A consistent nutrient to fish model for the Baltic Sea

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Real system

Different ways to describe the reality

Lagrangian
follow the path of individuals

Eulerian
follow the evolution of distributions of inds

Limitations

many individuals systems
require many equations
(technical issue)

Superindividual → to repesent
very many inds.

inapplicable to few animal systems

Real system

Lagrangian	Eulerian

interaction

Lagrangian	Eulerian
creation and annihilation of inds (birth and mortality) Interaction of superinds of prey and predator	interaction of distribution fields through mass flux up- or down the food web. life cycle resolution through mass-class structuring

observation, conservation laws

Lagrangian	Eulerian
properties of superindividual are not directly observable. numbers of inds are not conserved	biomass concentration and abundances are directly observable. conservation of mass applies

Life cycles and size classes

Phytoplankton, cells cycle between two levels of mass
→mass levels before and after division, (about factor 2)

Zooplankton of fish mass vary by several orders of magnitude
Biomass B= m N.
(m- individual mass, N – number of ind.)

$$\frac{d}{dt}B \approx m\frac{d}{dt}N,$$

phytoplankton

$$\frac{d}{dt}B = m\frac{d}{dt}N + N\frac{d}{dt}m.$$

zooplankton and fish

Cohort approach:

growth of 'typical indiviual' of mass m

and

dynamics of number of inds N

$$\frac{d}{dt}m = (g-l)m, \quad m(t_0) = m_0$$

$$\frac{d}{dt}N = -\mu N, \quad N(t_0) = N_0.$$

biomass → $B=Nm$

This is equivalent to:

$$\frac{d}{dt}B = -\mu B + (g-l)B,$$

Repro-
duction

$$\frac{d}{dt}N = -\mu N,$$

$$N(t_0) = N_0, B(t_0) = B_0 = N_0 m_0.$$

where $m=B/N$

For many cohorts

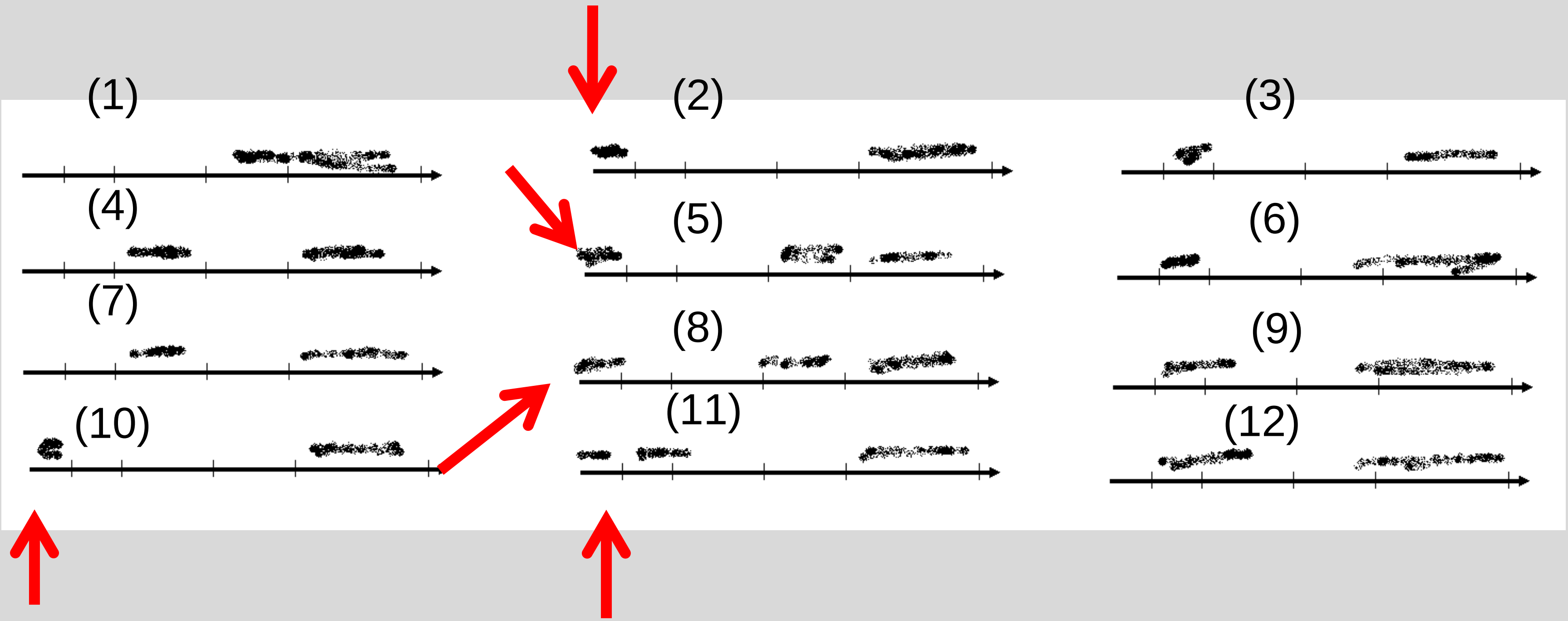
→ many equations; at least one for each cohort

Biomass approach (no tagging of specific cohorts)

→ characterize stages by mass intervals and count how many inds are in each mass class, fixed number of equations

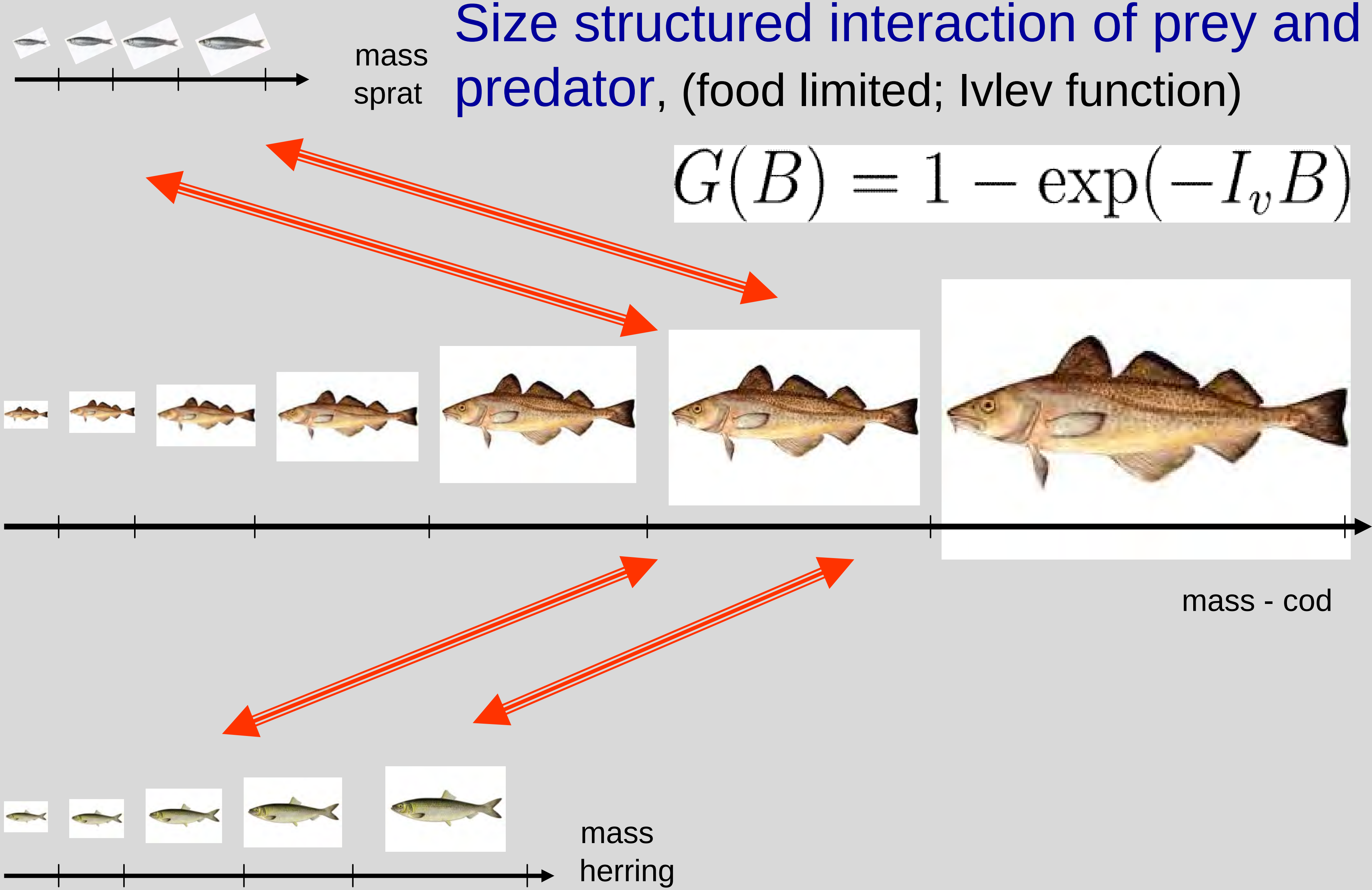
(two for each mass class, no matter how many inds)

similar as Eulerian for the derivation, ‘advection terms’ are needed to promote inds to the next interval if the maximum mass is approached


(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)

Size structured interaction of prey and predator, (food limited; Ivlev function)

$$G(B) = 1 - \exp(-I_v B)$$



Predator- prey interaction, (e.g. cod-herring), the predator can eat all smaller prey animals

$$\mathbf{P}_k(Her) = g_{C_k}^{max} B_k^{Cod} \frac{\sum_{i=1}^{k-1} B_i^{Her} G(B_i^{Her})}{\sum_{i=1}^{k-1} B_i^{Her}}, \qquad (\text{for } 2 \leq k \leq 7)$$

Prey-predator interaction, (e.g. herring –cod), the prey can be eaten by all larger predator animals

$$\mathbf{\Pi}_i(Her) = G(B_i^{Her}) B_i^{Her} \sum_{k=i+1}^{7} \frac{g_{C_k}^{max} B_k^{Cod}}{\sum_{k=1}^{i-1} B_k^{Her}}$$

Further dynamic ingredients:

Metabolism:

respirations- and excretion rates transferring part of the ingested food (or body mass) to nutrients and detritus

→*(rating: good, quantification of parameters can be improved)*

Reproduction:

off-spring approach → *(rating: reasonable, but needs refinement)*

Mortality:

natural deaths and starvation rates, fishing mortalities,

→*(rating: reasonable, but difficult,*
partly questionable, needs further consideration)

The result is:

Warnemuende **F**ood web **M**odel (WFM)

WMF

(show just a few equations)

