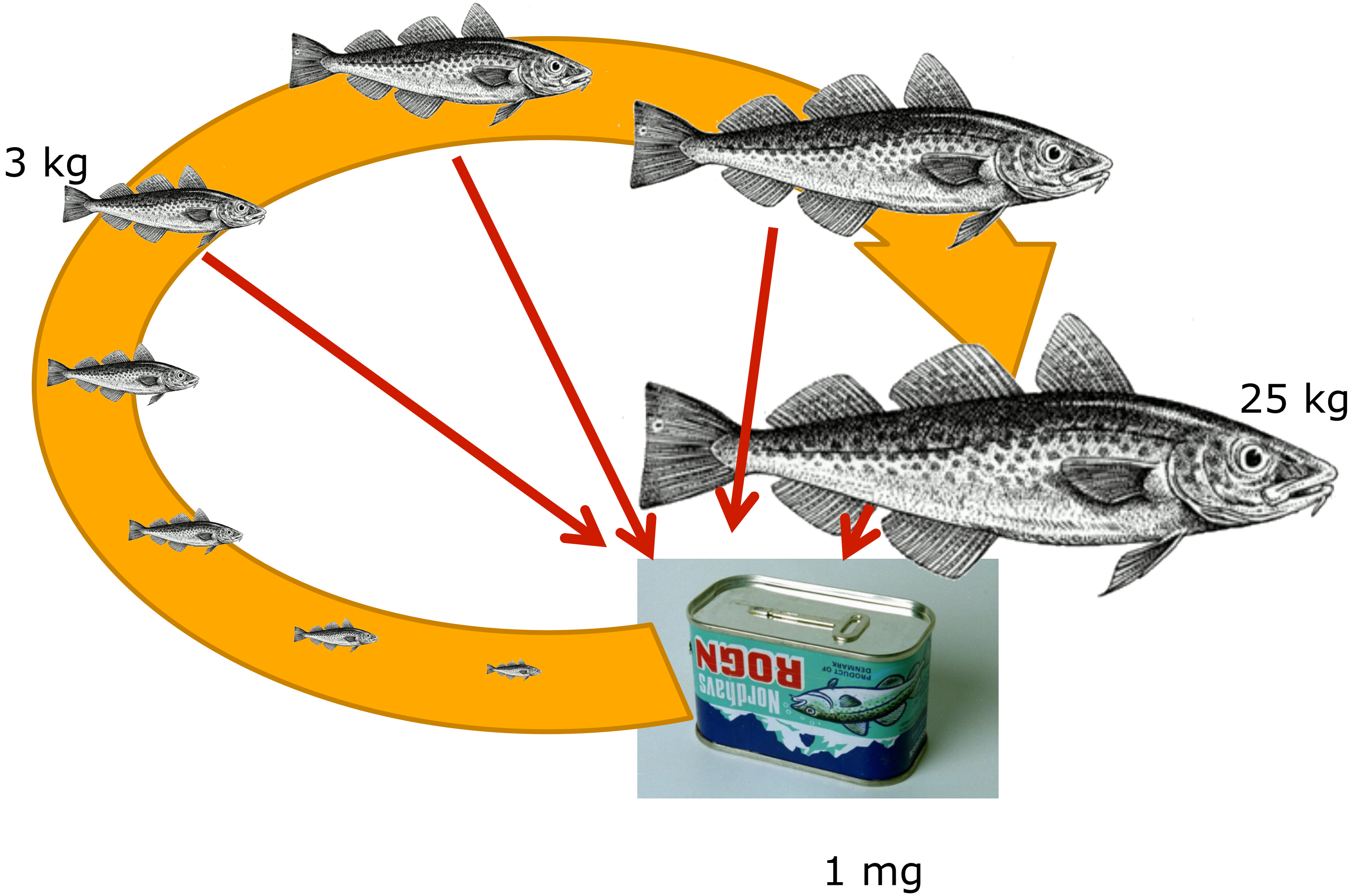
$$N(w) \propto w^{-2-q+n}$$

$$\frac{B_{i+1}}{B_i} \propto w^{n-q} \approx \text{constant}$$

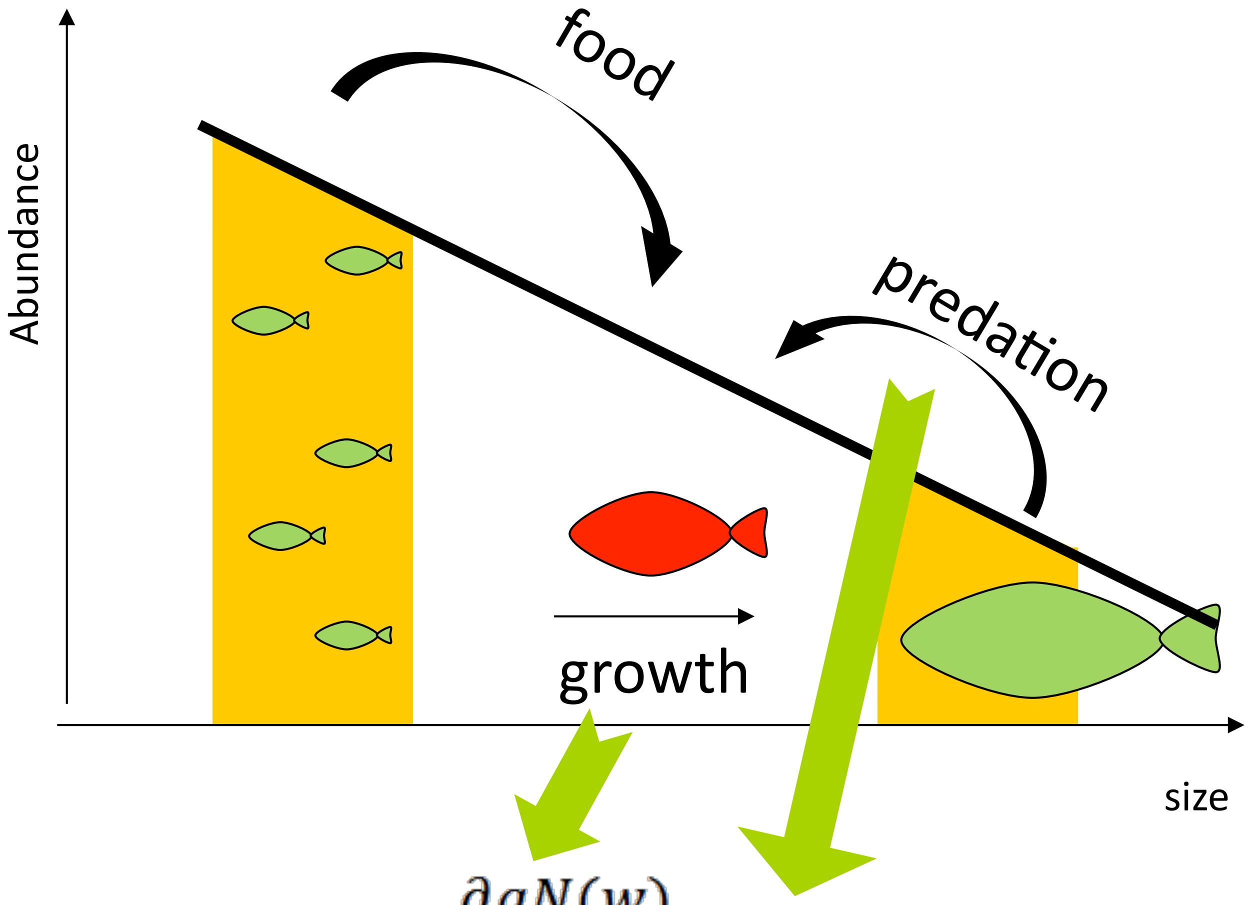


Boudreu and Dickie, CJFAS, 1992

Life history of fish



Individuals -> populations



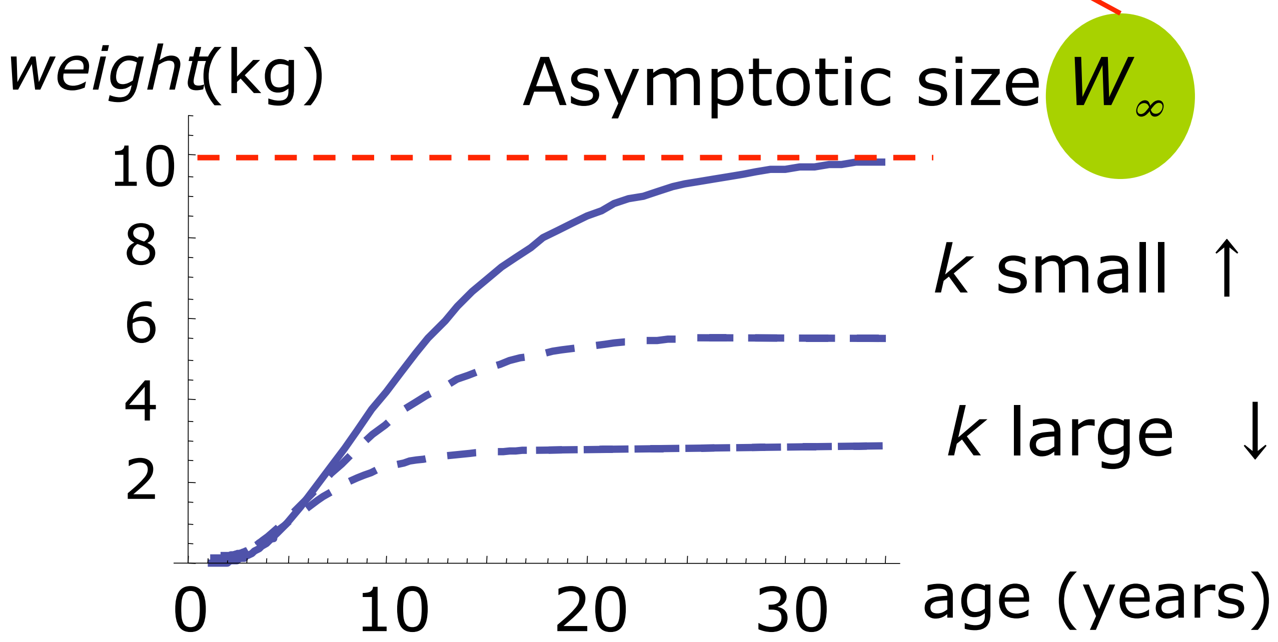
$$\frac{\partial g N(w)}{\partial w} + \mu N(w) = 0$$

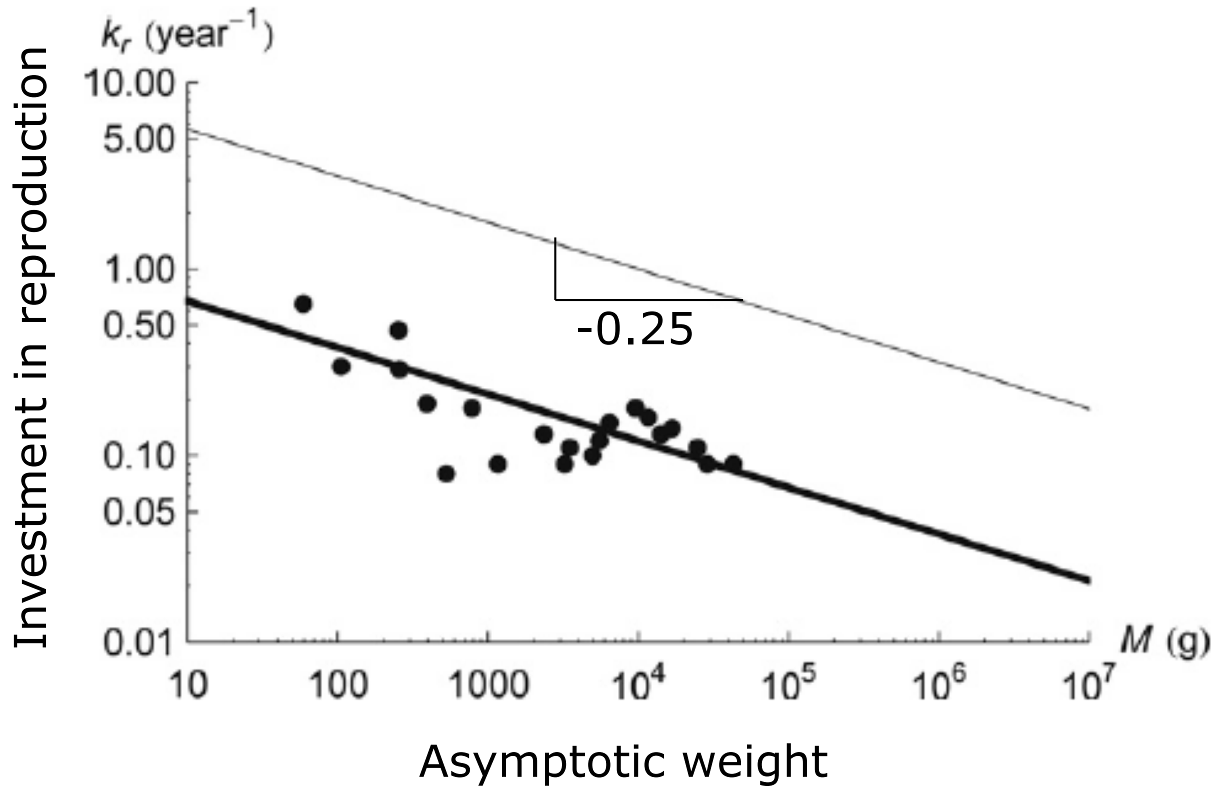
Fish traits

$$growth = \alpha \cdot consumption - reproduction$$

$$g(w) = \alpha h w^n - kw$$

$$g(w) = \alpha h w^n (1 - W_\infty^{n-1} w)$$

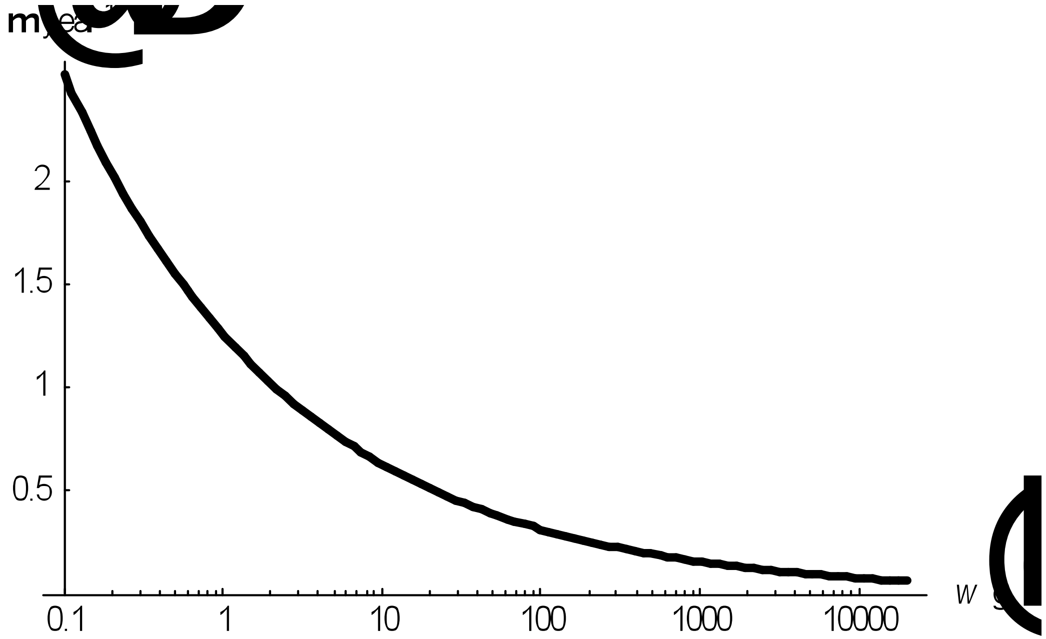




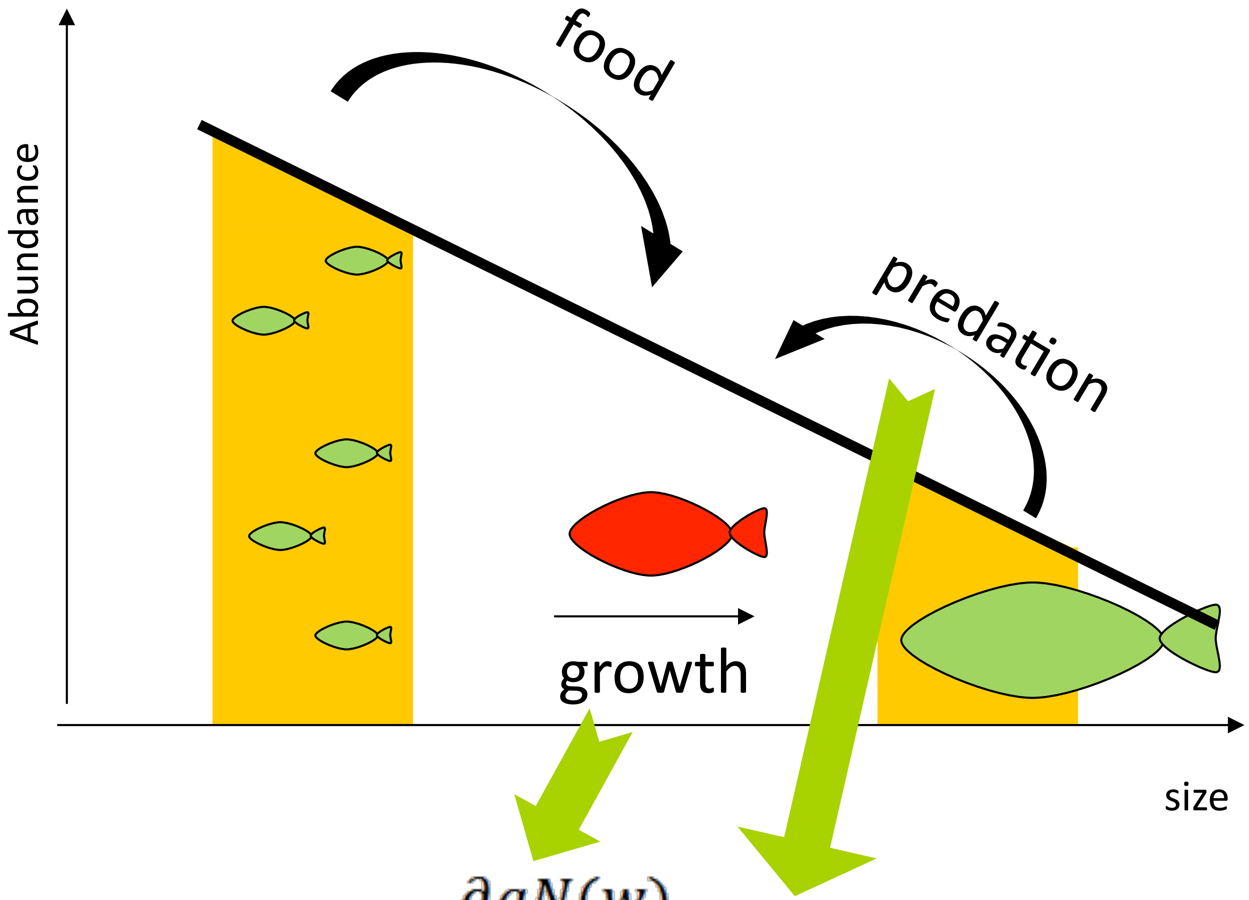
Data from Gundersen, CJFAS, 1997

Predation

$$\mu(w) = \alpha_p w^{1+q-\lambda} = \alpha_p w^{n-1} \approx \alpha_p w^{-1/4}$$



