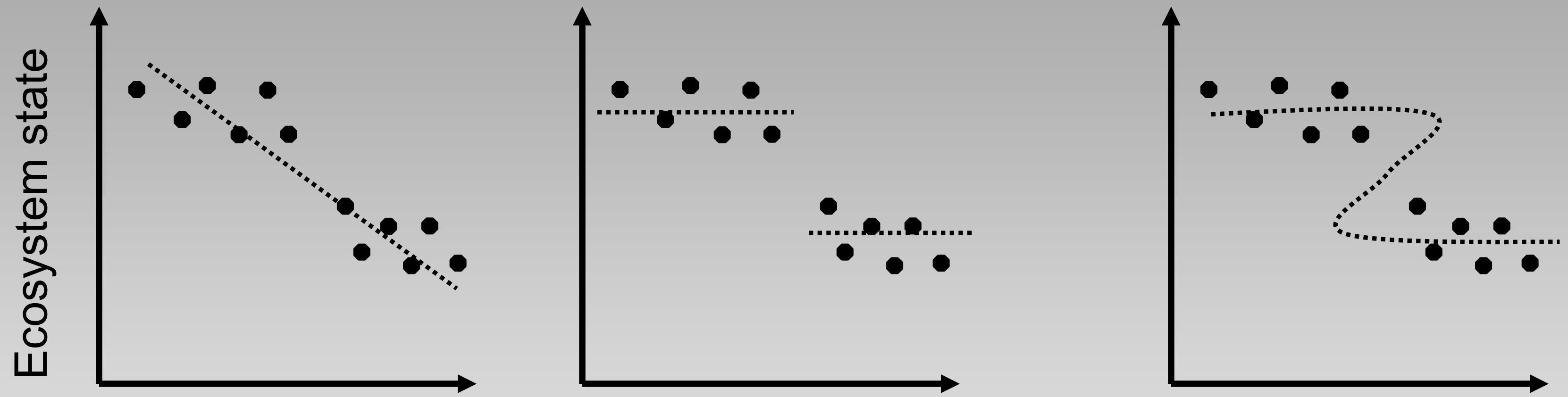


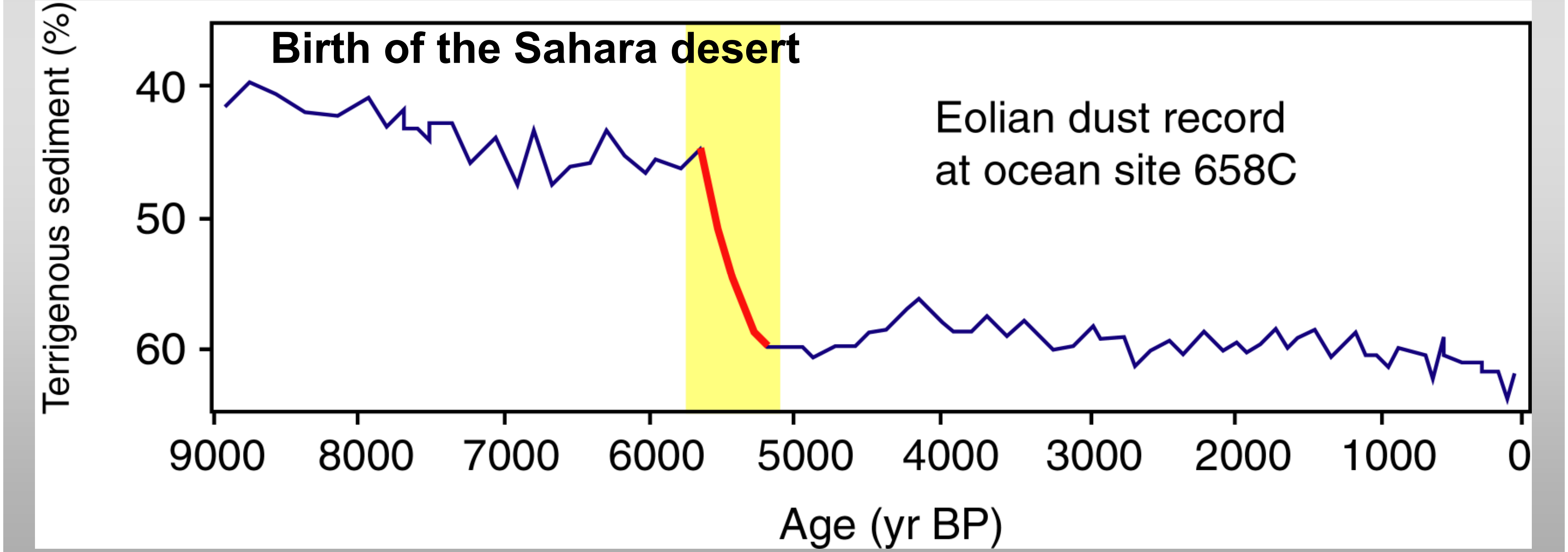
Regime Shifts in the Ocean: From Detection to Prediction?