Predator (cod): Model-equations

for biomass

$$\frac{d}{dt}B_1^{Cod} = \mathrm{os}_{C6}B_6^{Cod} + \underline{\mathrm{os}_{C7}B_7^{Cod}} + (g_1^{Cod} - L_{C_1N} - L_{C_1D} - \mu_{C_1})B_1^{Cod} - \tau_{C_1}B_1^{Cod},$$

....

$$\frac{d}{dt}B_i^{Cod} = \tau_{C_{i-1}}B_{i-1}^{Cod} - (L_{C_iN} + L_{C_iD})B_i^{Cod} - \tau_{C_i}B_i^{Cod} - \mathbf{P}_i,$$

....

$$\frac{d}{dt}B_7^{Cod} = \tau_{C_6}B_6^{Cod} - (L_{C_7N} + L_{C_7D} + \underline{\mathrm{os}_{C7}} + \mathrm{F}_{C_7} + \mu_{C_7} + \mu_{C_7}^{starv})B_7^{Cod} + \mathbf{P}_7,$$

and

abundance

$$\frac{d}{dt}N_1^{Cod} = \frac{1}{m_0}\left(\mathrm{os}_{C6}B_6^{Cod} + \underline{\mathrm{os}_{C7}B_7^{Cod}}\right) - \mu_{C_1}N_1^{Cod} - \tau_{C_1}\frac{B_1^{Cod}}{CX_1},$$

....

$$\frac{d}{dt}N_i^{Cod} = \tau_{C_{i-1}}\frac{B_{i-1}^{Cod}}{CX_{i-1}} - \mu_{C_i}^{*}N_i^{Cod} - \tau_{C_i}\frac{B_i^{Cod}}{CX_i},$$

....

$$\frac{d}{dt}N_7^{Cod} = \tau_{C_6}\frac{B_6^{Cod}}{CX_6} - (\mu_{C_7} + \mu_{C_7}^{starv} + \mathrm{F}_{C_7})N_7^{Cod}.$$

averaged individual mass **m=B/N**

Prey (herring): Model-equations

for biomass

$$\frac{d}{dt}B_1^{Her} = os_{H_5}B_5^{Her} + os_{H_6}B_6^{Her} + (g_1^{Her} - L_{H_1N} - L_{H_1D} - \mu_{H_1})B_1^{Her} - \tau_{H_1}B_1^{Her} - \mathbf{\Pi}_1(Her),$$

....

$$\frac{d}{dt}B_i^{Her} = \tau_{H_{i-1}}B_{i-1}^{Her} + (g_i^{Her} - L_{H_iN} - L_{H_iD})B_i^{Her} - \tau_{H_i}B_i^{Her} - \mathbf{\Pi}_i(Her),$$

....

$$\frac{d}{dt}B_6^{Her} = \tau_{H_5}B_5^{Her} + (g_6^{Her} - L_{H_6N} - L_{H_6D})B_6^{Her} - (os_{H_6} + \mathrm{F}_{\mathrm{H}_6} + \mu_{H_6} + \mu_{H_6}^{starv})B_6^{Her} - \mathbf{\Pi}_6(Her),$$

and

abundance

$$\frac{d}{dt}N_1^{Her} = \frac{1}{m_0}(os_{H5}B_5^{Her} + os_{H6}B_6^{Her}) - \mu_{H_1}N_1^{Her} - \tau_{H_1}\frac{B_1^{Her}}{HX_1} - \frac{\mathbf{\Pi}_1(Her)}{m_1^{Her}},$$

....

$$\frac{d}{dt}N_i^{Her} = \tau_{H_{i-1}}\frac{B_{i-1}^{Her}}{HX_{i-1}} - \mu_{H_i}^{*}N_i^{Her} - \tau_{H_i}\frac{B_i^{Her}}{HX_i} - \frac{\mathbf{\Pi}_i(Her)}{m_i^{Her}},$$

....

$$\frac{d}{dt}N_6^{Her} = \tau_{H_5}\frac{B_5^{Her}}{HX_5} - (\mathrm{F}_{\mathrm{H}_6} + \mu_{H_6} + \mu_{H_6}^{starv})N_6^{Her} - \frac{\mathbf{\Pi}_6(Her)}{m_6^{Her}}.$$

Feeding on herring reduces prey biomass **and** numbers!!!

State variables:

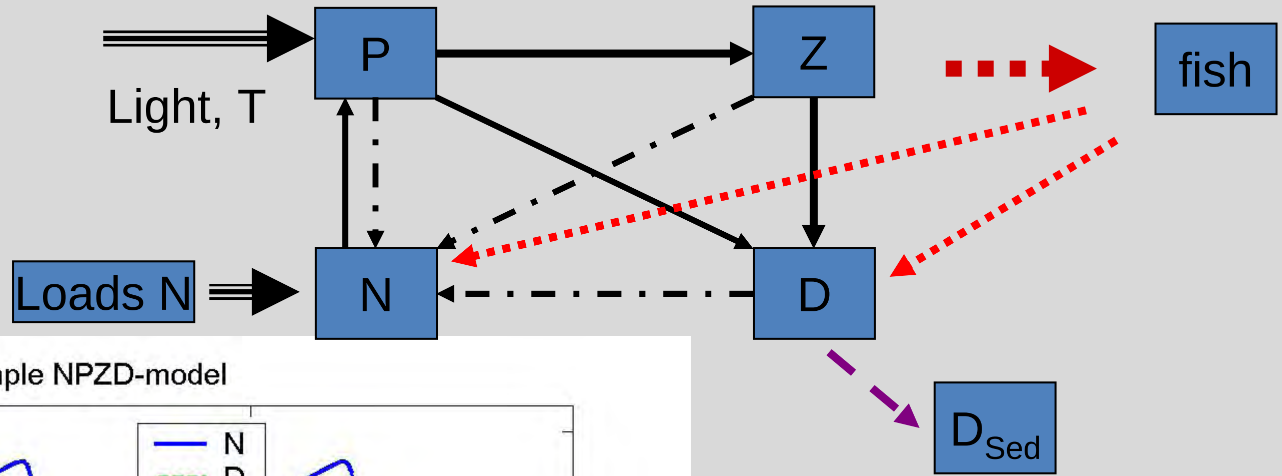
numbers,
biomass, and
average growth (weight versus age)

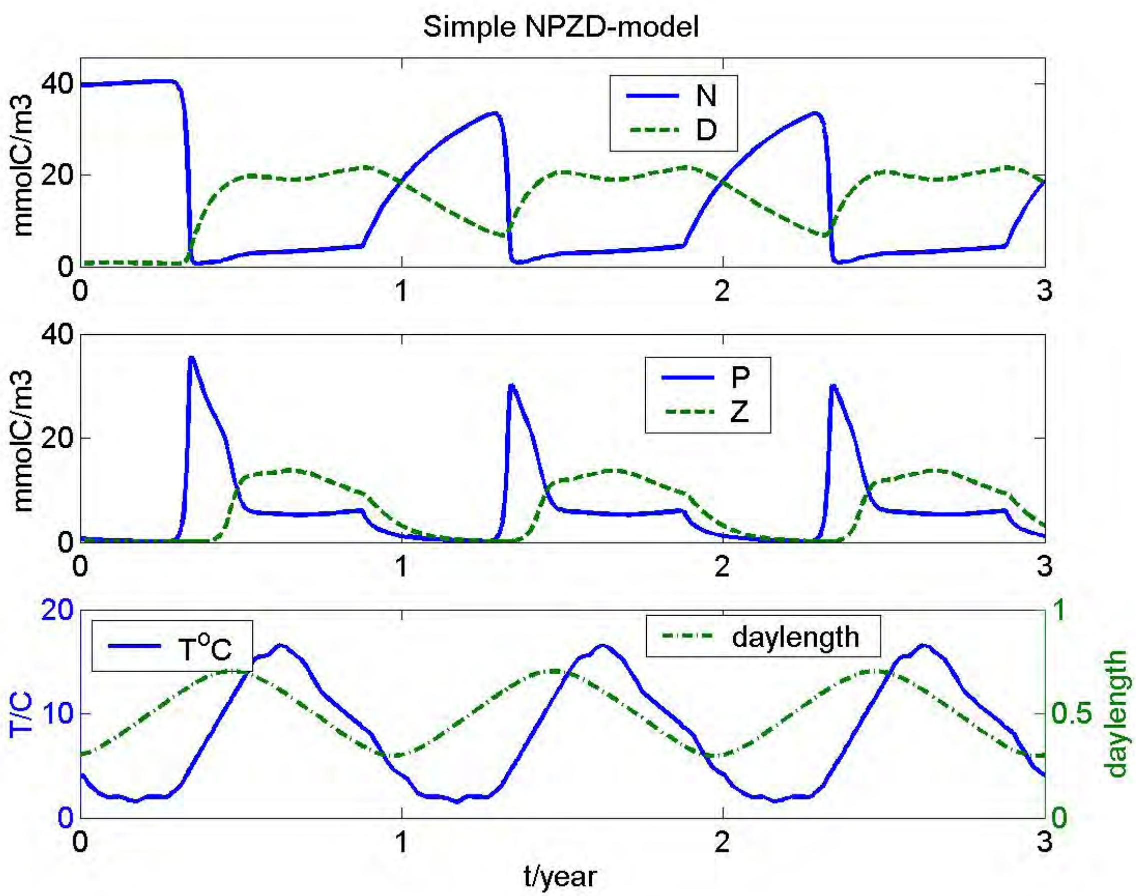
Are directly observed in catches and surveys

Link to lower food web

Two-way coupling

(as start use a simple toy model for the NPZD part)





Truncated model
$l_{ZD} = 0.03$ /d

Coupled model

add action of fish on zooplankton mortality, g^{Her} and g^{Spra}.

A simple periodic physical forcing.