Individuals -> populations

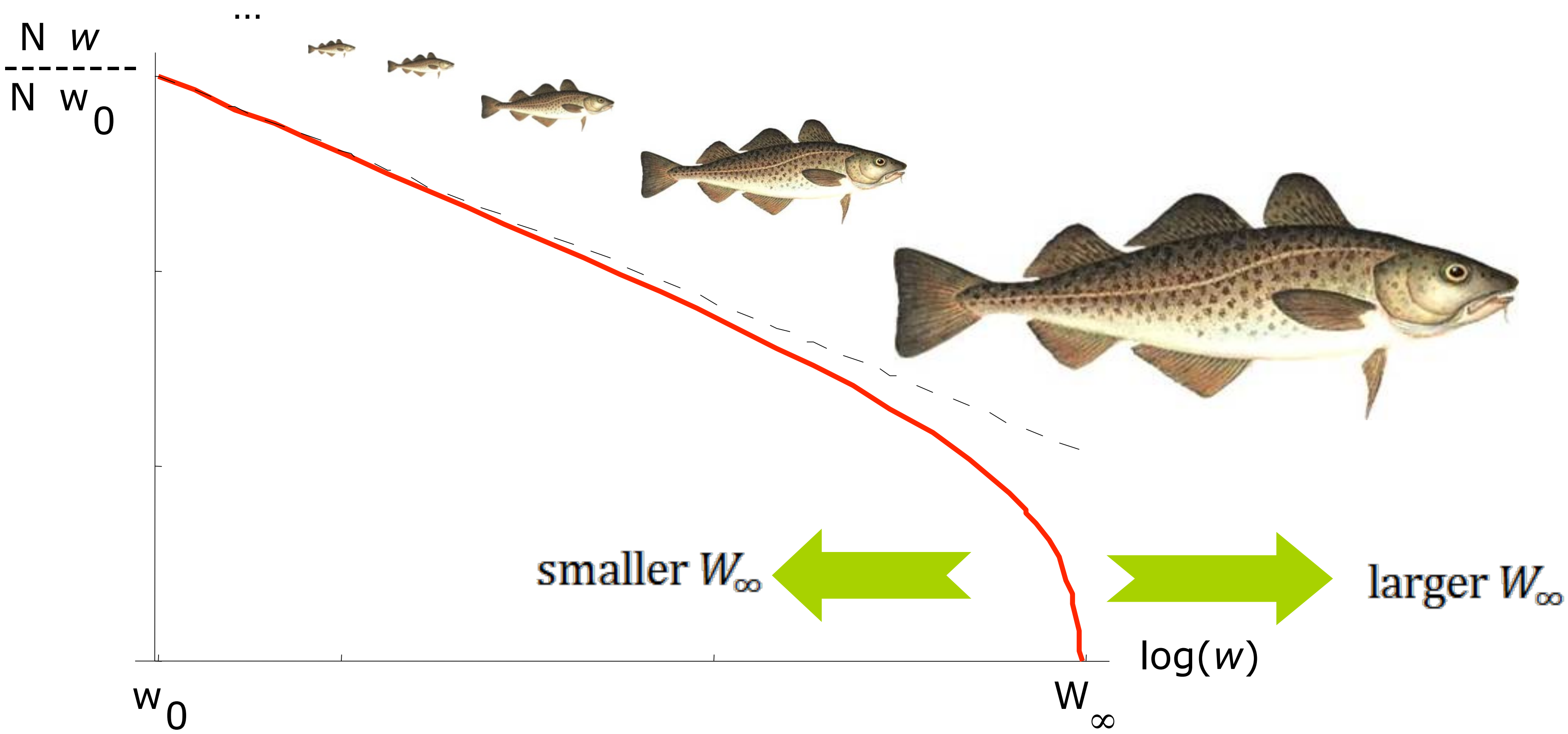


$$\frac{\partial g N(w)}{\partial w} + \mu N(w) = 0$$

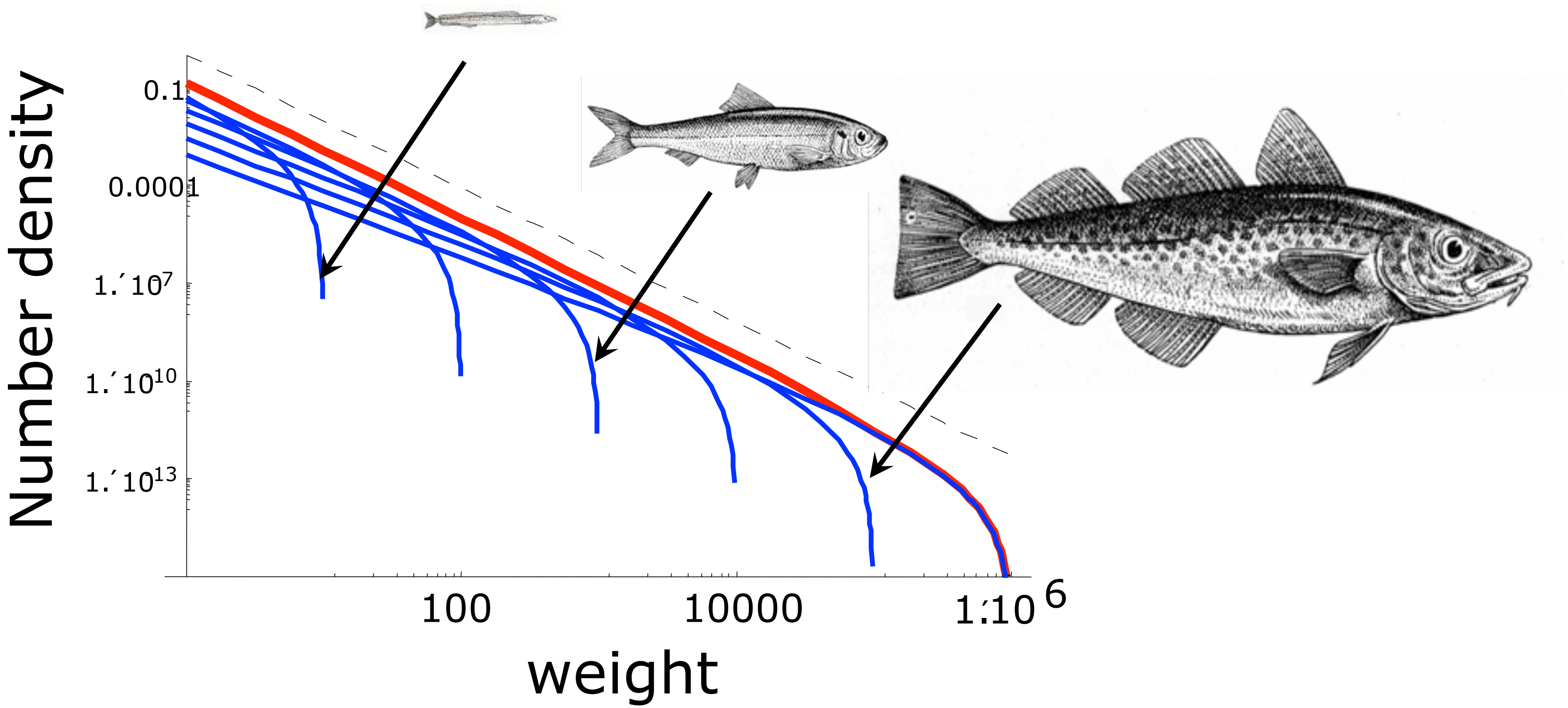
Population structure

Physiological rate of predation: mortality/(growth/weight)

$$N(w) = \kappa w^{-n-a}\left[1-\left(\frac{w}{W_\infty}\right)^{1-n}\right]^{\frac{a}{1-n}-1}$$



Community structure



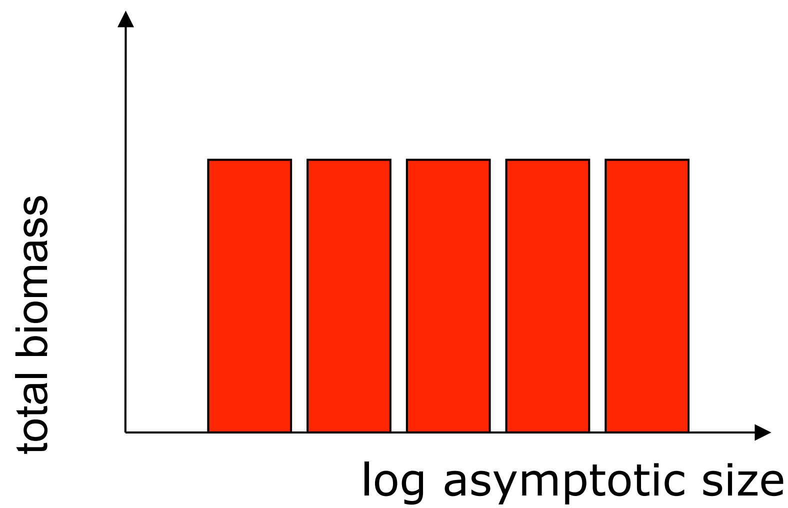
Andersen & Beyer: *Am. Nat.* (168) 54-61 (2006)

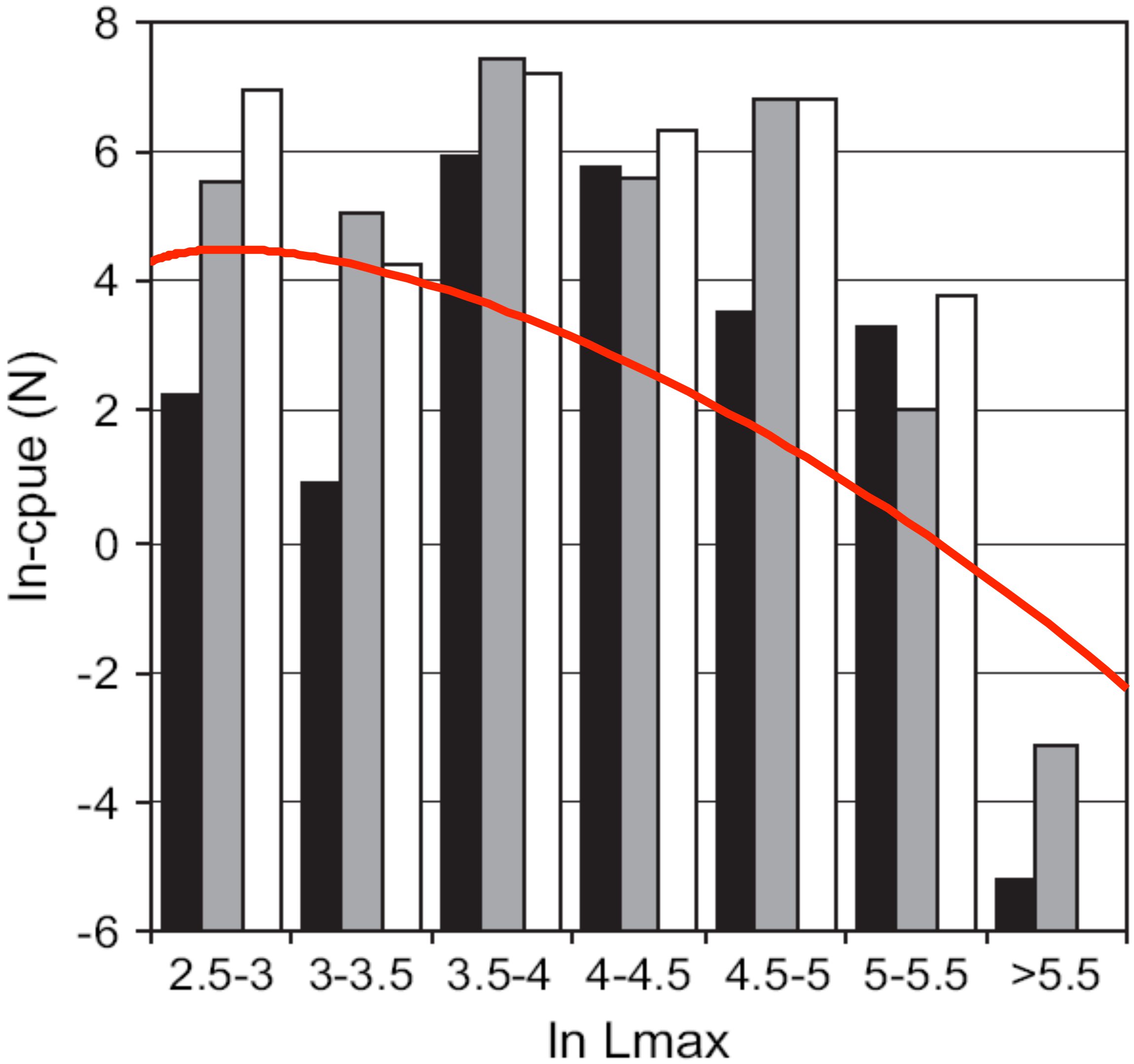
Extended Sheldon

Sheldon hypothesis:

Extended

Sheldon hypothesis:



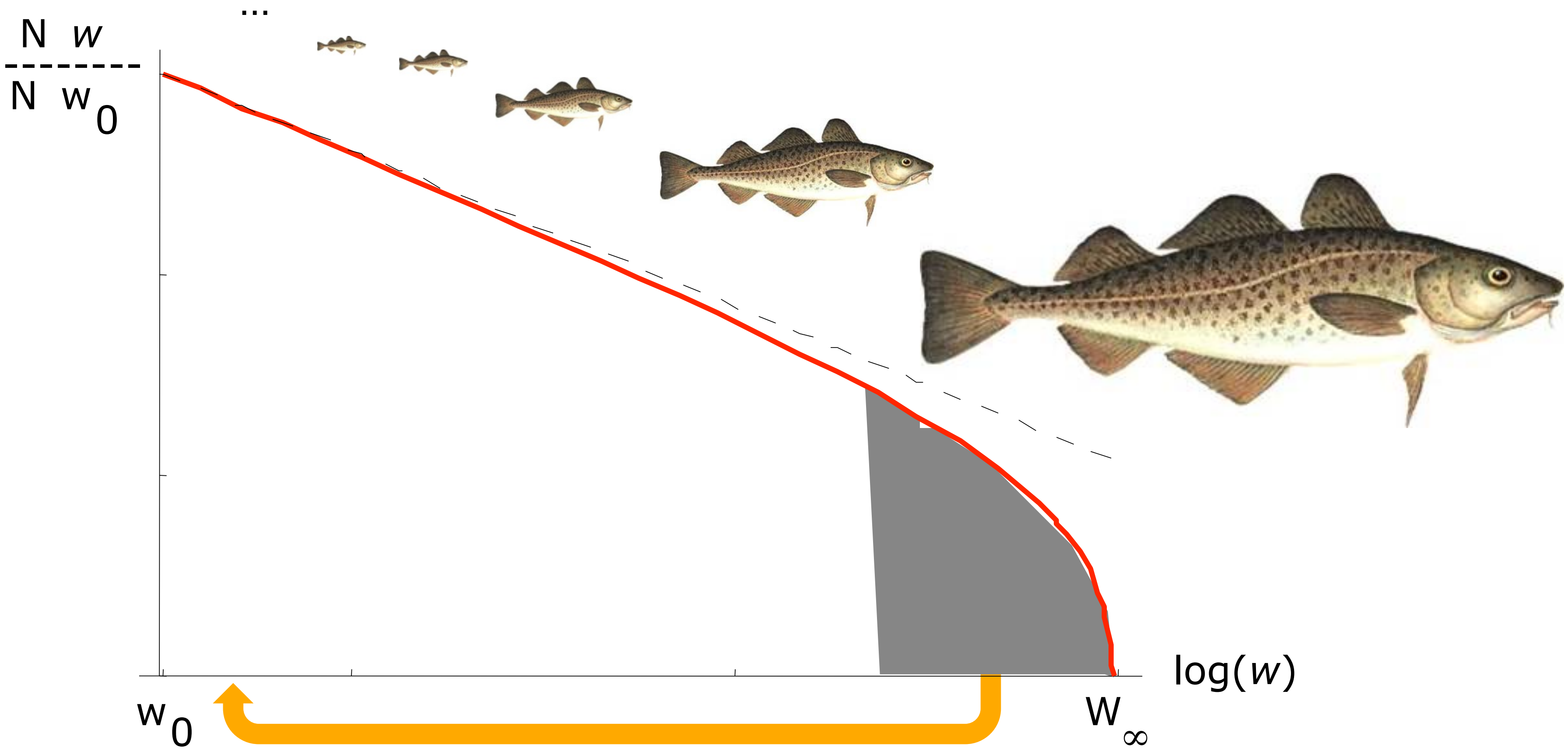


Red line calculated assuming that the lower range of fish caught was 10 cm

data from Daan et al, JMS (2003)

Optimal life-history strategy

$$N(w) = \kappa w^{-n-a}\left[1-\left(\frac{w}{W_\infty}\right)^{1-n}\right]^{\frac{a}{1-n}-1}$$