Conversion:
1mmolC => 12 mgC
=> 100 mg = 0.1 g wetmass

Coupling the NPZD-model to fish - three channels

$$\frac{dN}{dt} = -u(N)P + l_{PN}P + l_{DN}D + l_{ZN}Z + N^{import} + L_{FN},$$

← Respiration of fish

$$\frac{dP}{dt} = u(N)P - l_{PN}P - g(P)Z - l_{PD}P,$$

$$\frac{dZ}{dt} = -g(P)ZP - l_{ZN}Z + G_F,$$

← Feeding of fish on Z

$$\frac{dD}{dt} = l_{ZN}Z + l_{PN}P - l_{DN}D - l_{DD_{sed}}D + L_{FD},$$

← Fish mortality feeds back into D

$$\frac{dD_{sed}}{dt} = l_{DD_{sed}}D.$$

1mmolC => 12 mgC => 100 mg = 0.1 g wetmass conversion

The Baltic Sea Example

Cod,

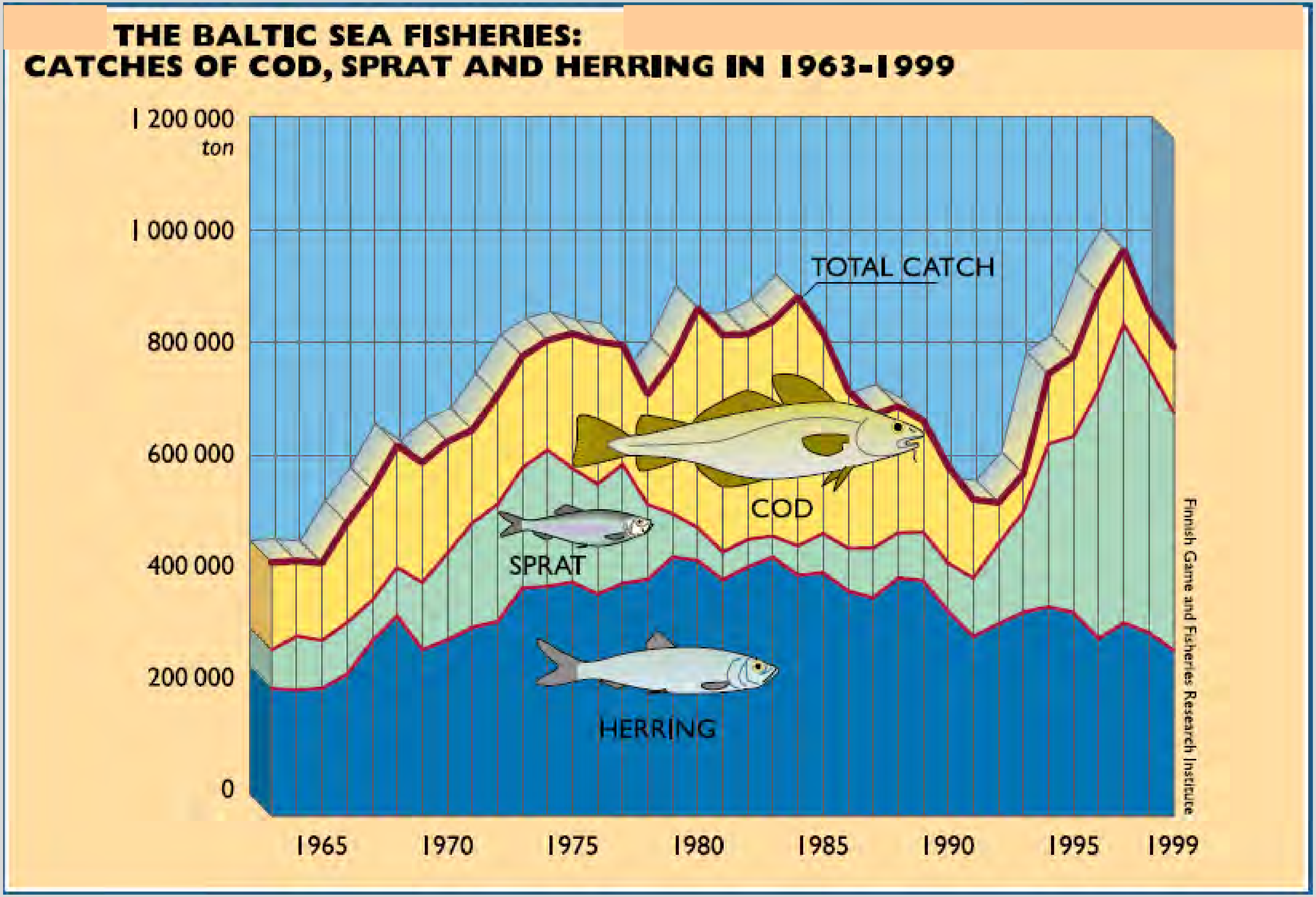
eats

herring and sprat

(zooplanktivors)

} -> 80% of fish biomass

Issue → what causes interannual variations?



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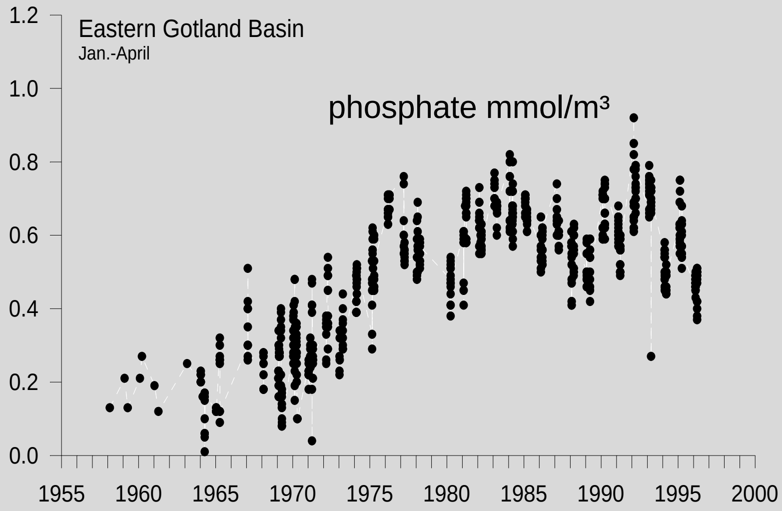
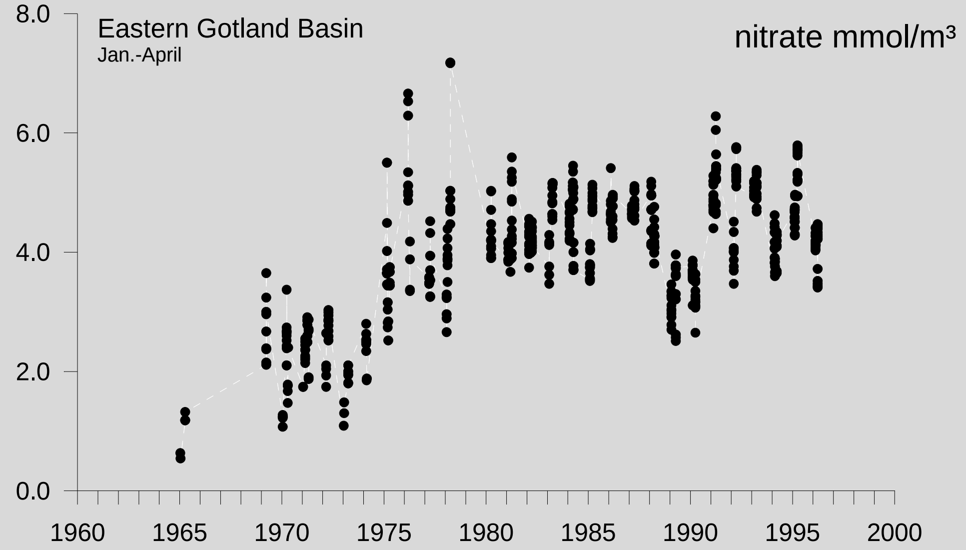


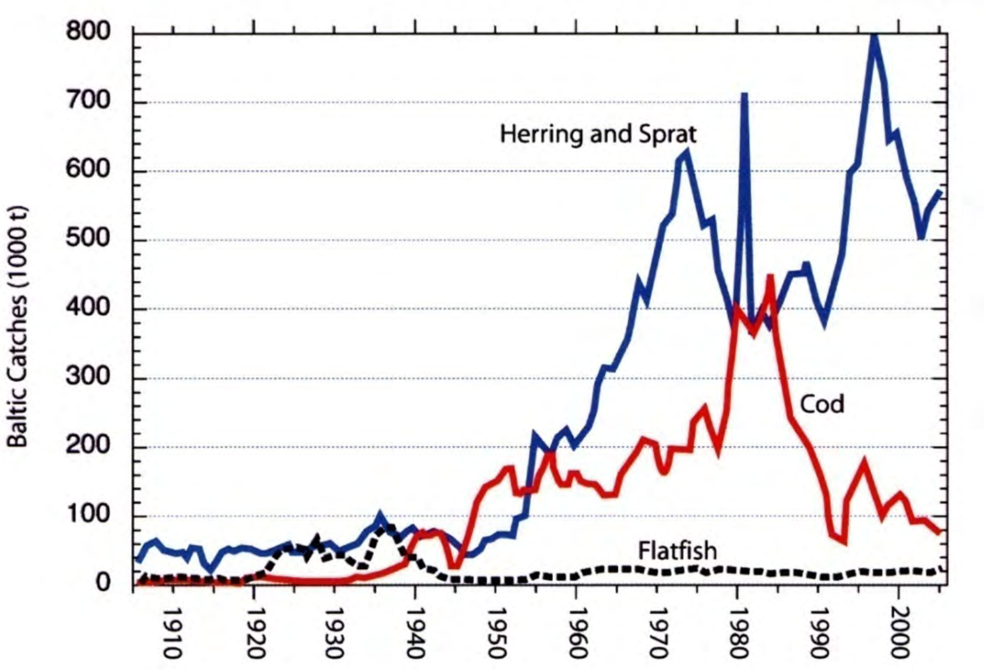


Bottom up?

Nutrient loads

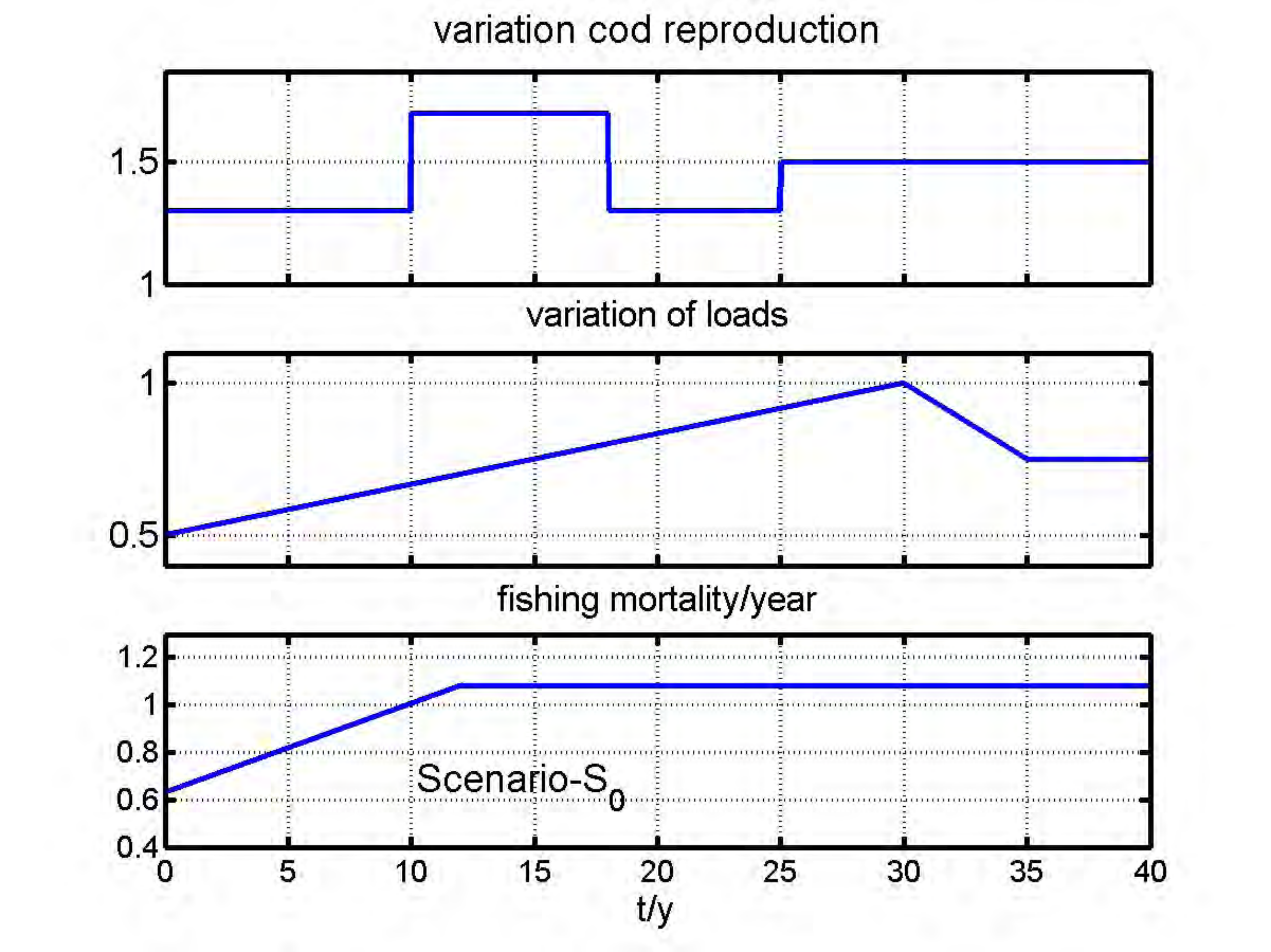
Top down?

Fishing



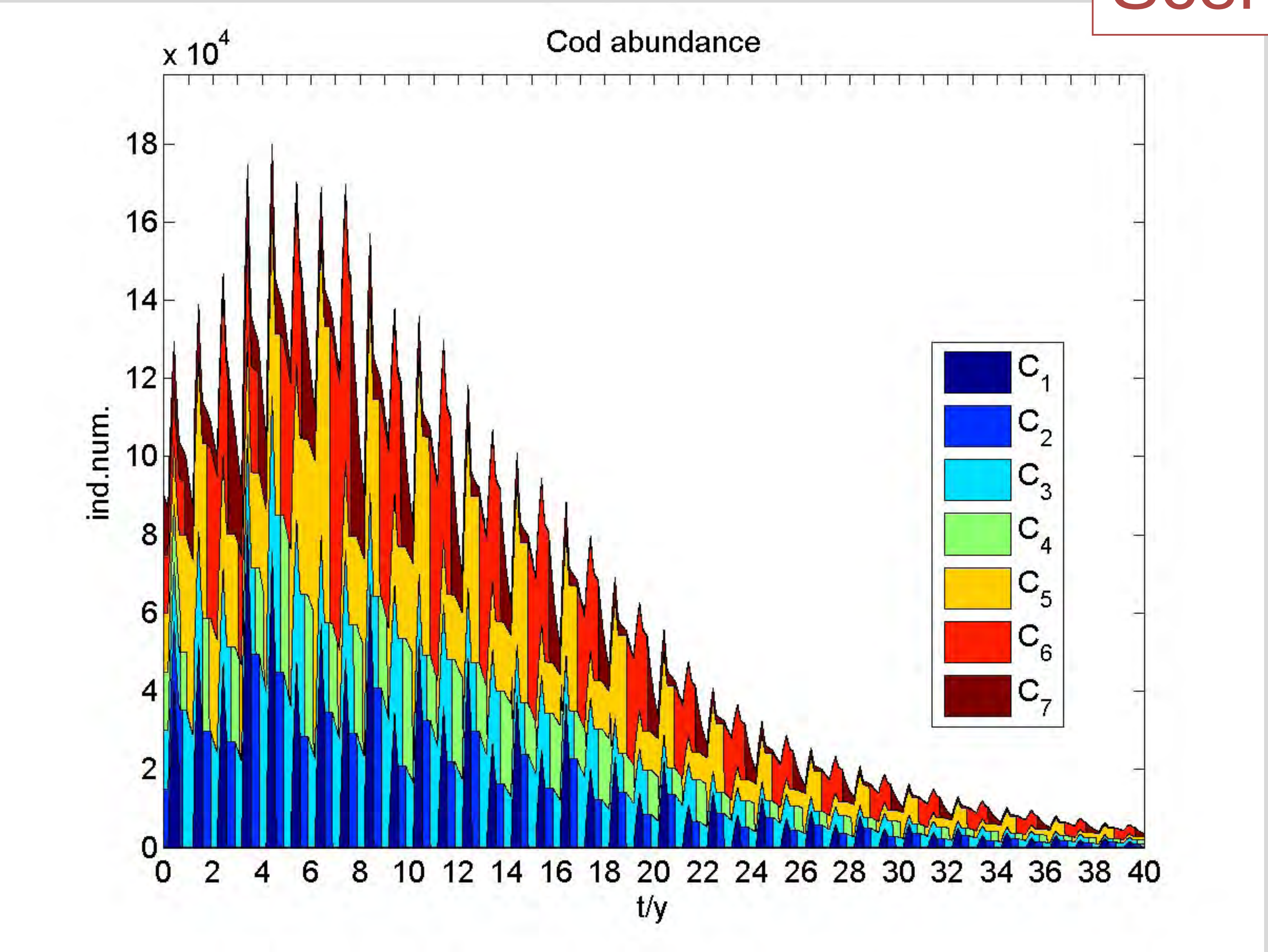
Baseline example:

Variation of reproduction conditions (S, O_2), fishing on cod, and nutrient input