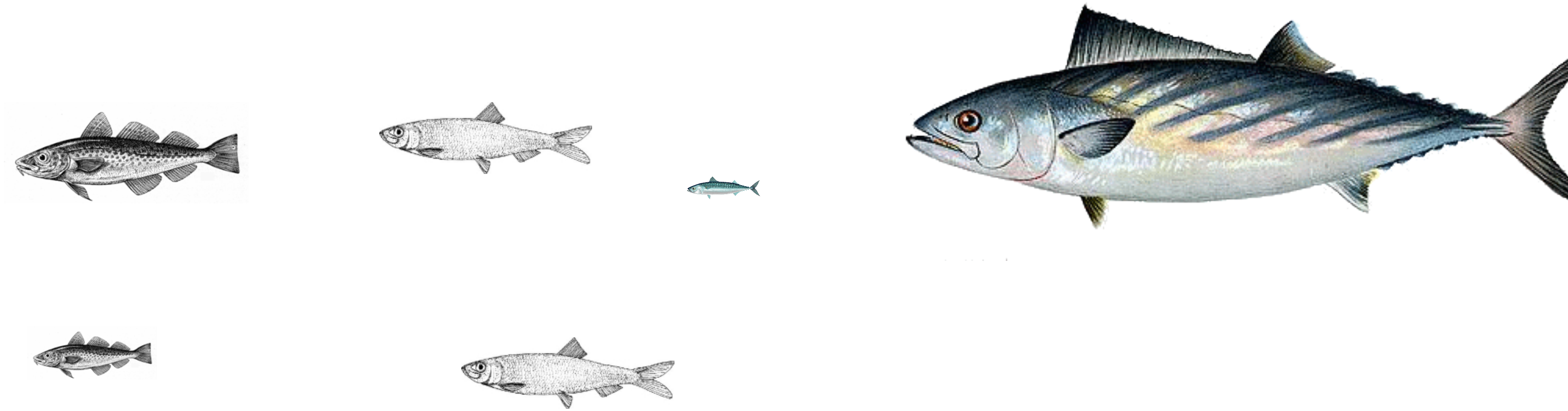
Optimal life-history strategy

$$R_0 \propto \frac{1}{2}\left(\frac{W_\infty}{w_{egg}}\right)^{1-a}$$

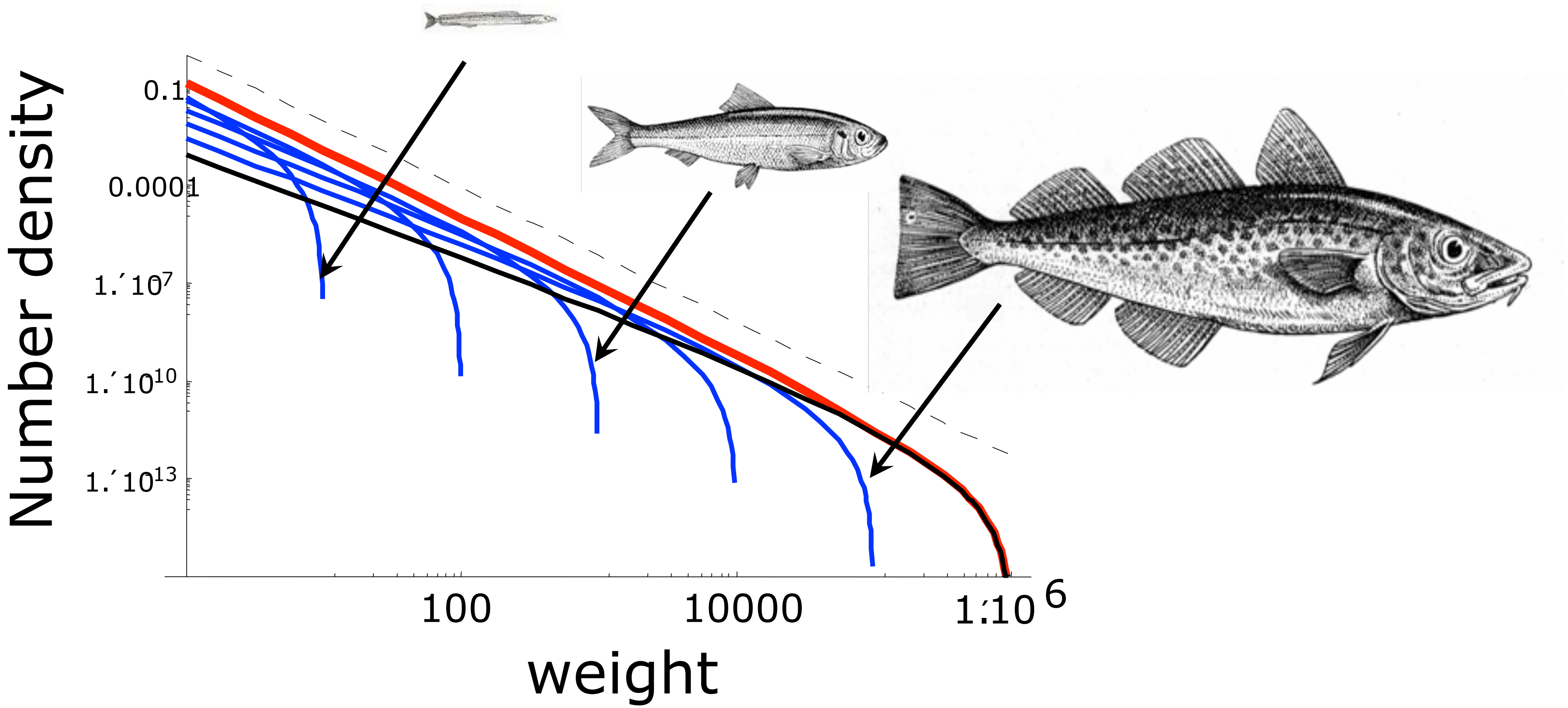
Andersen et al., Theo. Pop. Biol. (2008)

Conjectures

1) Why are there small fish species?



Community structure

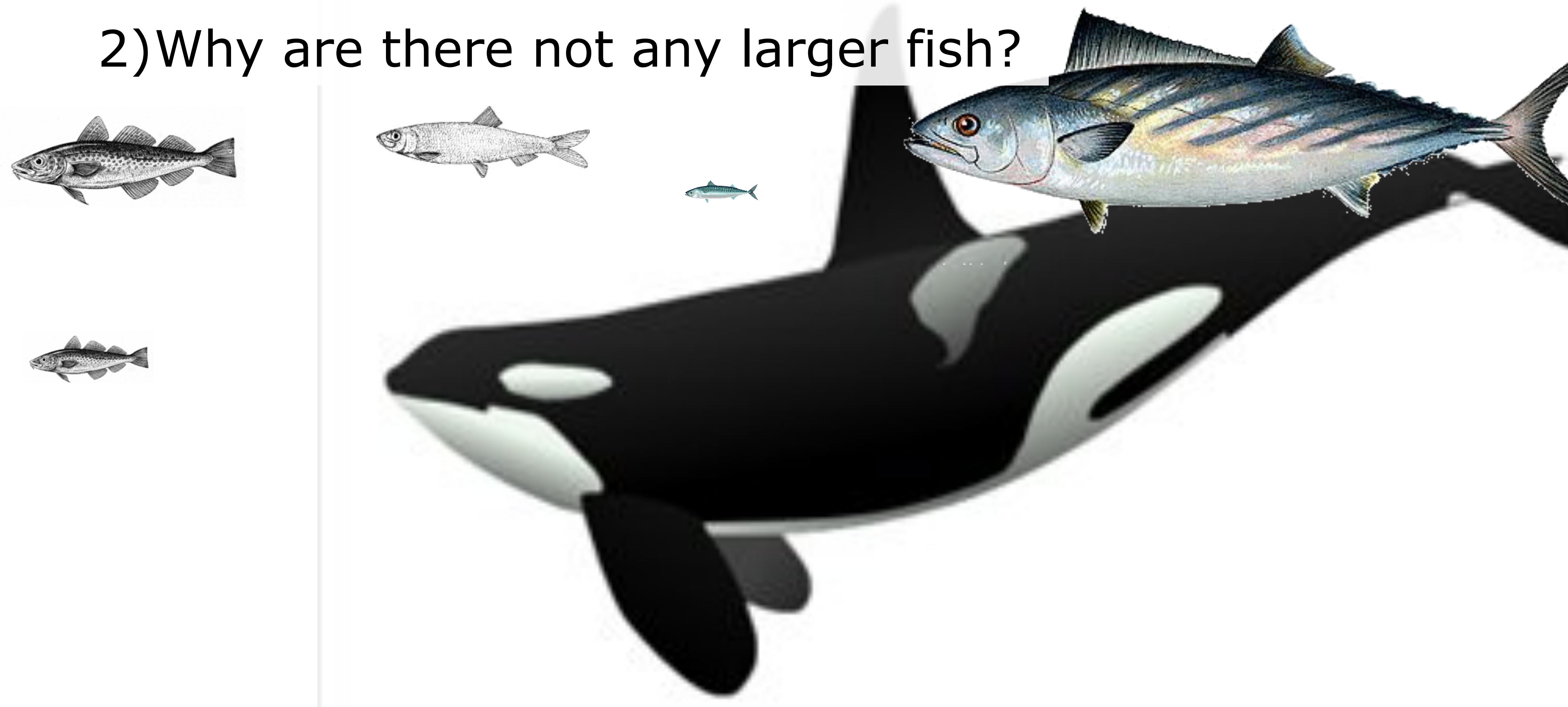


Andersen & Beyer: *Am. Nat.* (168) 54-61 (2006)

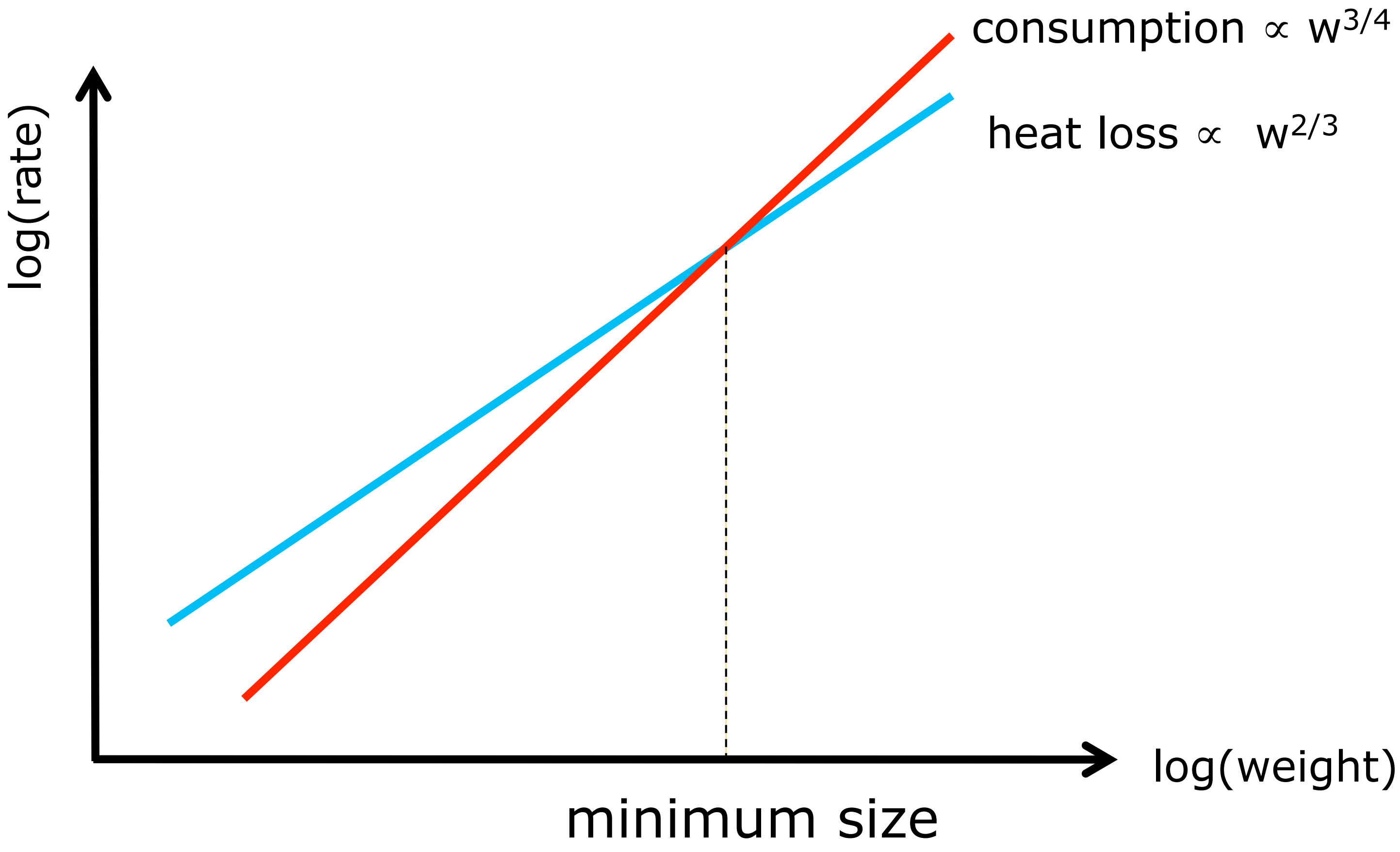
Conjectures

1) Why are there small fish?

2) Why are there not any larger fish?

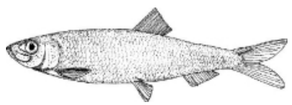


Energy budget

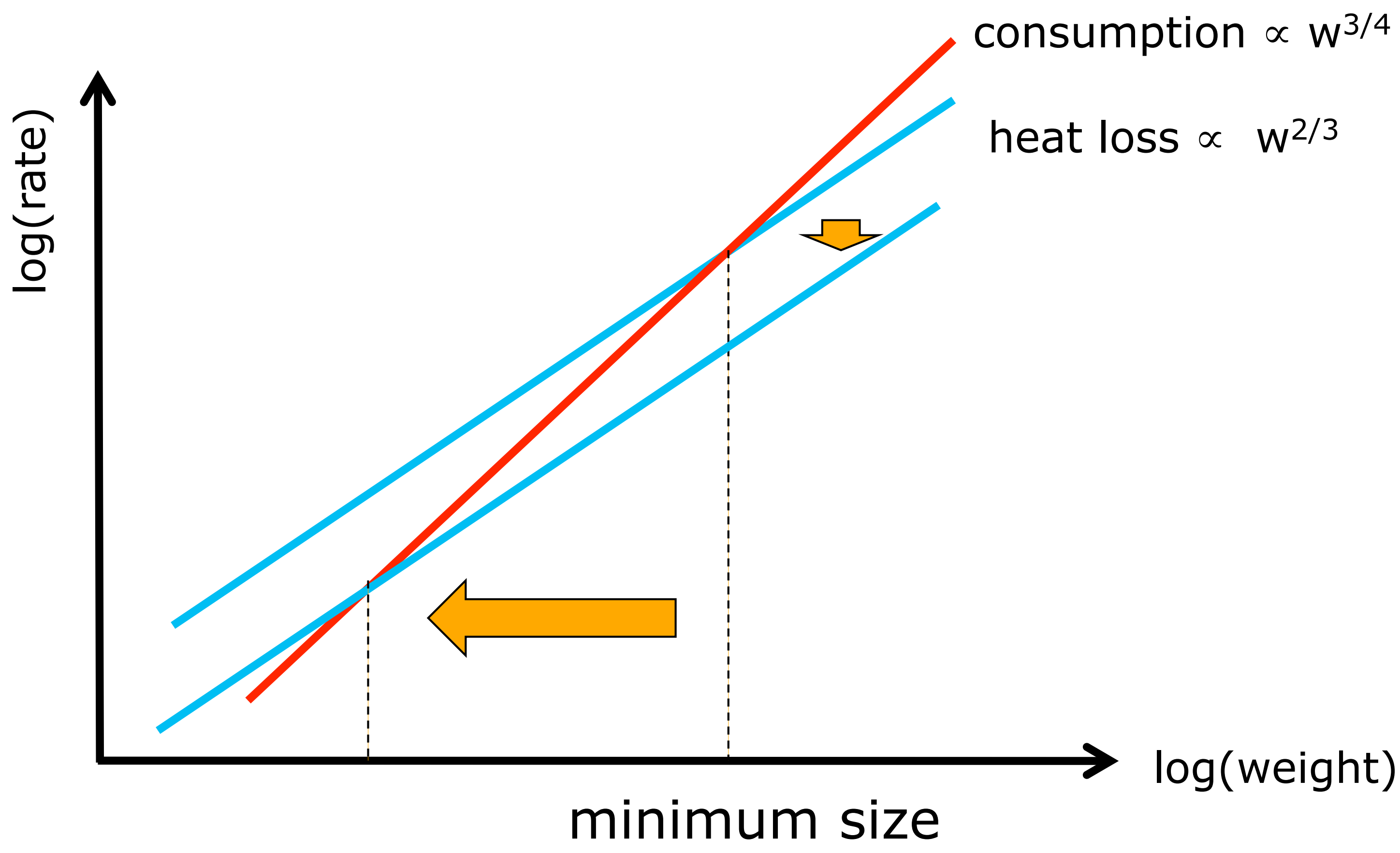


Conjectures

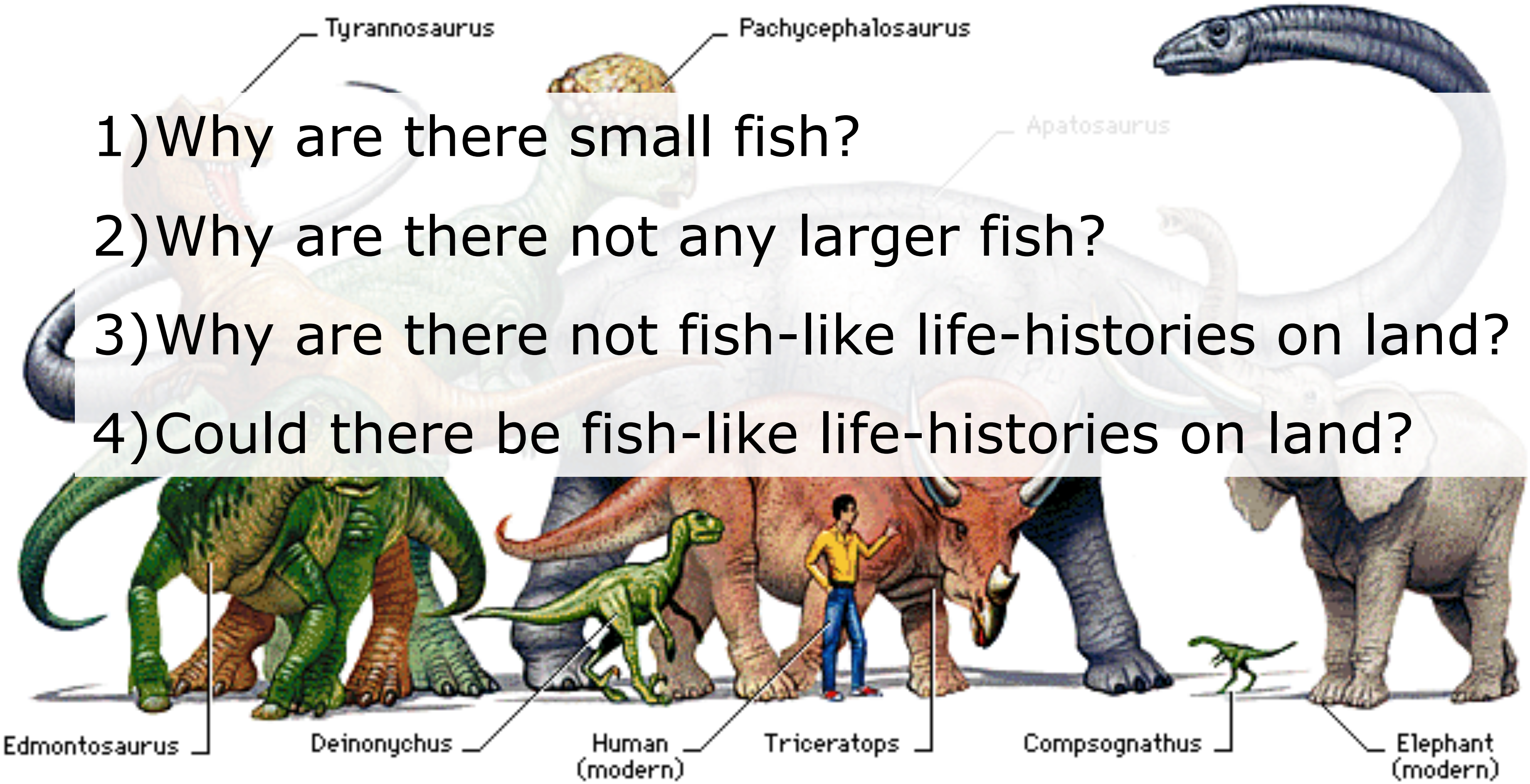
1) Why are there small fish?
2) Why are there not any larger fish?
3) Why are there not fish-like life-histories on land?