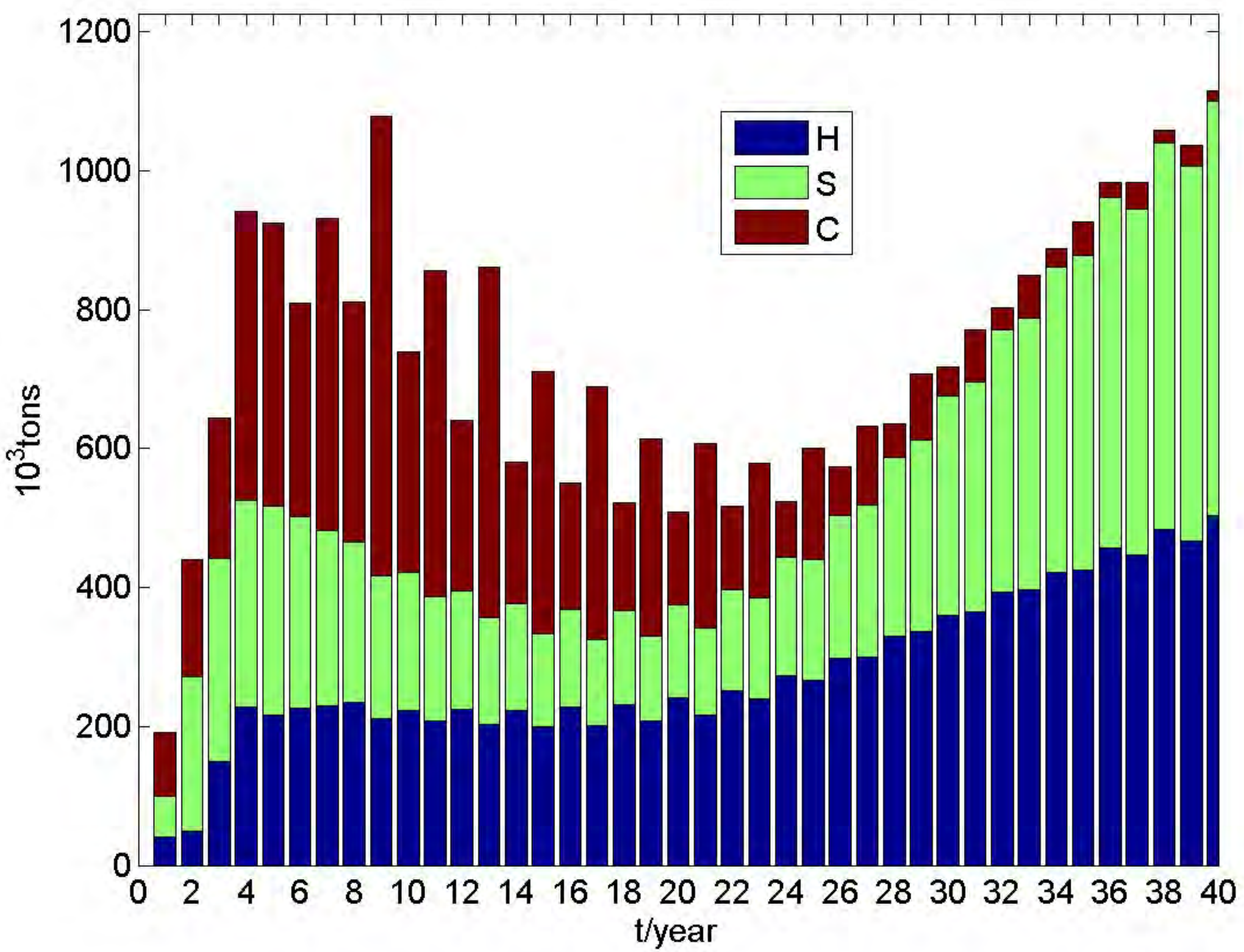
cod: numbers per size class/km^3

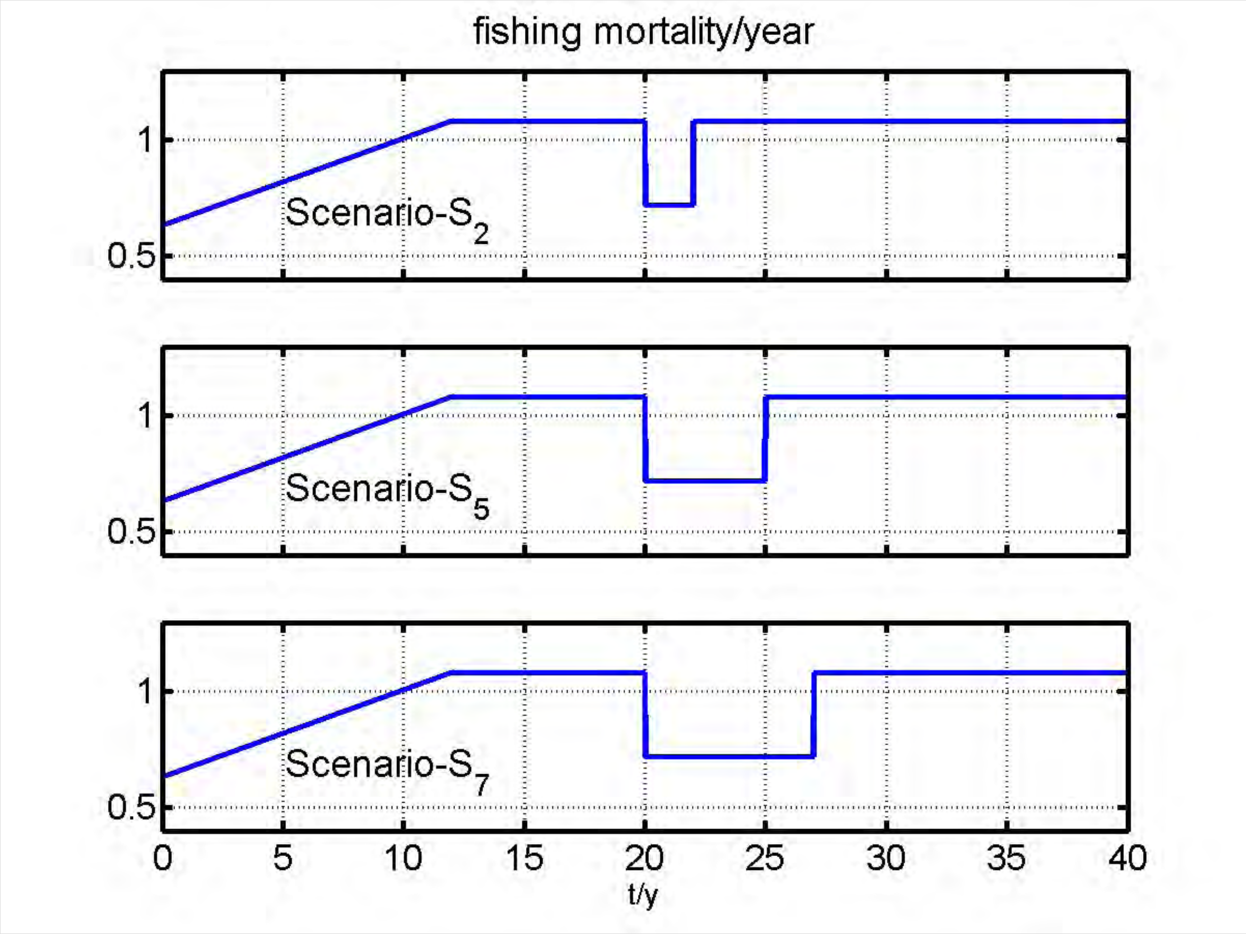
Scenario S_0



Simulated catches of herring (H), sprat (S) and cod (C)

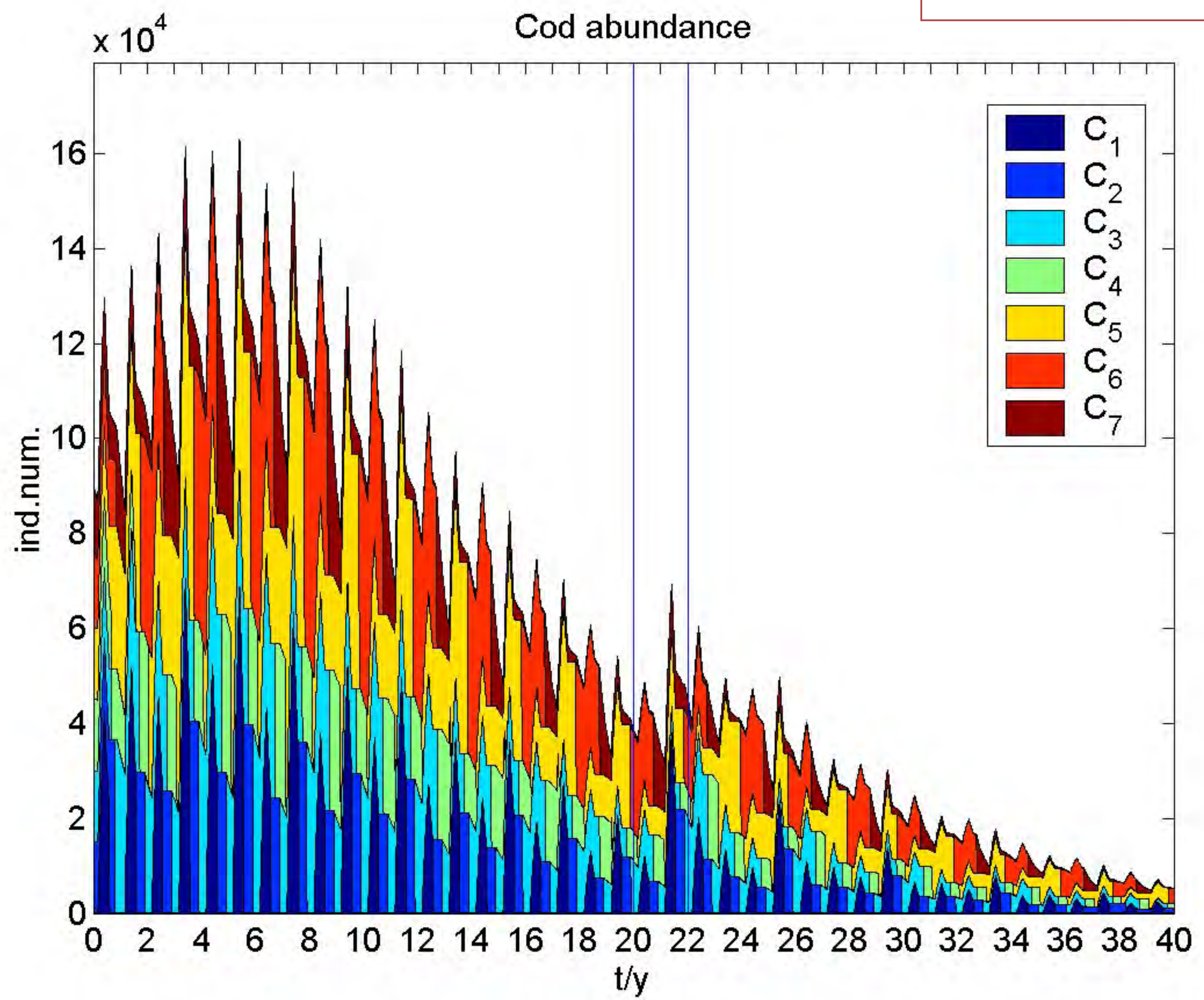
Scenario S_0



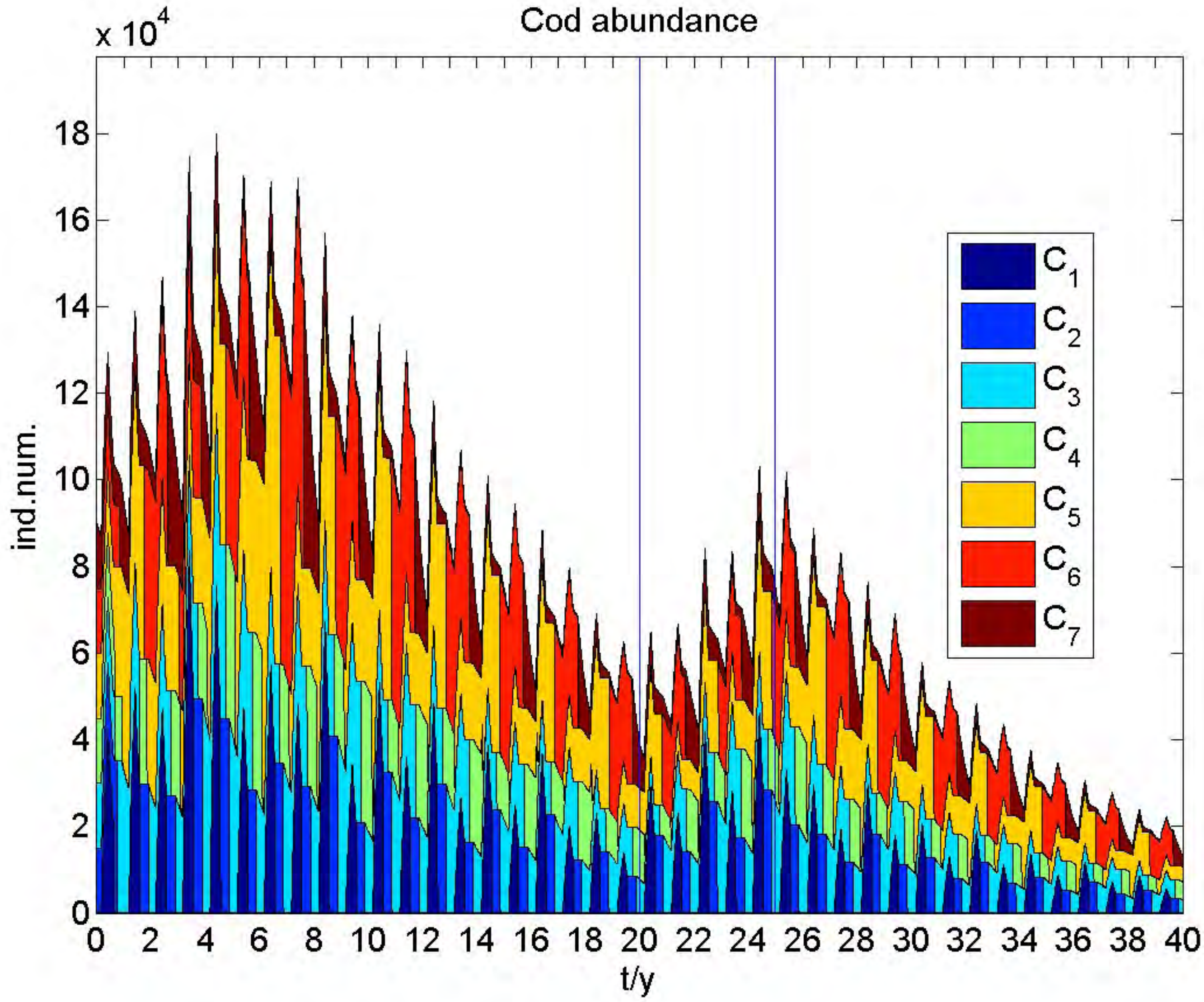


Scenarios – cod fishing reduced after 15 years

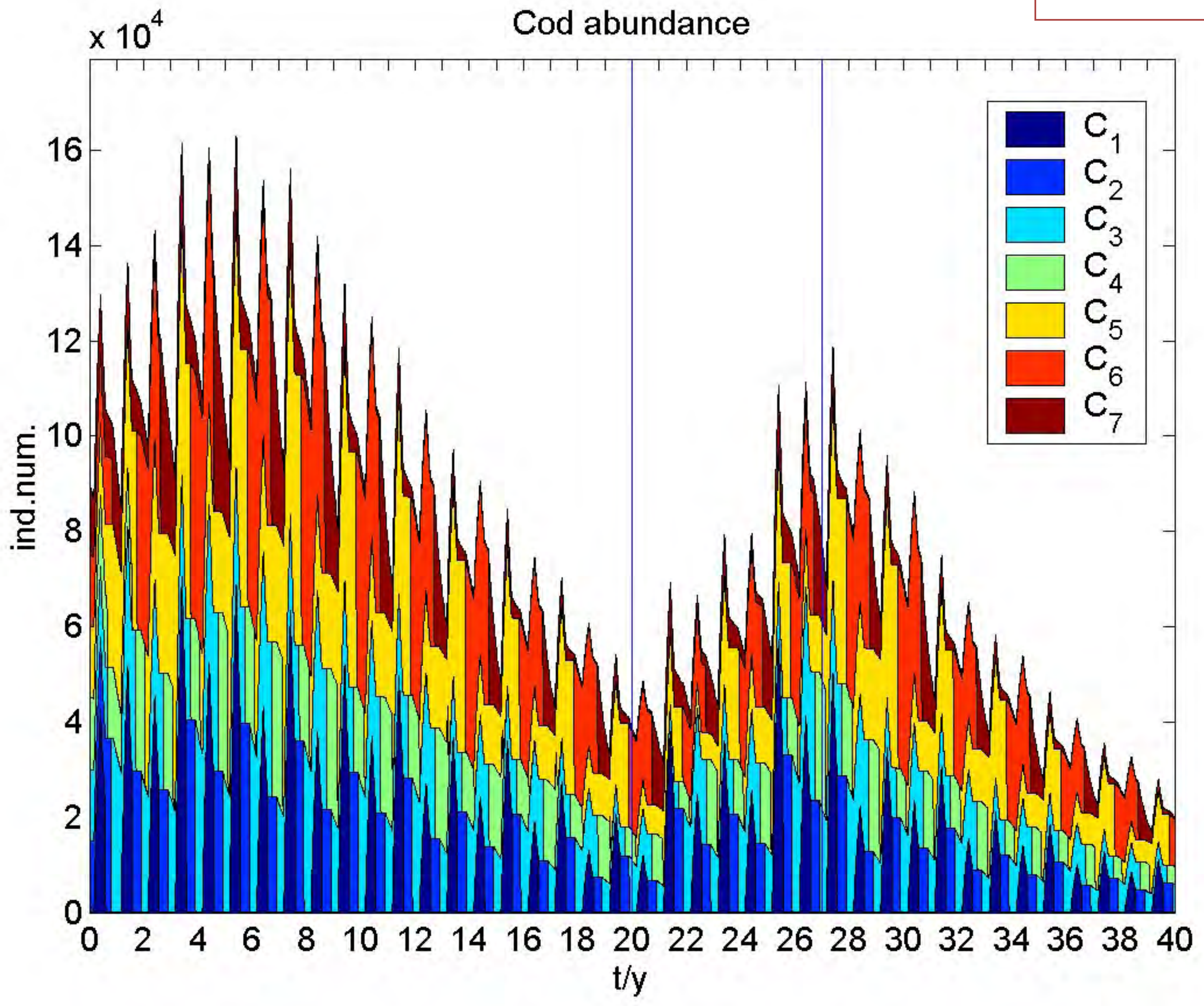
Scenario S_2


Cod abundance
x 10^4
ind.num.
t/y
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
C1
C2
C3
C4
C5
C6
C7

Scenario S_5


Cod abundance
x 10^4
ind.num.
t/y
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
C1
C2
C3
C4
C5
C6
C7

Scenario S_7


Cod abundance
x 10^4
ind.num.
0
2
4
6
8
10
12
14
16
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
t/y
C1
C2
C3
C4
C5
C6
C7

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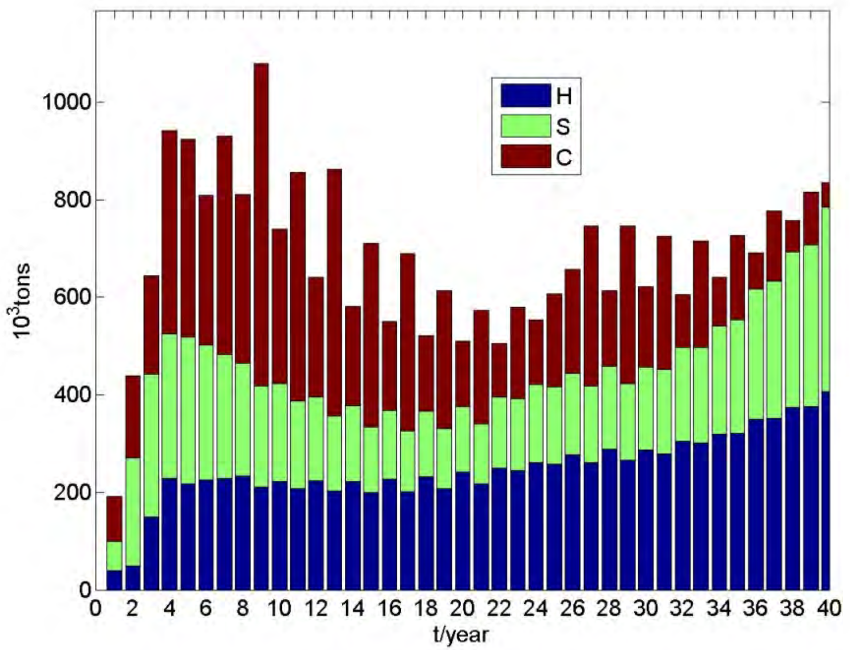
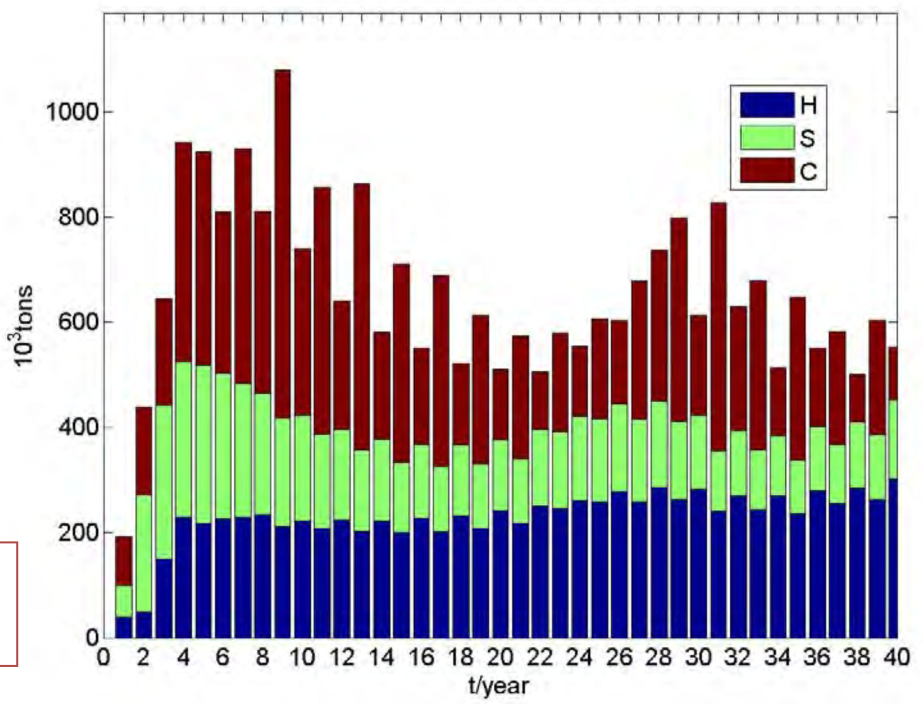
Scenario S_5

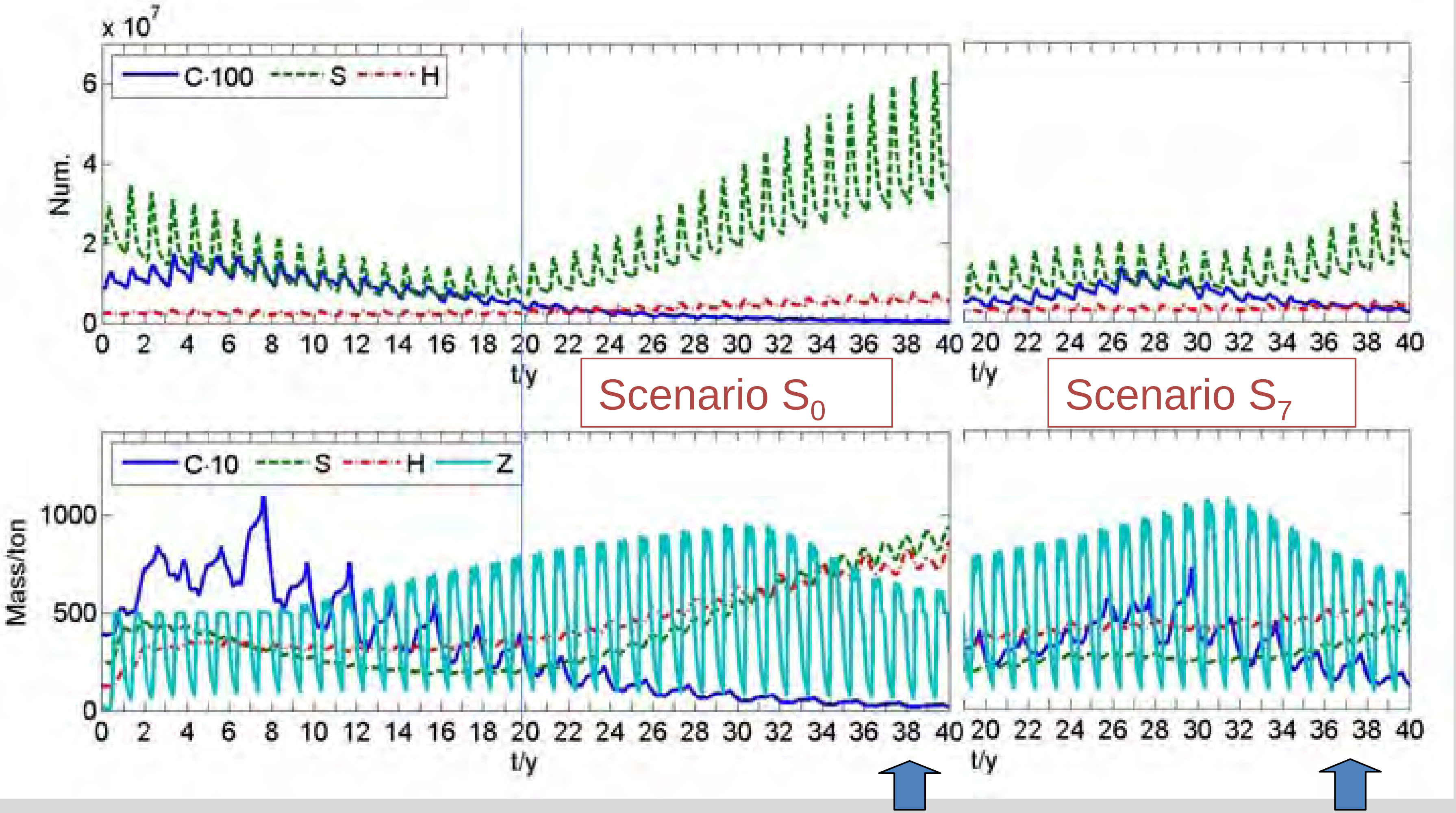


Simulated total catches of herring (H), sprat (S), and cod (C)