Energy budget



Conjectures

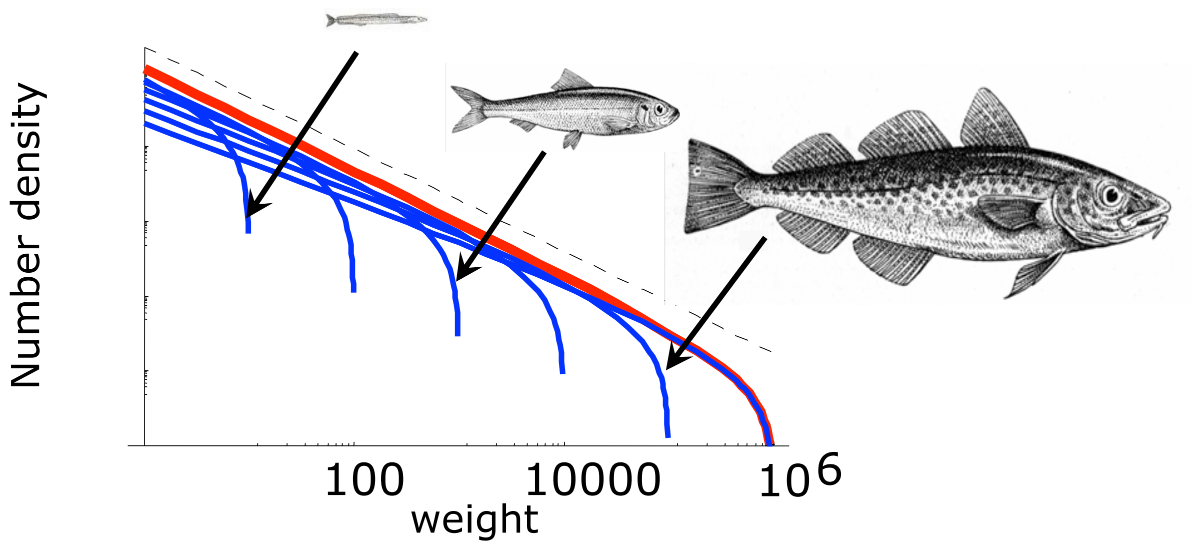


1) Why are there small fish?
2) Why are there not any larger fish?
3) Why are there not fish-like life-histories on land?
4) Could there be fish-like life-histories on land?

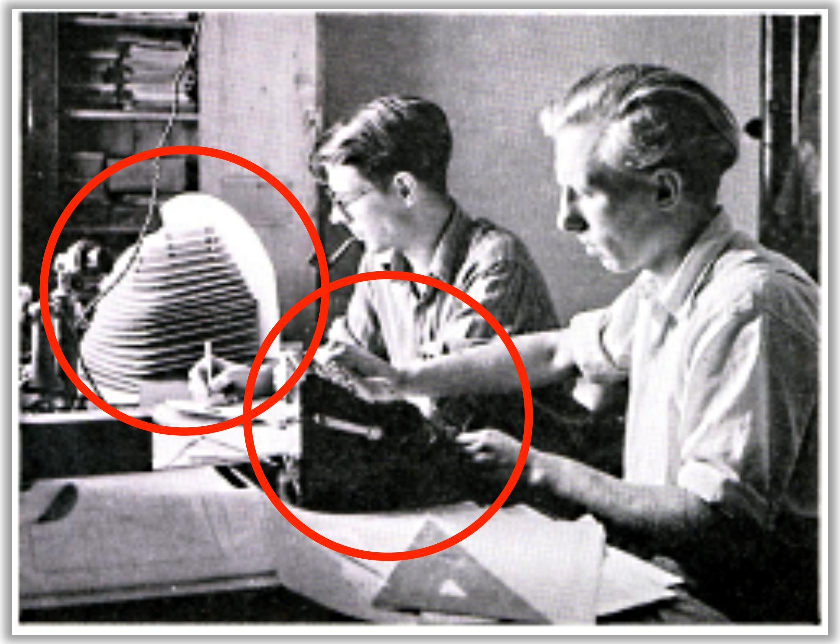
Equilibrium size-spectrum theory

Starting from a basic "metabolic" assumption:
consumption $w^{3/4}$:

- Exponent of size spectrum is $-2-q+n \approx -2$
- Main trait: asymptotic size
- Population structure can be solved analytically
- Many-small-eggs strategy is optimal

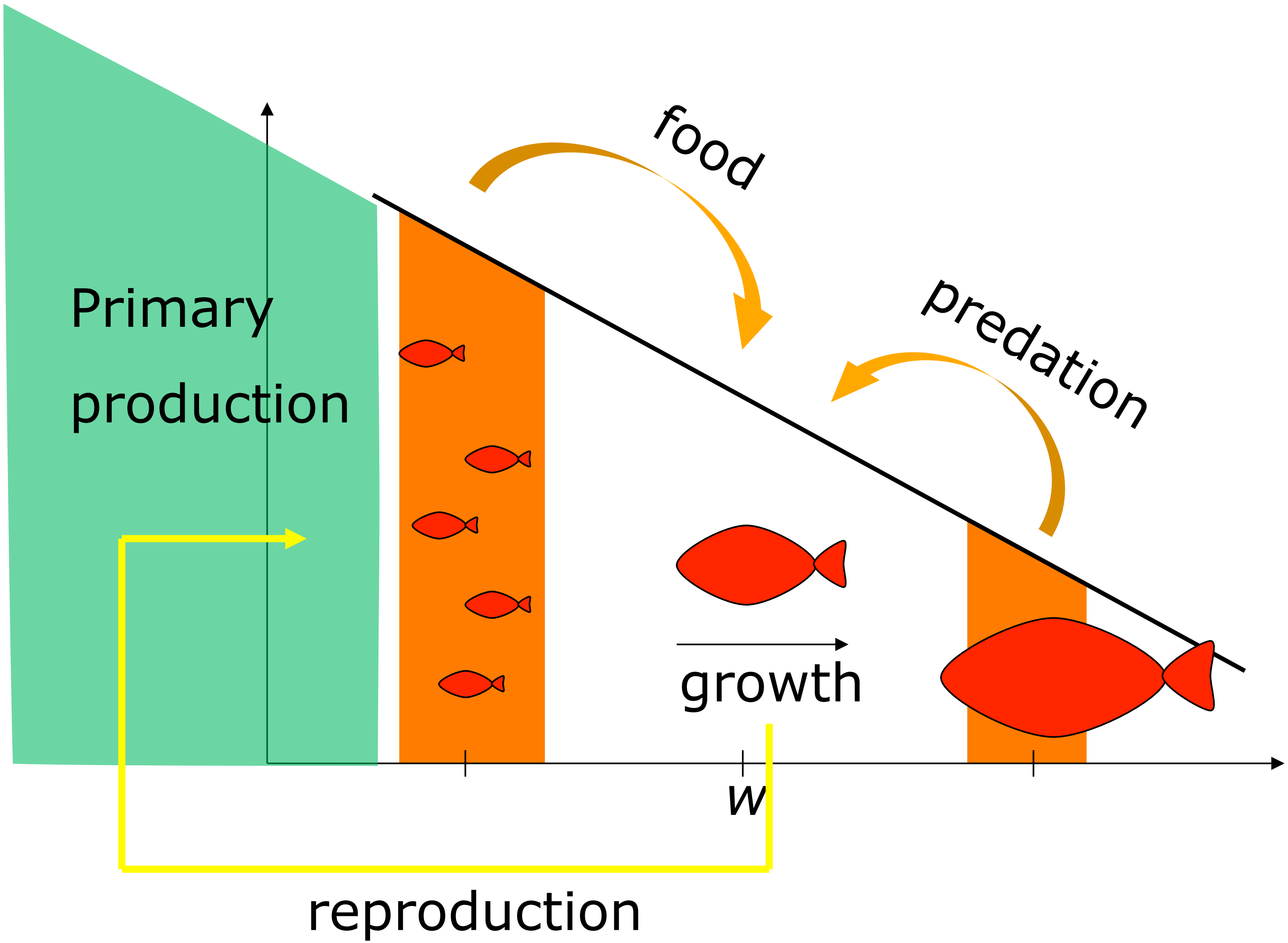


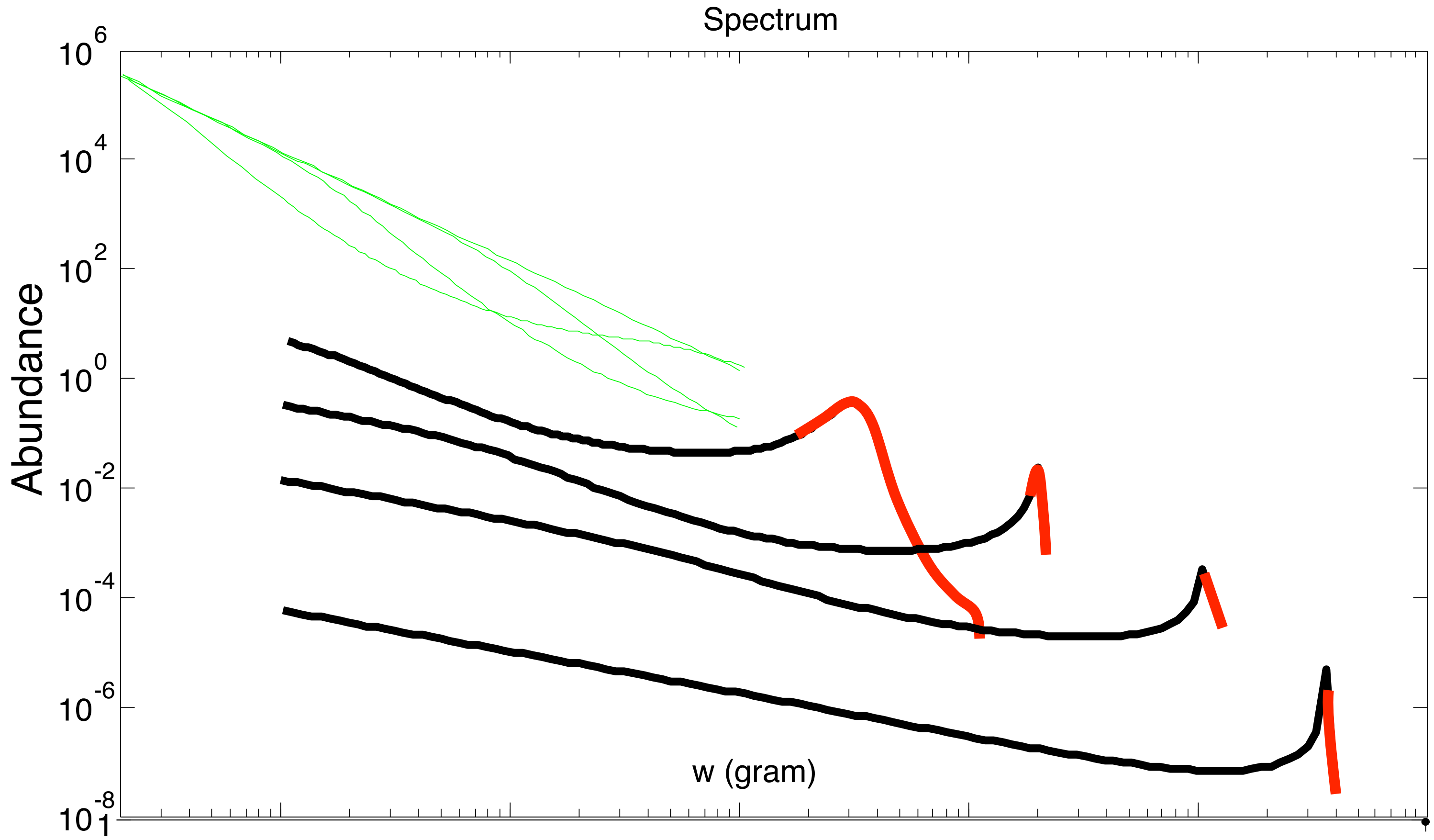
Dynamical size-spectrum models: Impact assessments of fishery



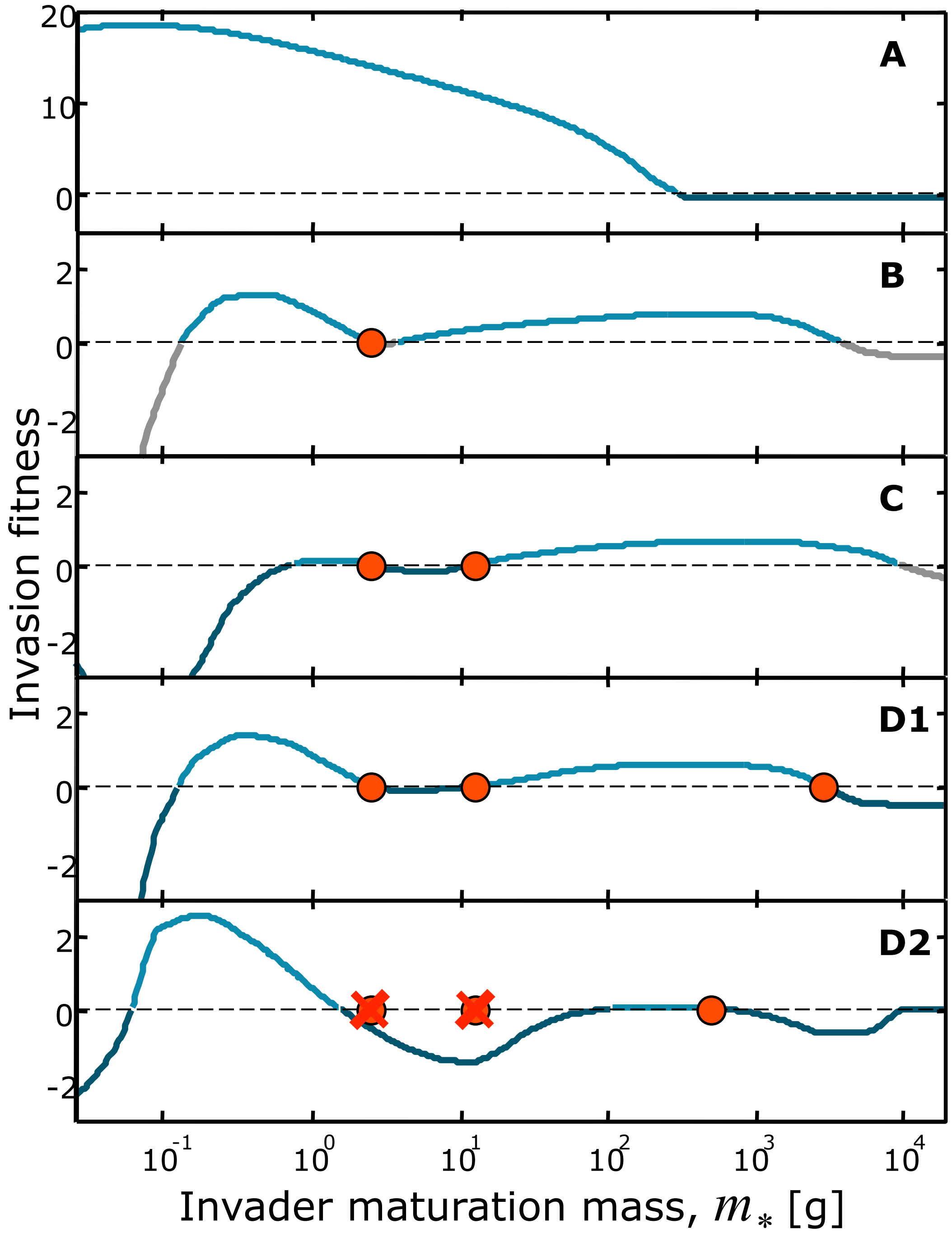
In the beginning there was Beverton & Holt ...