Scenario S_7

Fish (num.&mass) and zooplankton (mass)

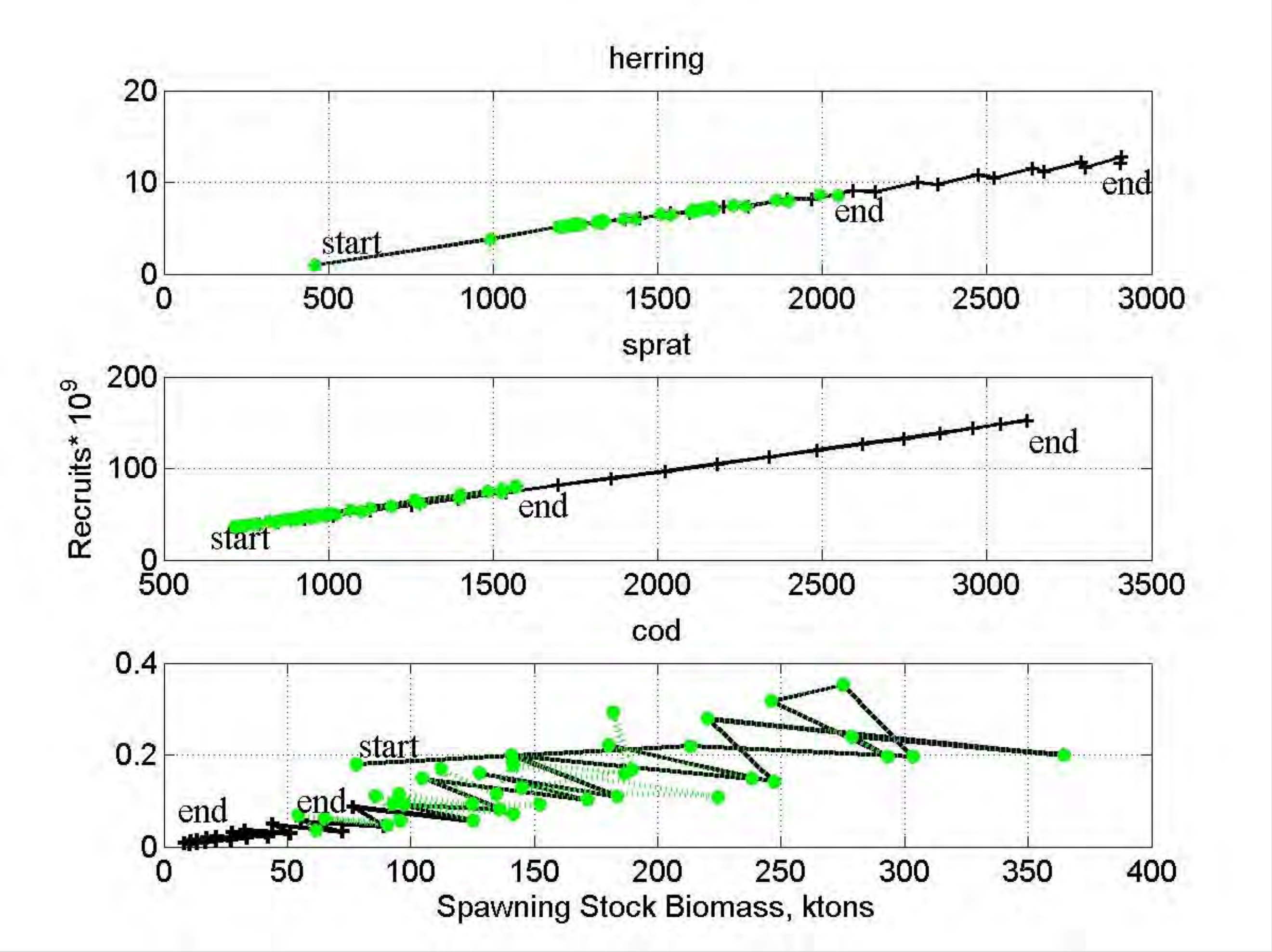


low predation of Cod → decrease in Z

Bottom up

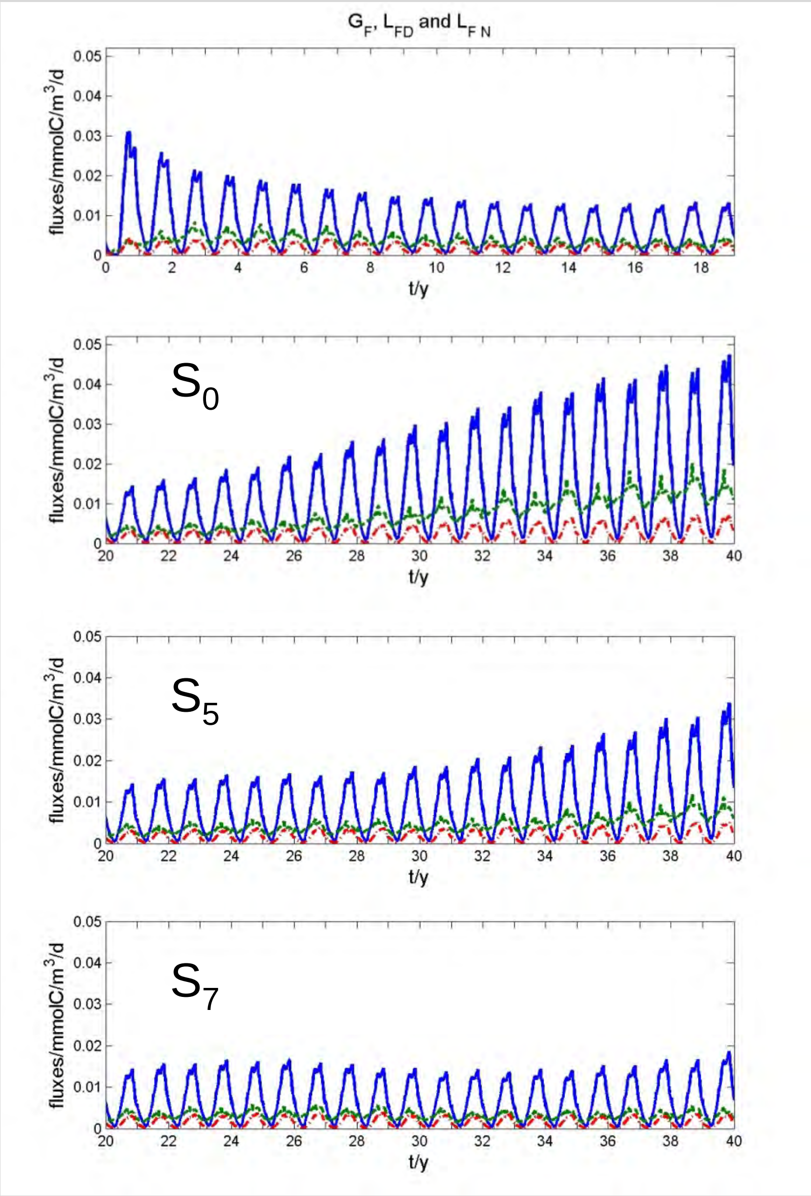
High predation of Cod → increase in Z

Top-down



herring
start
end
end
sprat
start
end
end
cod
start
end
end
end
Recruits* 10^9
Spawning Stock Biomass, ktons

Interactions between upper and lower food web



Fluxes between upper and lower parts of the food web

G_F zooplankton consumed by fish

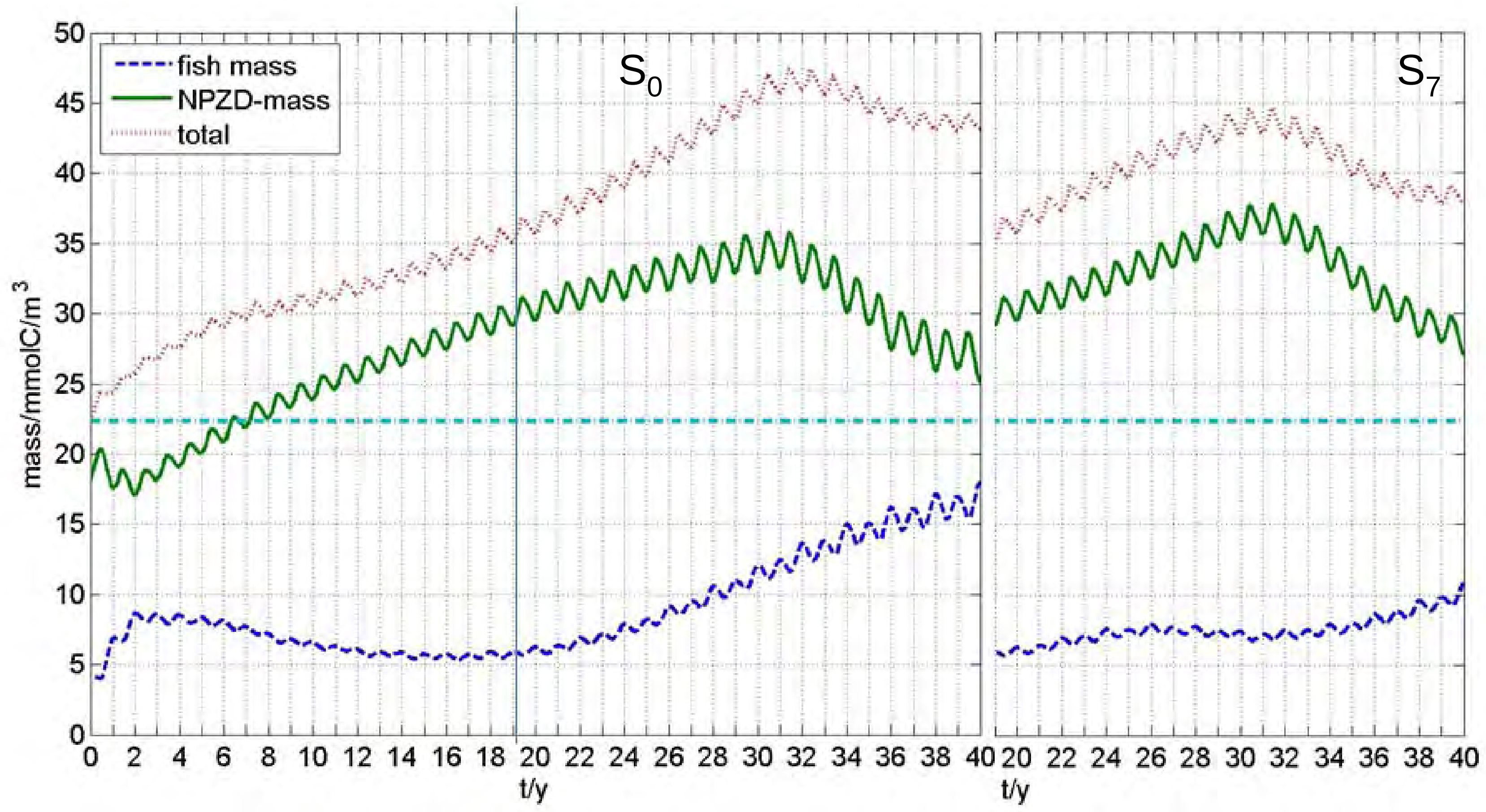
L_{FN} fish to nutrient

L_{FD} fish to detritus

Moderation of cod fishing reduces fluxes between upper and lower food web.

Budgets of biomass: potential biomass in the NPZD model, fish and total biomass

Moderation of cod fishing: → NPZD biomass increases
→ fish biomass decreases



accumulated inputs: N^{import}

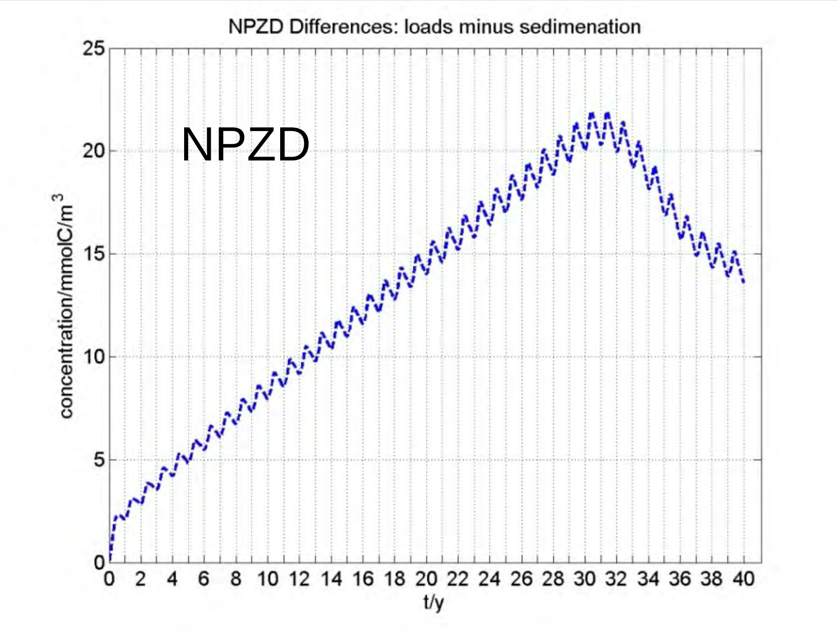
minus

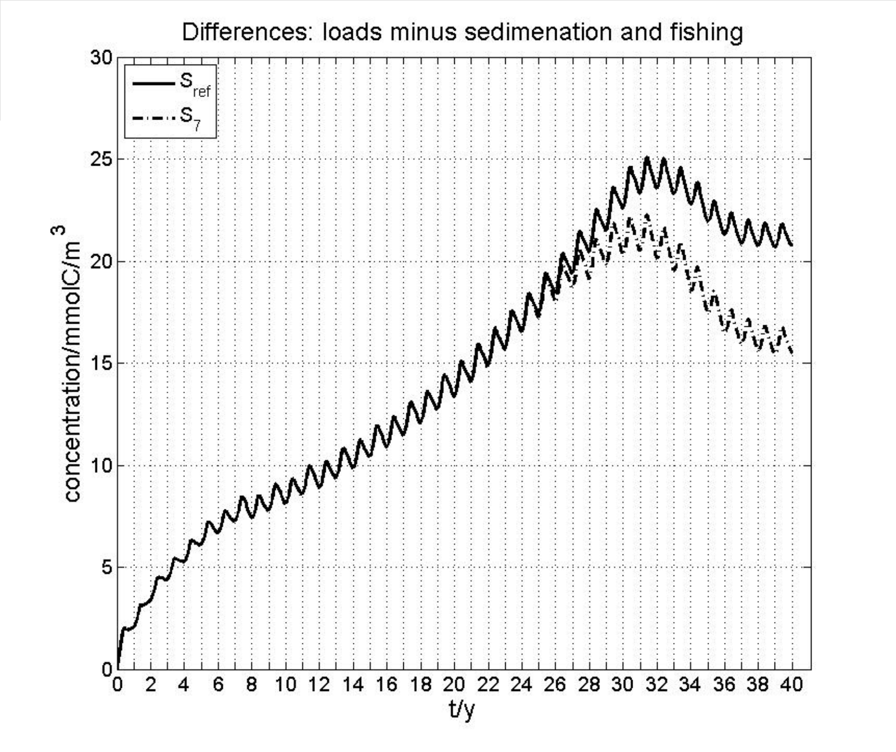
exports:

sedimentation ~ $l_{DD_{sed}} D$

fisching ~ $F_{H_6} B_6^{Her}, \quad F_{C_6} B_6^{Cod}, \quad F_{C_7} B_7^{Cod}$

etc.





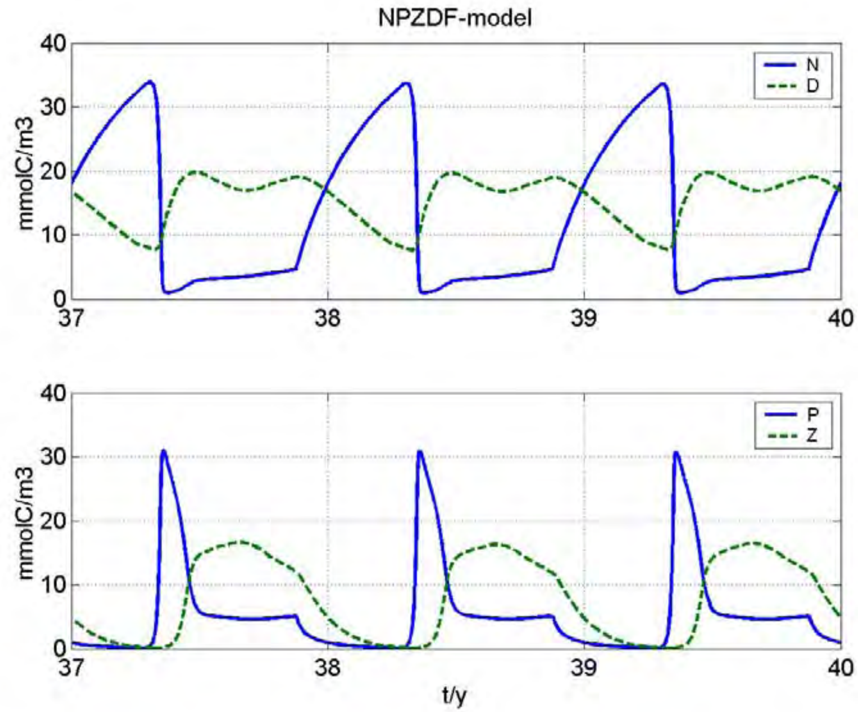
→

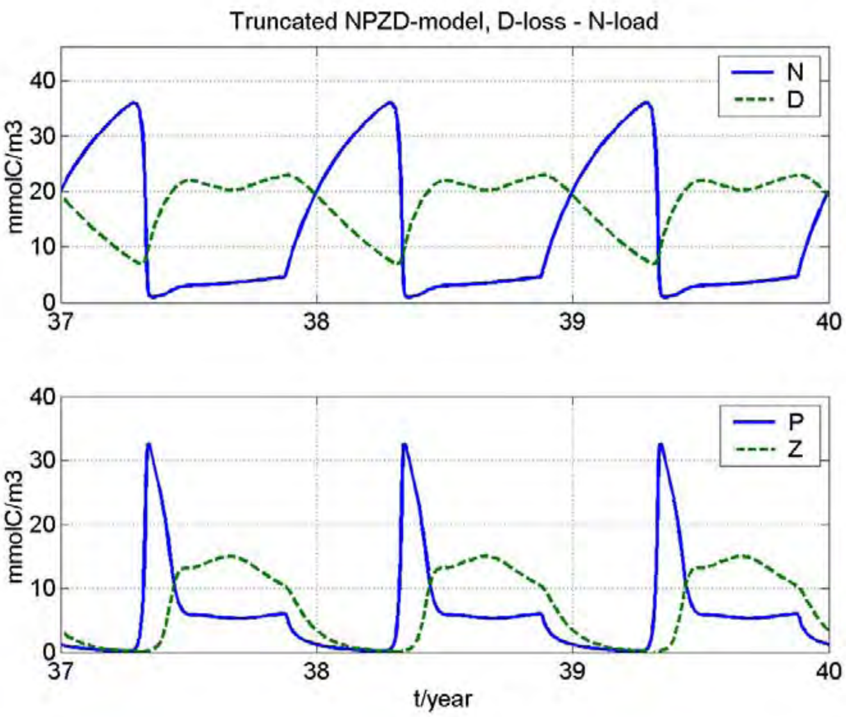
the model can describe interannual variations, the key-controls are:

- Fishing mortality,
- Reproduction, and
- External nutrient inputs

Opportunity for Theory

Skill assessment of truncated models





virtually identical results for:
N-load: $dN/dt \sim 3\ 10^{-3}$ mmolC/m³/d,
$l_Z = 2\ 10^{-4}$/d, extra Z mortality, and
D-loss - flux into sediments:
$dD/dt \sim -1.25\ 10^{-3}$ mmolC/m³/d
or
extra Z-mortality,
$l_Z = 4.1\ 10^{-4}$/d,
and no D-loss

Stamp:
Exp=30.15;
option_mort=1.1;
import_N=0.0063g/m³/d
(0.003 mmolC/m³/d),

Goal for the next years:

Transition to a spatially explicit version (full three dimensional) to run fishing and climate scenarios.
Issues are, e.g. oxygen, stage resolved zooplankton, migration patterns

(success depends also on partnerships in future projects)

thanks