Food web model by Martin Hartvig





Spectrum
Abundance
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-8
w (gram)
1

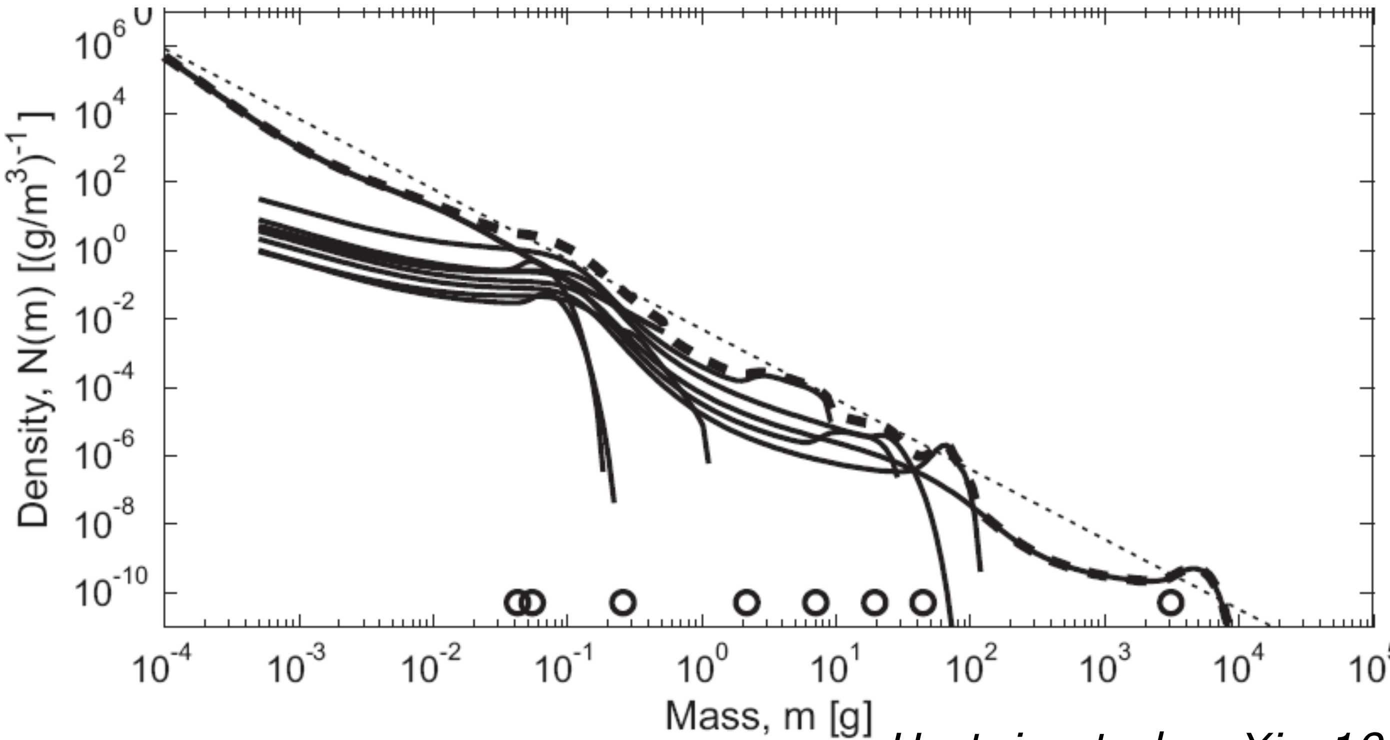


20
10
0
A
2
0
-2
B
C
D1
D2
Invasion fitness
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Invader maturation mass, m_* [g]

One trait

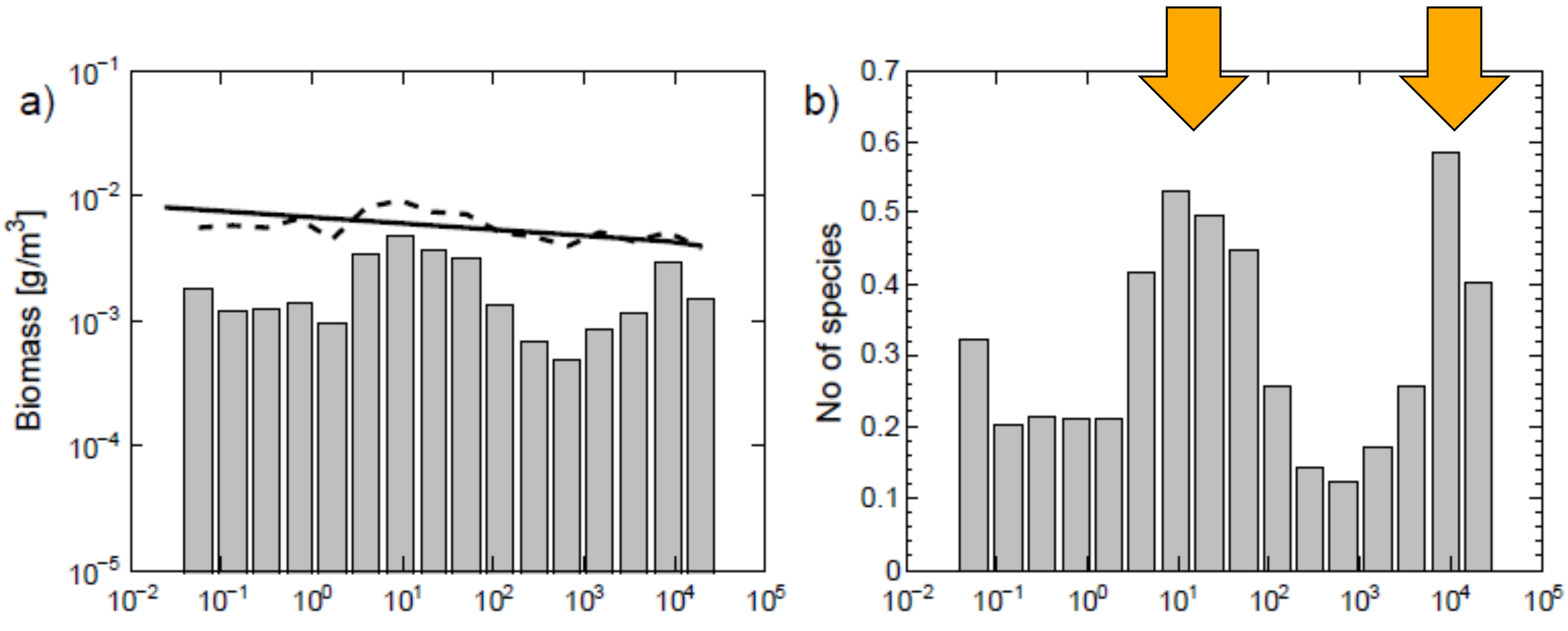
Typical results: one-two small fish, one large fish

Random species interactions



Hartvig et al, arXiv:1004.4138v1

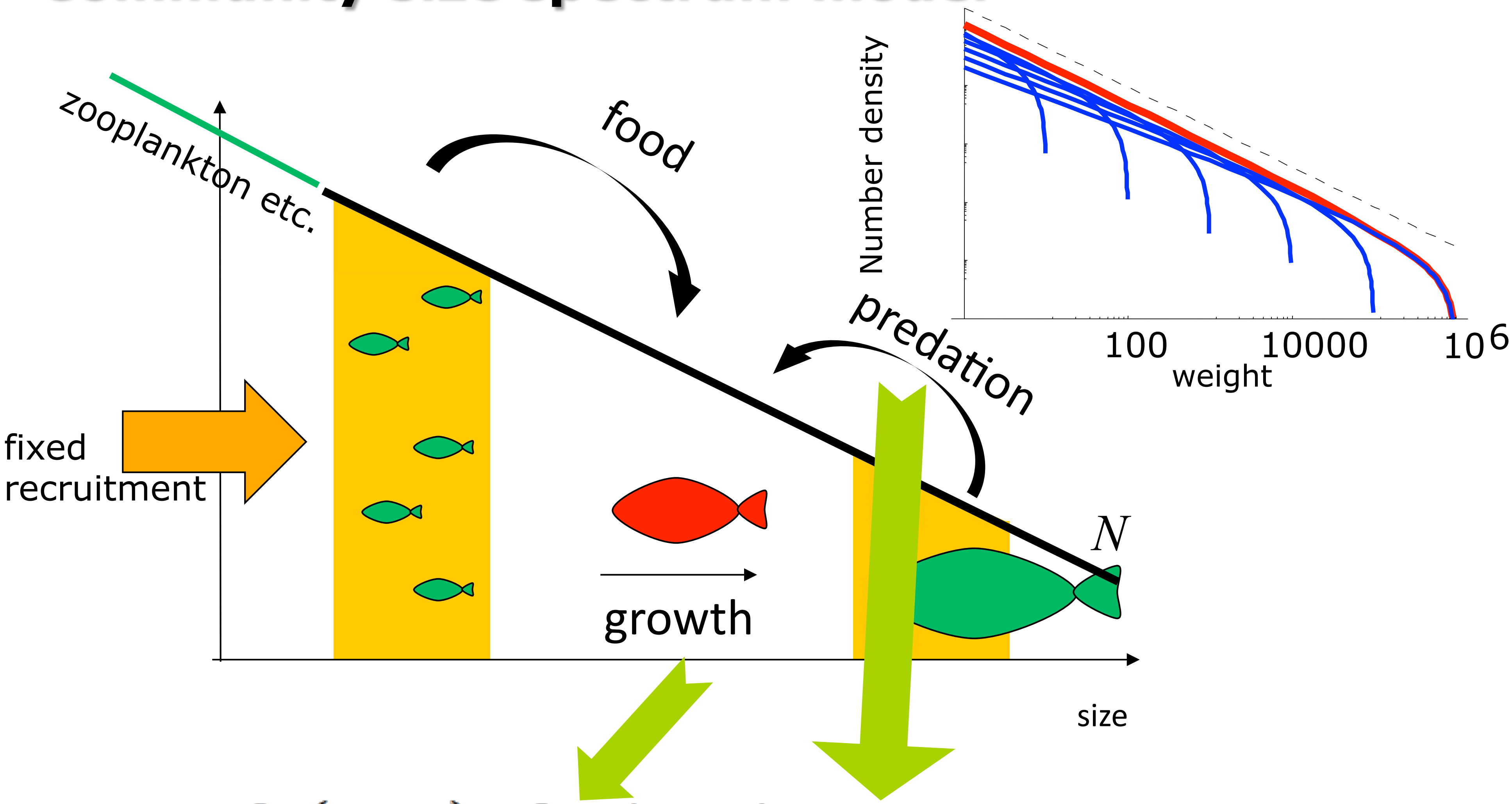
Biomass & diversity distributions



Size at maturation   Size at maturation

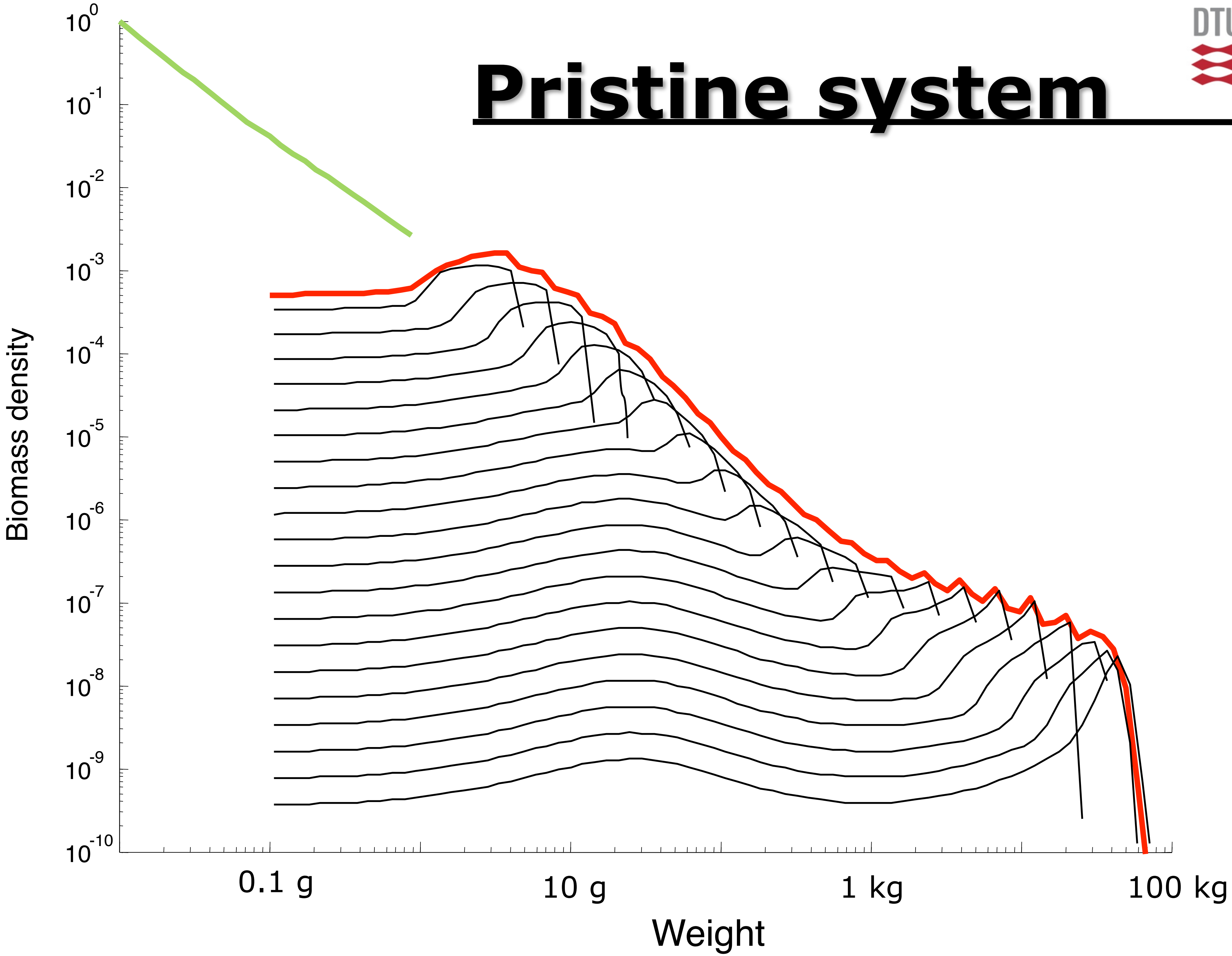
Hartvig et al, arXiv:1004.4138v1

Community size spectrum model

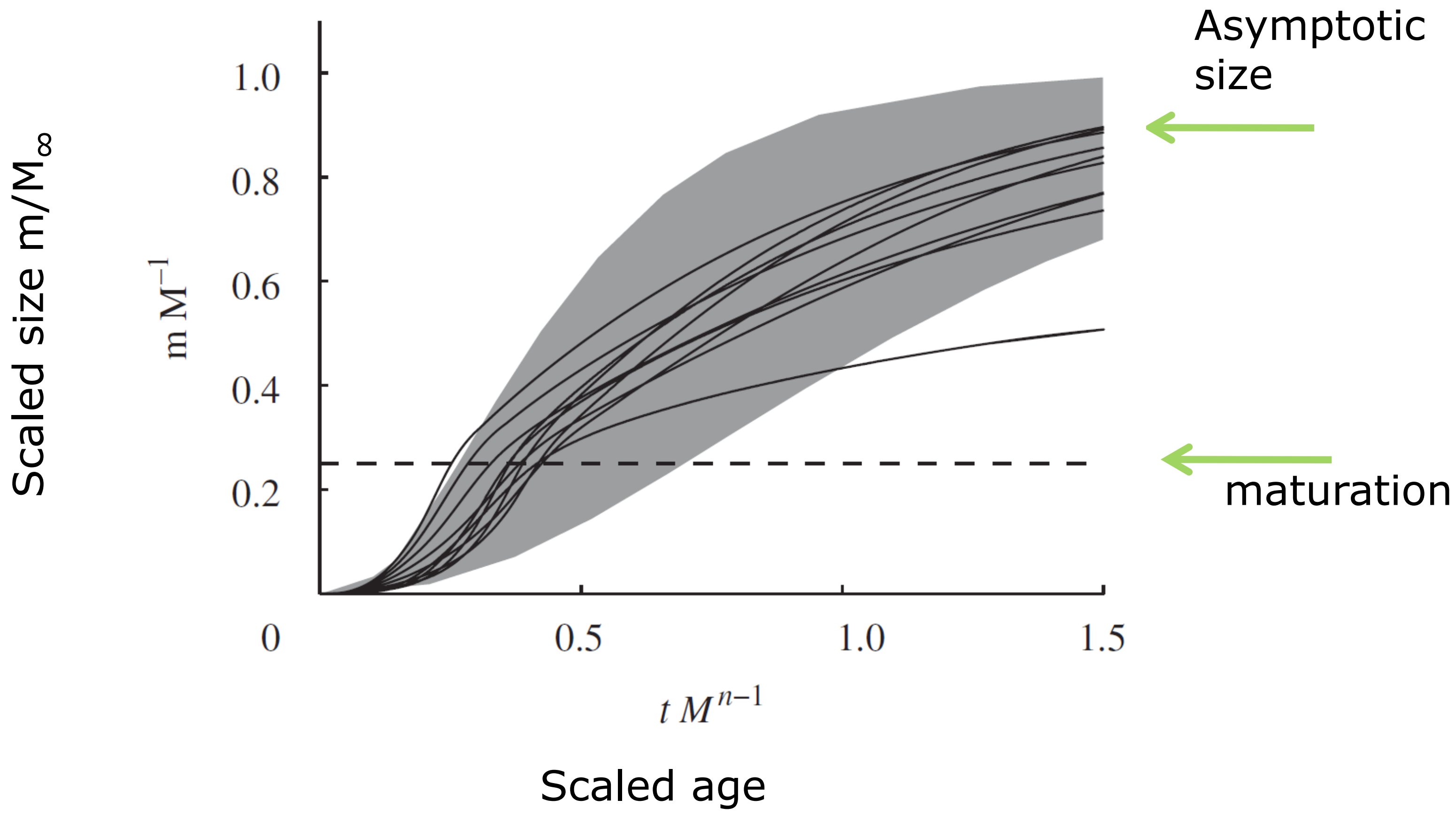


$$\frac{\partial N(w, W_\infty)}{\partial t} + \frac{\partial g N(w, W_\infty)}{\partial w} = -\mu N(w, W_\infty)$$

Pristine system



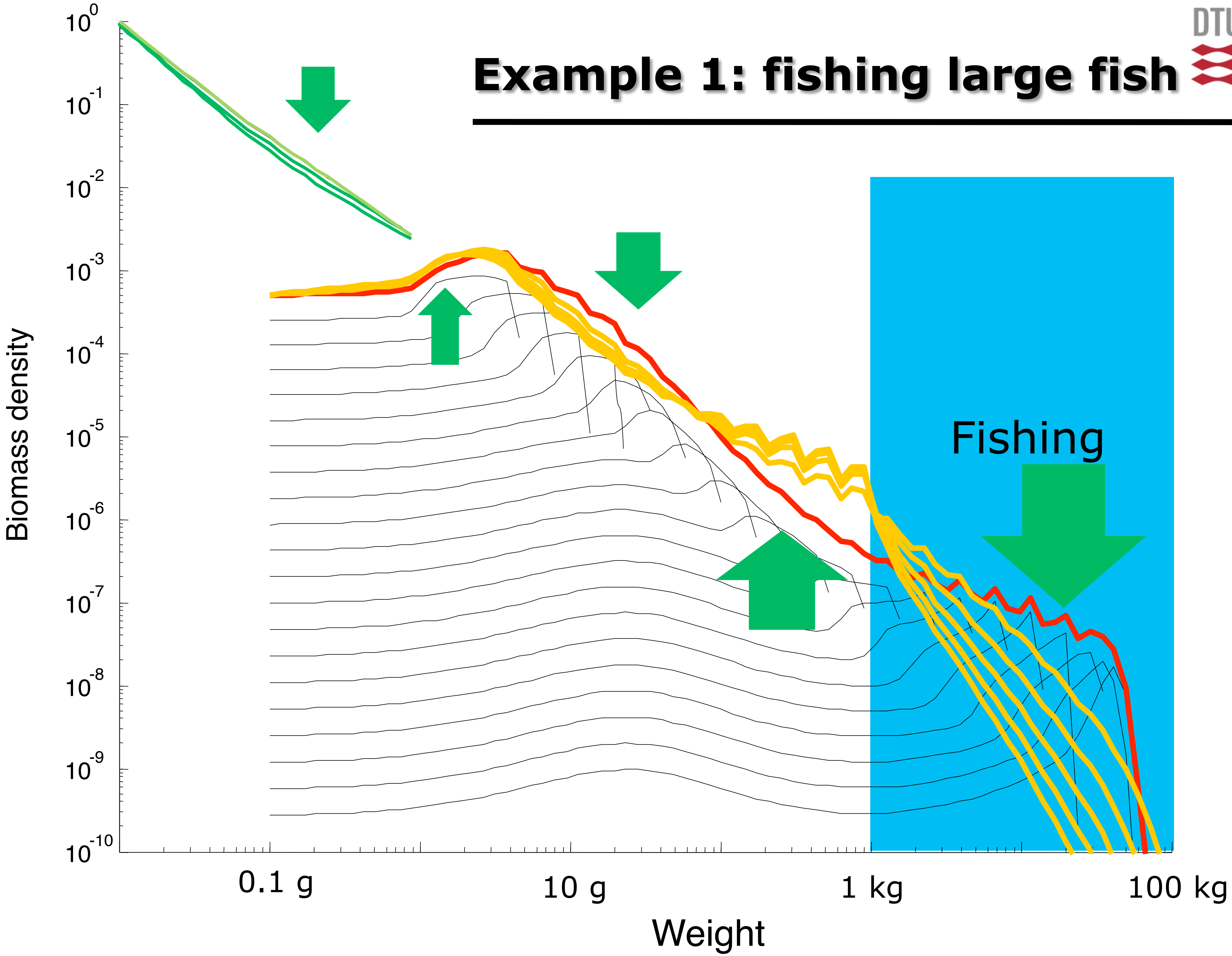
Results: growth curves

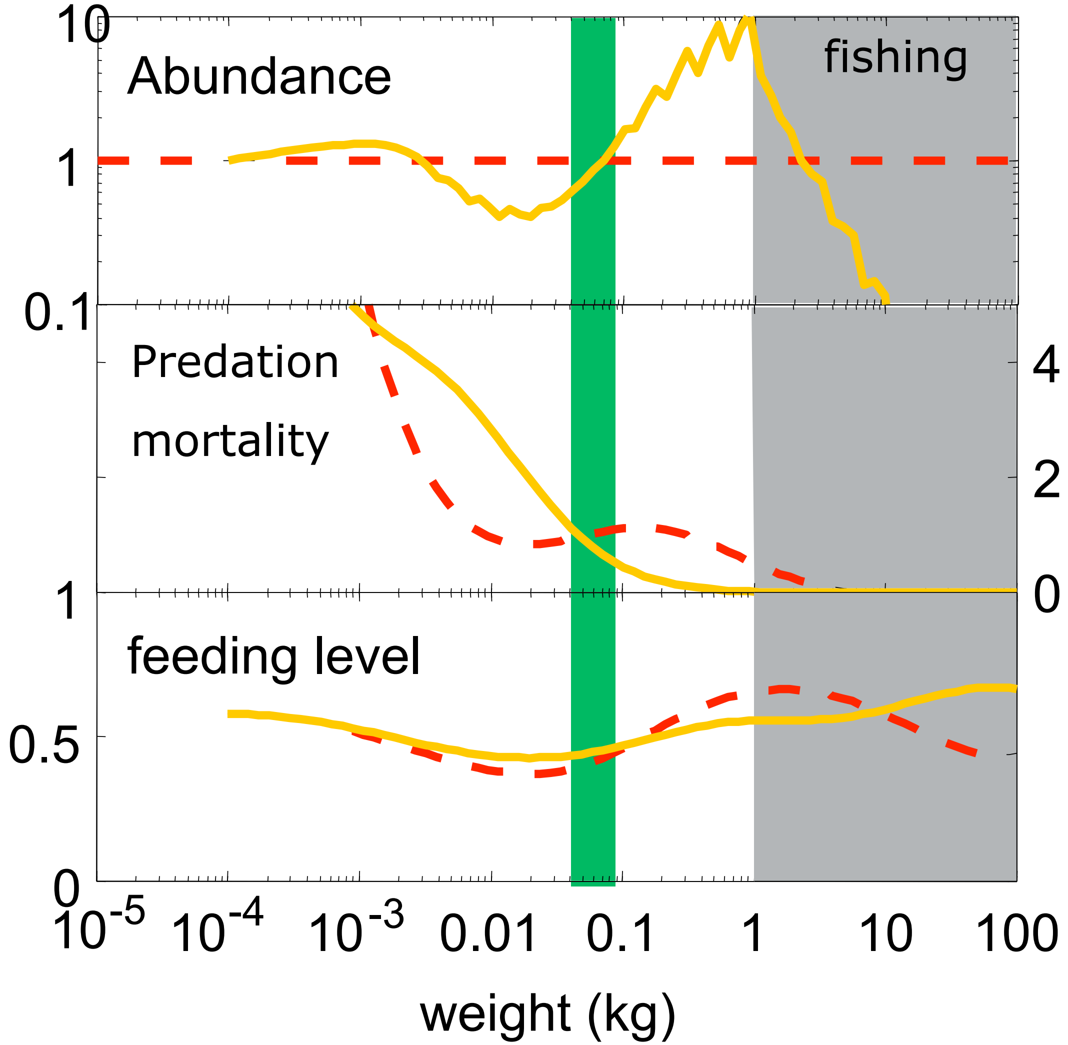


Four examples of fishing

1) Fishing large fish
2) Fishing on the whole ecosystem
3) Fishing forage fish
4) Recovery from fishing

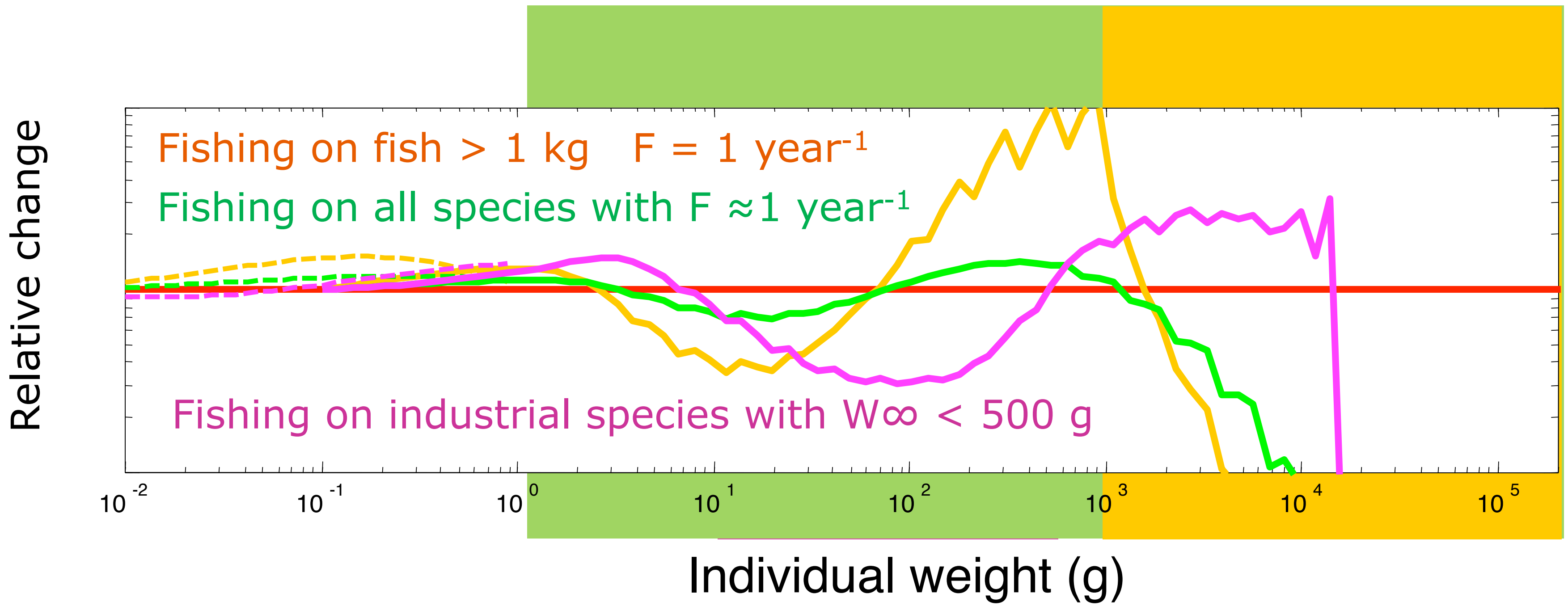
Example 1: fishing large fish





Abundance
fishing
10
1
0.1
Predation
mortality
4
2
0
1
feeding level
0.5
0
10^-5
10^-4
10^-3
0.01
0.1
1
10
100
weight (kg)

Example 2: fishing the whole system
Example 3: forage fishing



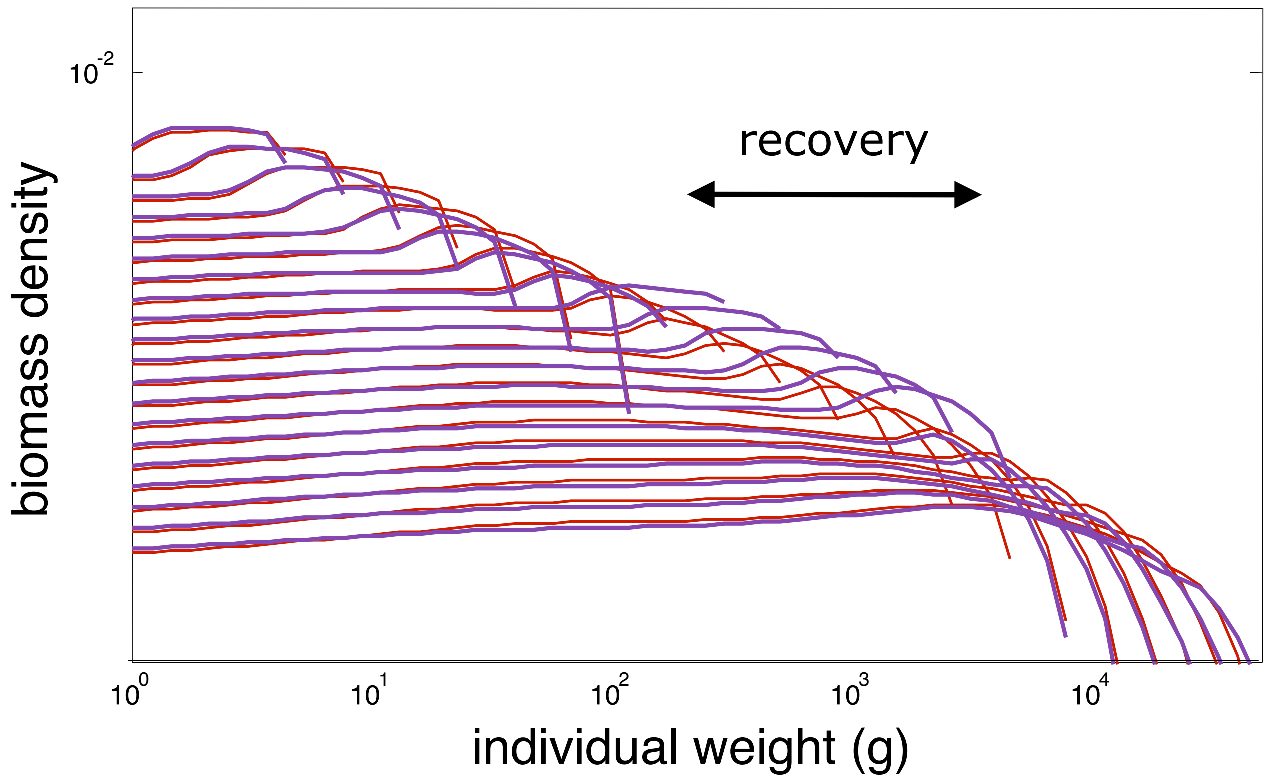
⇒ Two-way trophic cascades

⇒ Cascades are *damped*

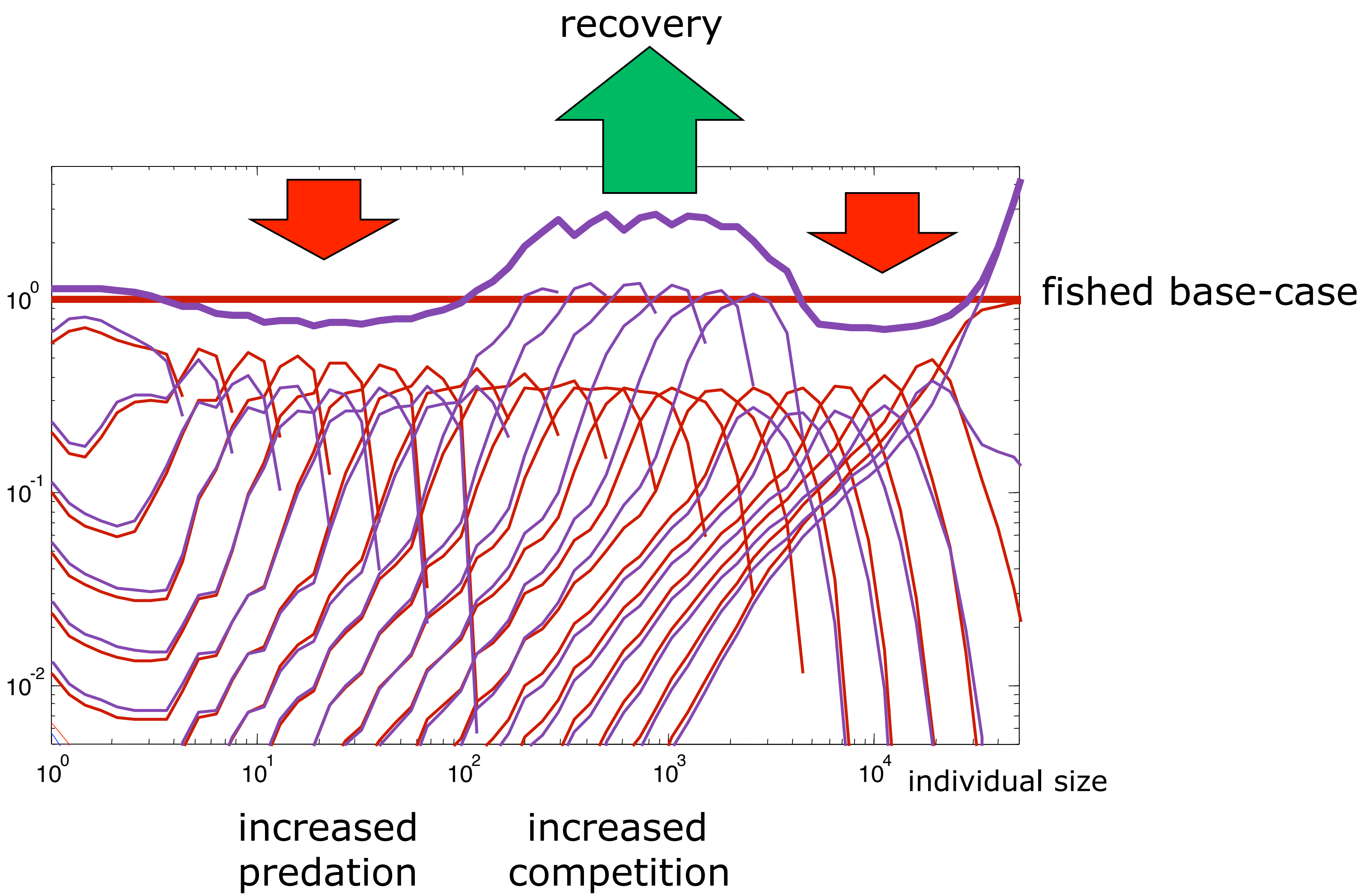
⇒ Fishing on all life histories removes cascades

Example 4: community effects of recoveries

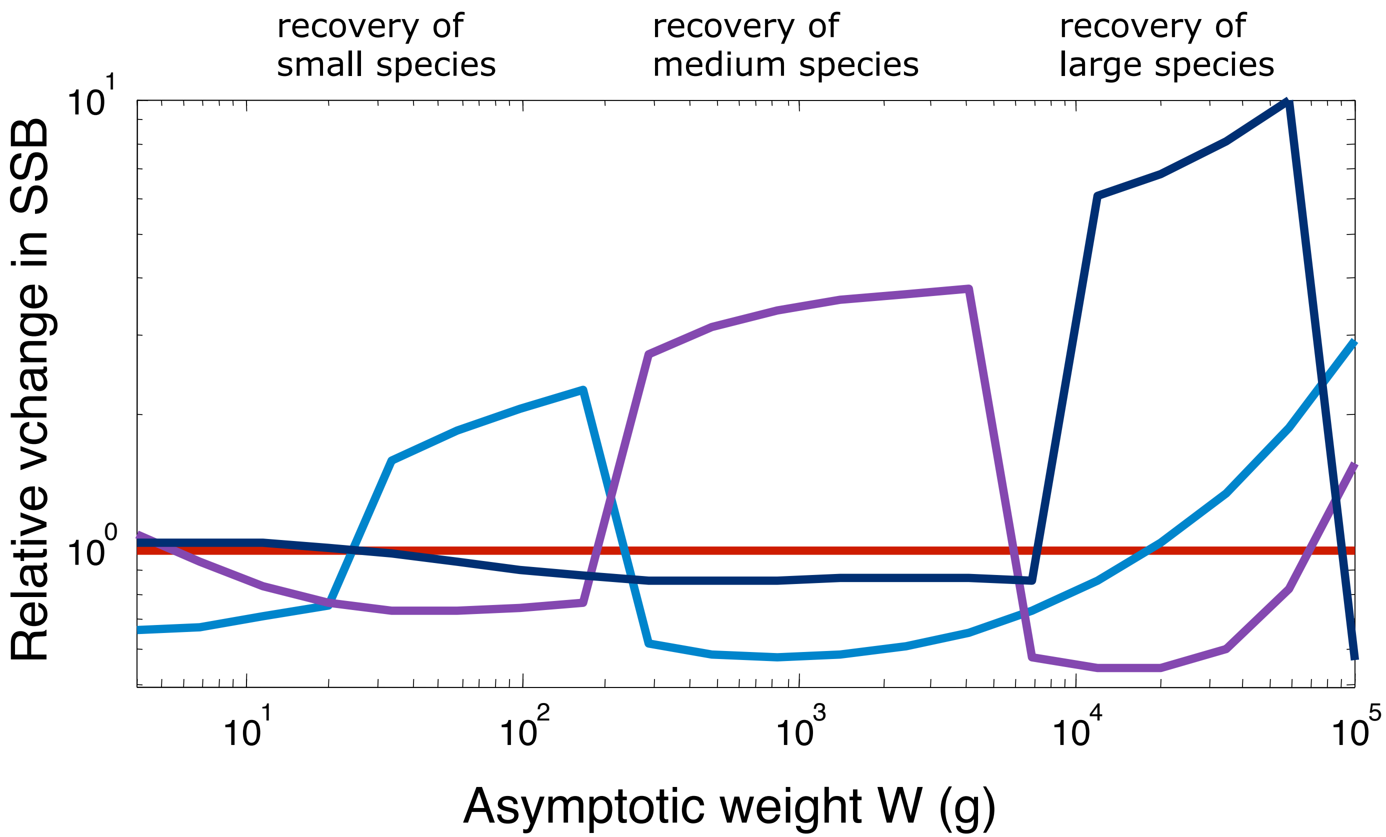
Base case: a heavily fished ecosystem (e.g. the North Sea)



Community effects



Community effects



Andersen and Rice, ICES JMS (2010)

spectrum.stockassessment.org

Size Spectrum Calculator

Calculate the expected ecosystem effect of a management plan involving changing the fishing effort on one aspect of the fish community. The fishing effort is divided on three groups of fish species:

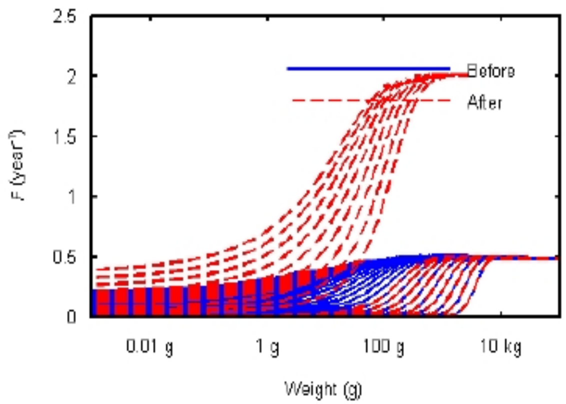
- Small species ("forage fish"): asymptotic weight less than 100 g
- Medium species ("small pelagics"): asymptotic weight between 100 g and
- Large species ("large demersals/pelagics"): asymptotic weight larger than 4 kg.

Input parameters

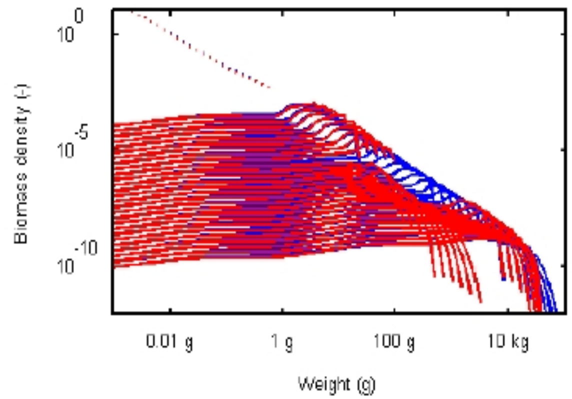
	Before change		After change	
F_{small}	0.5	$year^{-1}$	0.5	$year^{-1}$
F_{medium}	0.5	$year^{-1}$	2	$year^{-1}$
F_{large}	0.5	$year^{-1}$	0.5	$year^{-1}$

Calculate

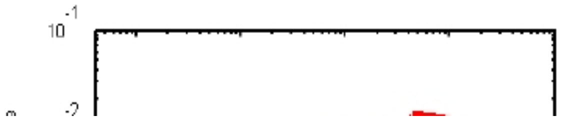
Results

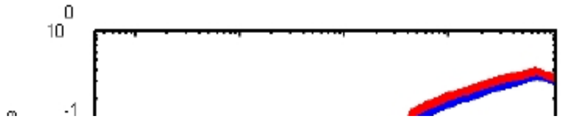


The fishing mortality as a function of individual size for the base case (before the change) in blue and after the change in red. Each line correspond to an asymptotic size class.



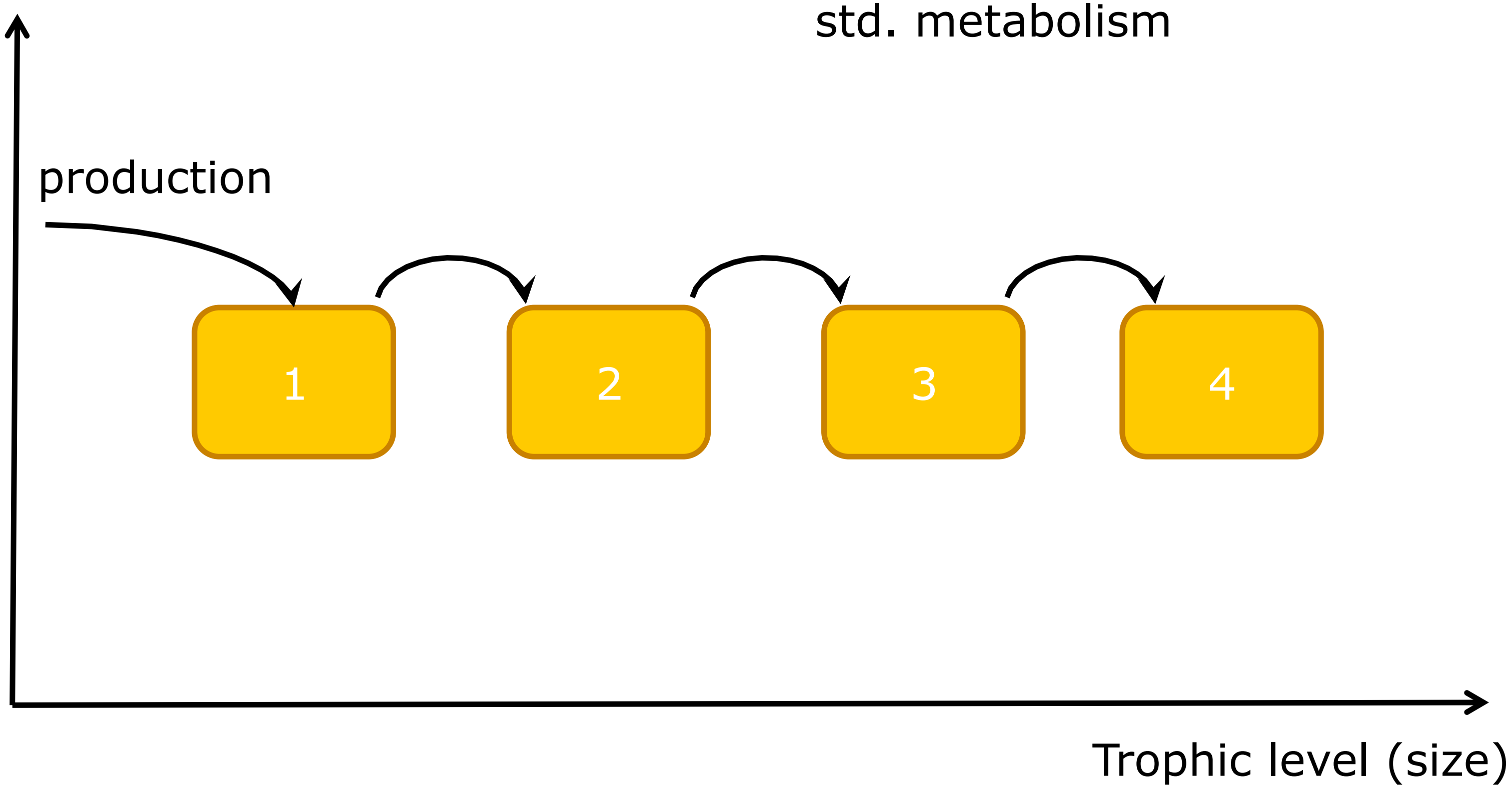
Size spectra for 18 asymptotic size classes as a function of individual weight. The dotted lines in the top left corner are the resource spectra.

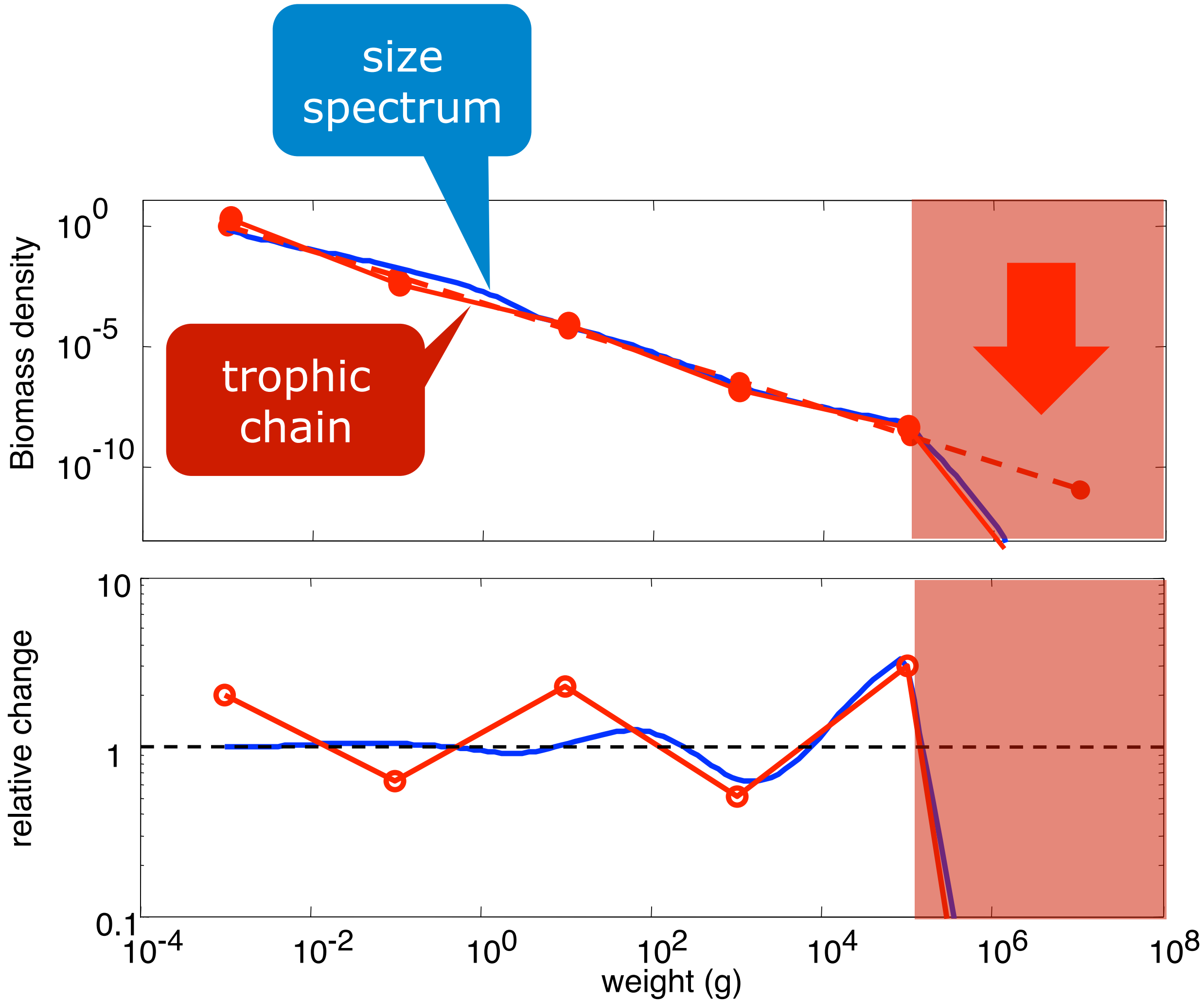




Does ontogenetic niche shifts matter?

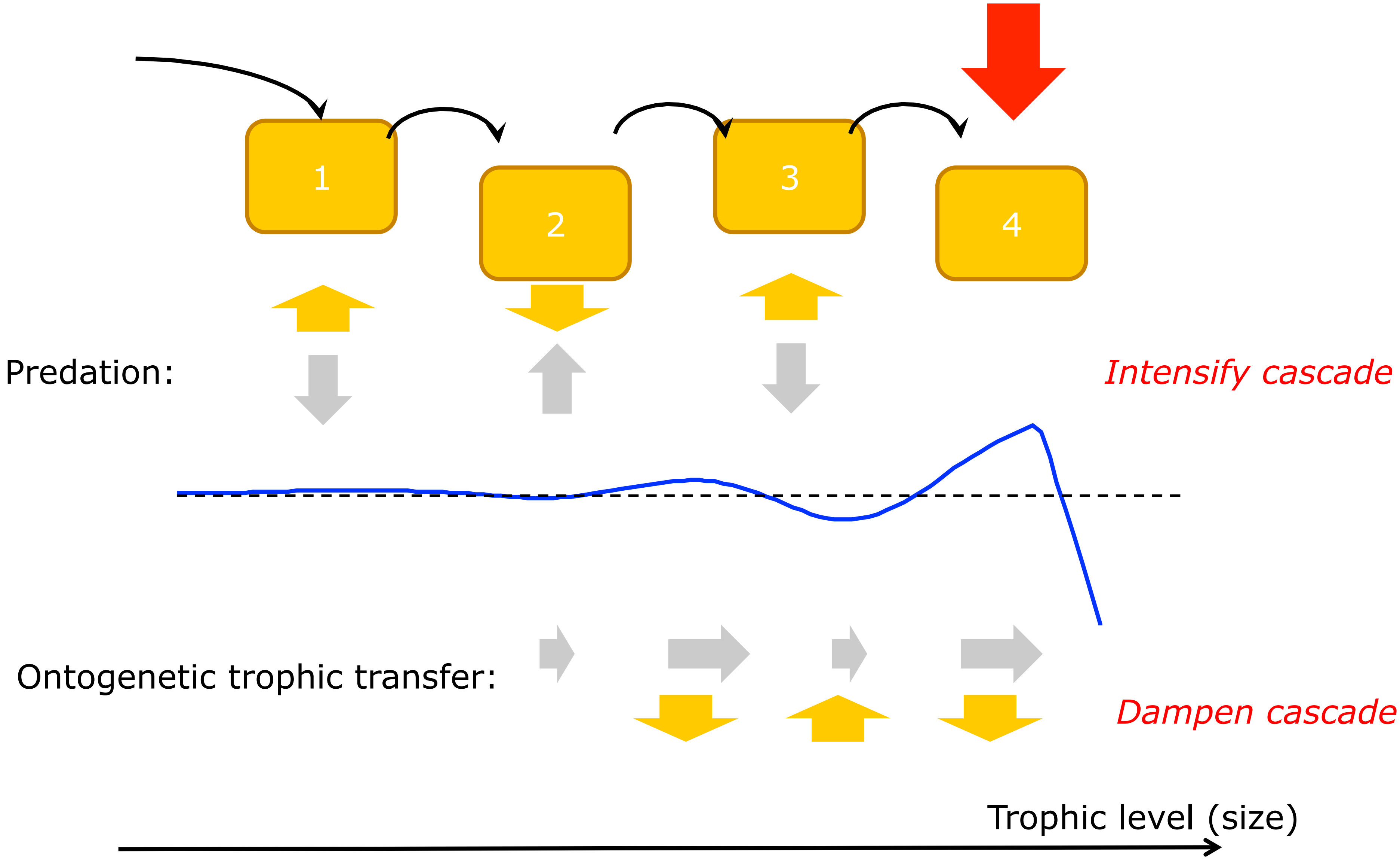
$$\frac{\dot{N}_i}{N_i} = \underbrace{\epsilon \gamma w_i^{q-1} w_{i-1} N_{i-1}}_{\text{reproduction rate}} - \underbrace{k w_i^{n-1}}_{\text{std. metabolism}} - \underbrace{\gamma w_{i+1}^{q} N_{i+1}}_{\text{predation losses}}$$

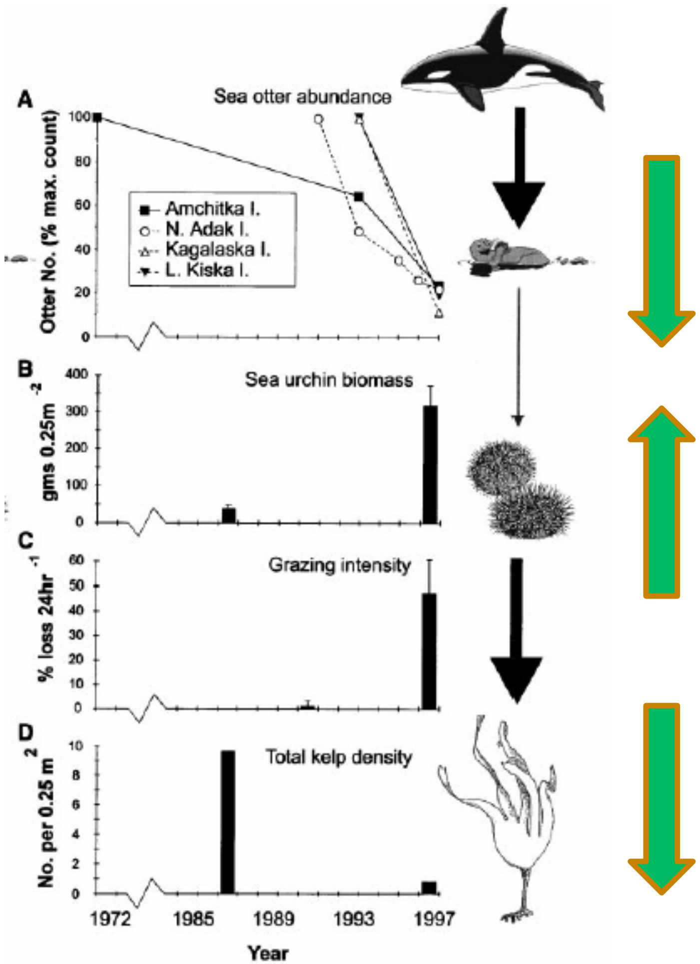




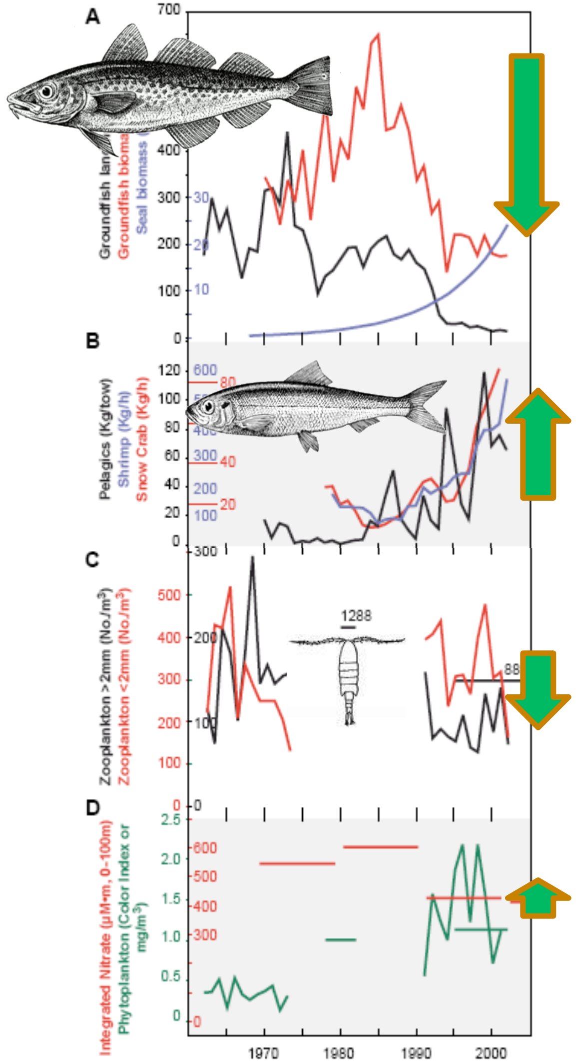
size spectrum
trophic chain
Biomass density
10^0
10^{-5}
10^{-10}
relative change
10
1
0.1
10^{-4}
10^{-2}
10^0
10^2
10^4
10^6
10^8
weight (g)

Why the difference?





Estes et al, Science (1998)



Cod biomass decreased by

a factor 2

Large zooplankton decreased

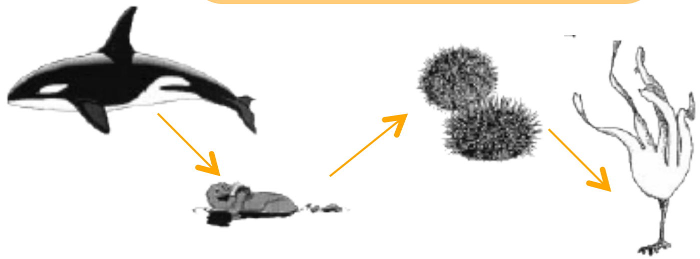
by a 30 %

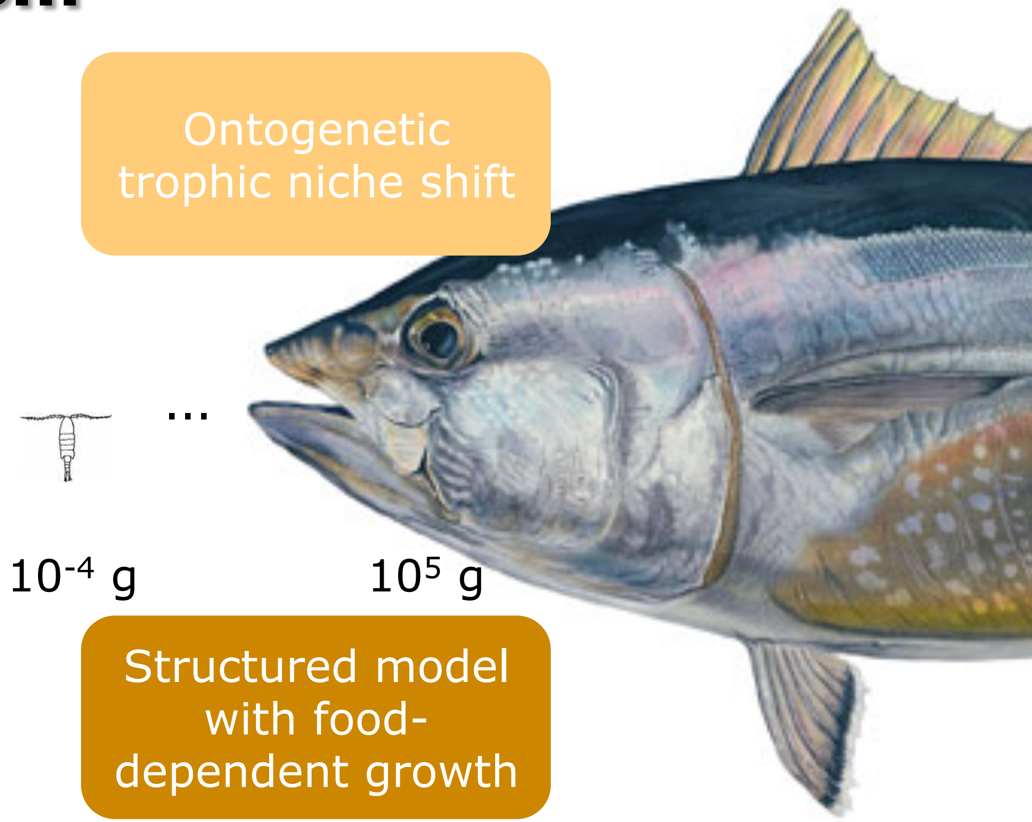
North-west Atlantic

Frank et al (2005)

Two kinds of ecosystems…

System	No ontogenetic trophic niche shift	Ontogenetic trophic niche shift

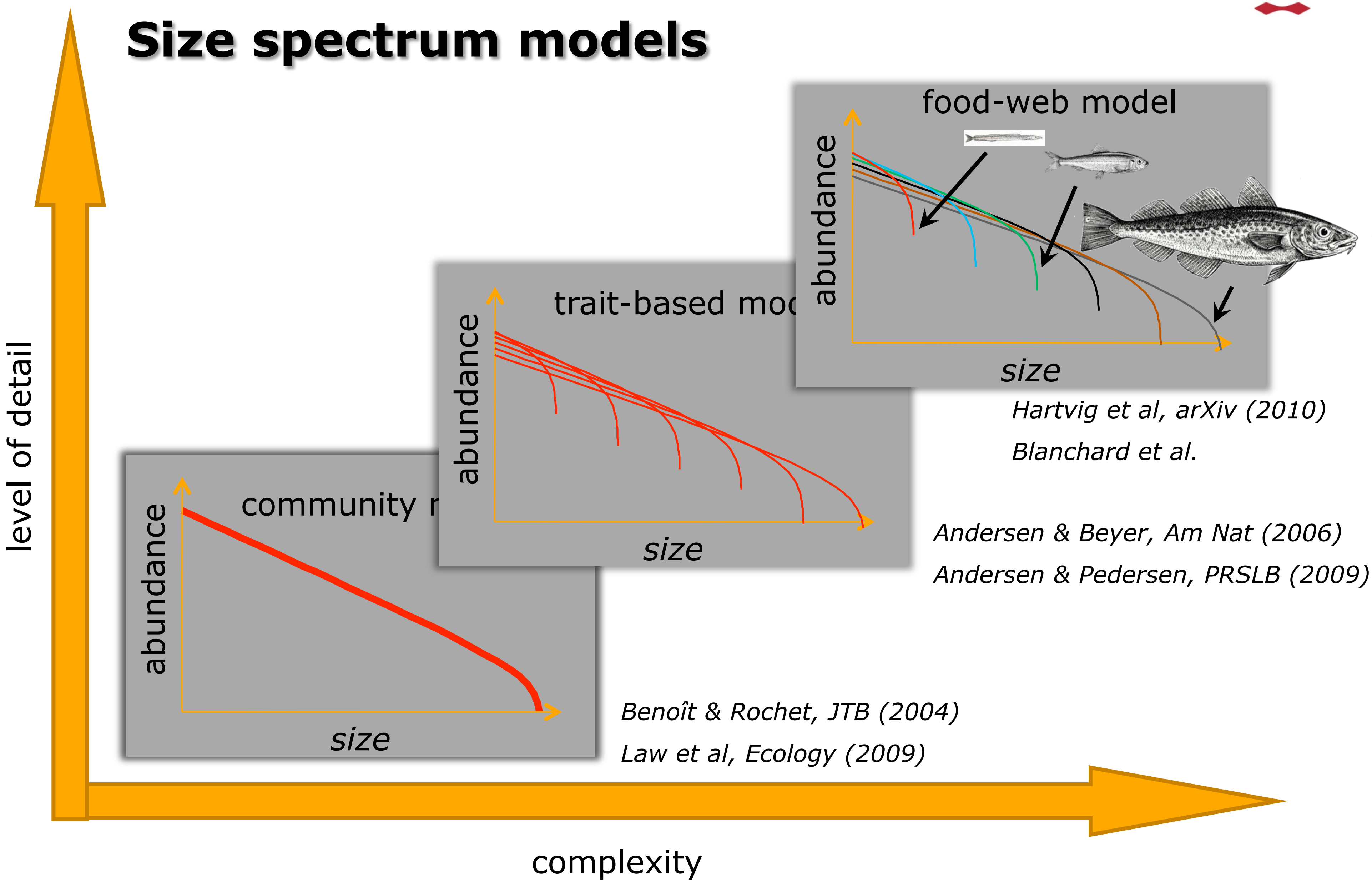




Model	Unstructured food web	Structured model with food-dependent growth
Control	*Global* control	*Local* control

… two kinds of control

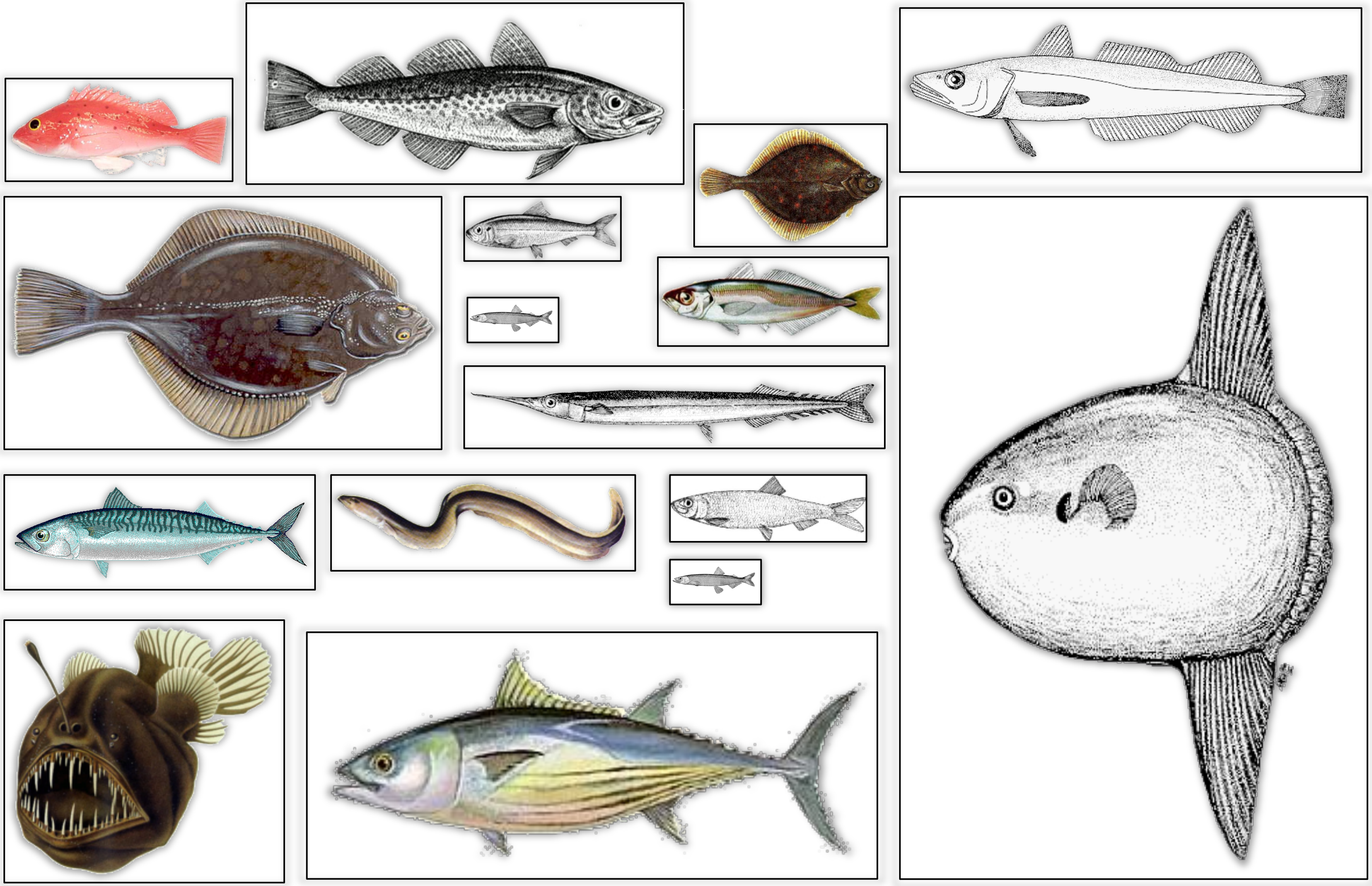
Size spectrum models



Questions & conjectures

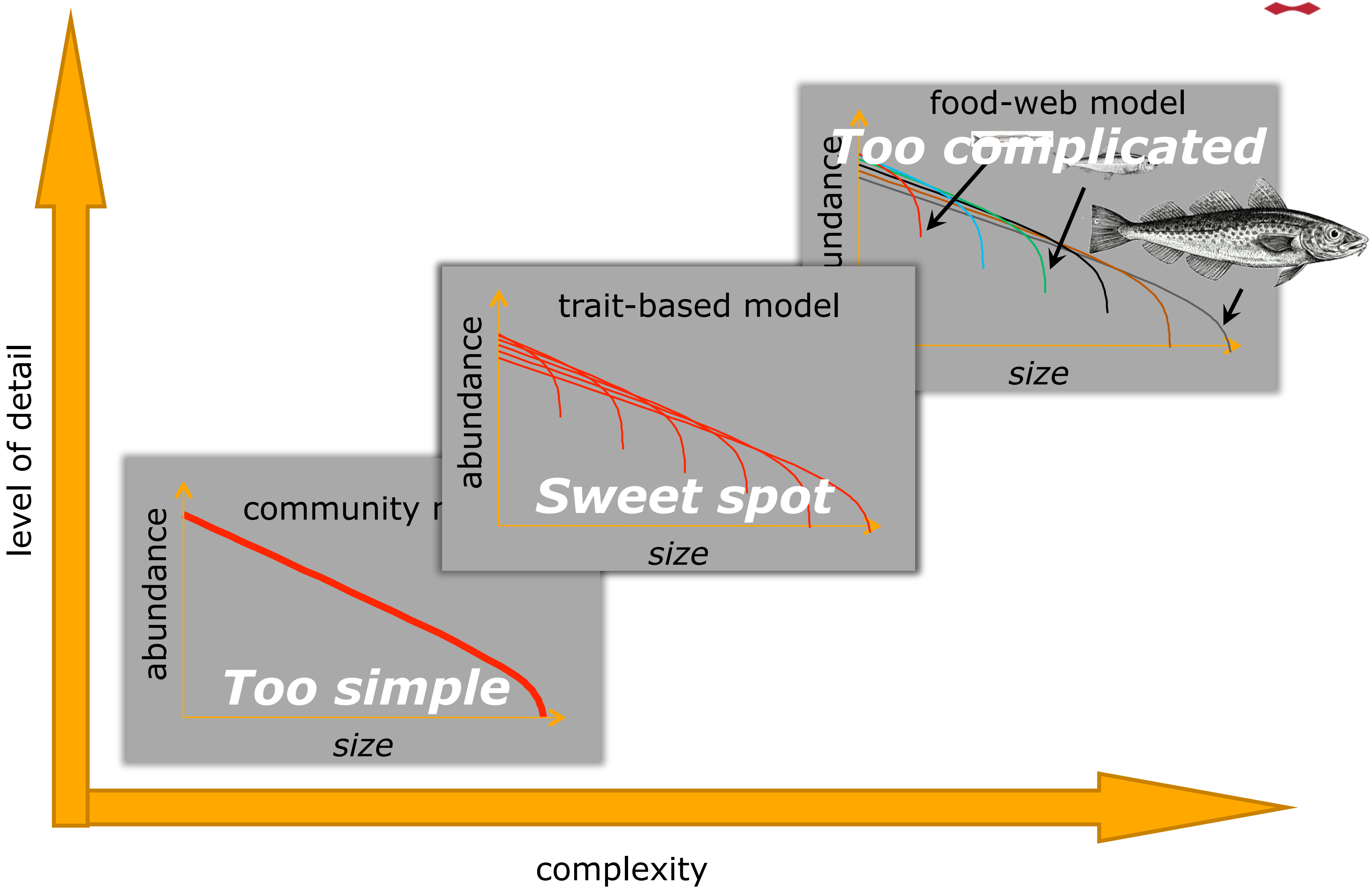
- Dinosaur community ≈ fish community
- Which are the governing traits, and what are the trade-offs?

Fish traits



Questions & conjectures

- Dinosaur community ≈ fish community
- Which are the governing traits, and what are the trade-offs?
- Which models shall we use for Ecosystem Approach to Fisheries Management?


food-web model
Too complicated
undance
size
trait-based model
abundance
Sweet spot
size
community r
abundance
Too simple
size
level of detail
complexity

Questions & conjectures

- Dinosaur community ≈ fish community
- Which are the governing traits, and what are the trade-offs?
- Which models shall we use for Ecosystem Approach to Fisheries Management?
- The fish community has local control
- Simple fish communities has one-two small species and one large species