Cisco Werner
Brad deYoung

(and many others: M. Barange, G. Beaugrand, R. Harris, C. Moloney, I. Perry and M. Scheffer)

DEFINITION OF REGIME SHIFT

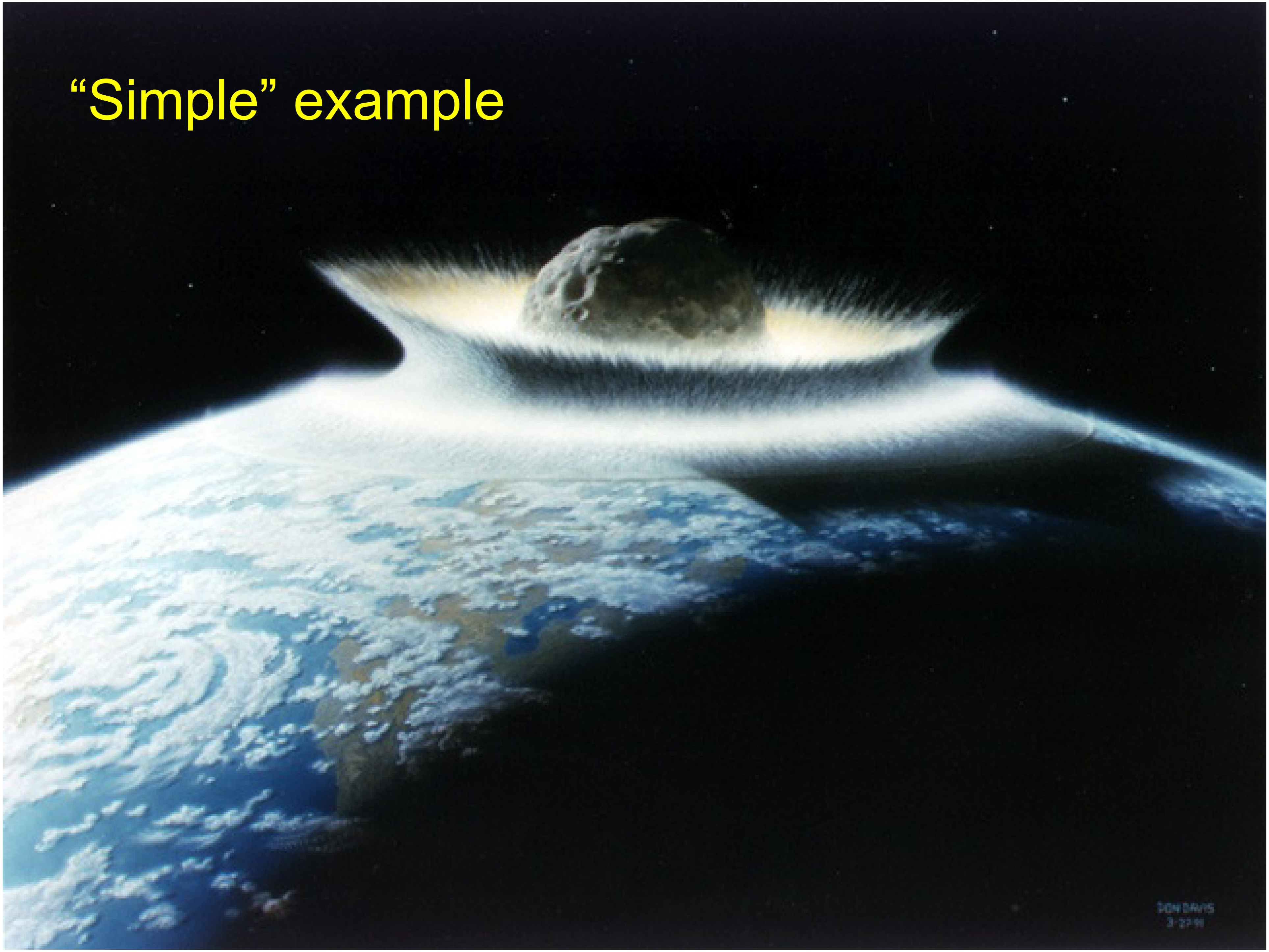
Working definition: a regime shift is a relatively abrupt change between contrasting persistent states in an ecosystem



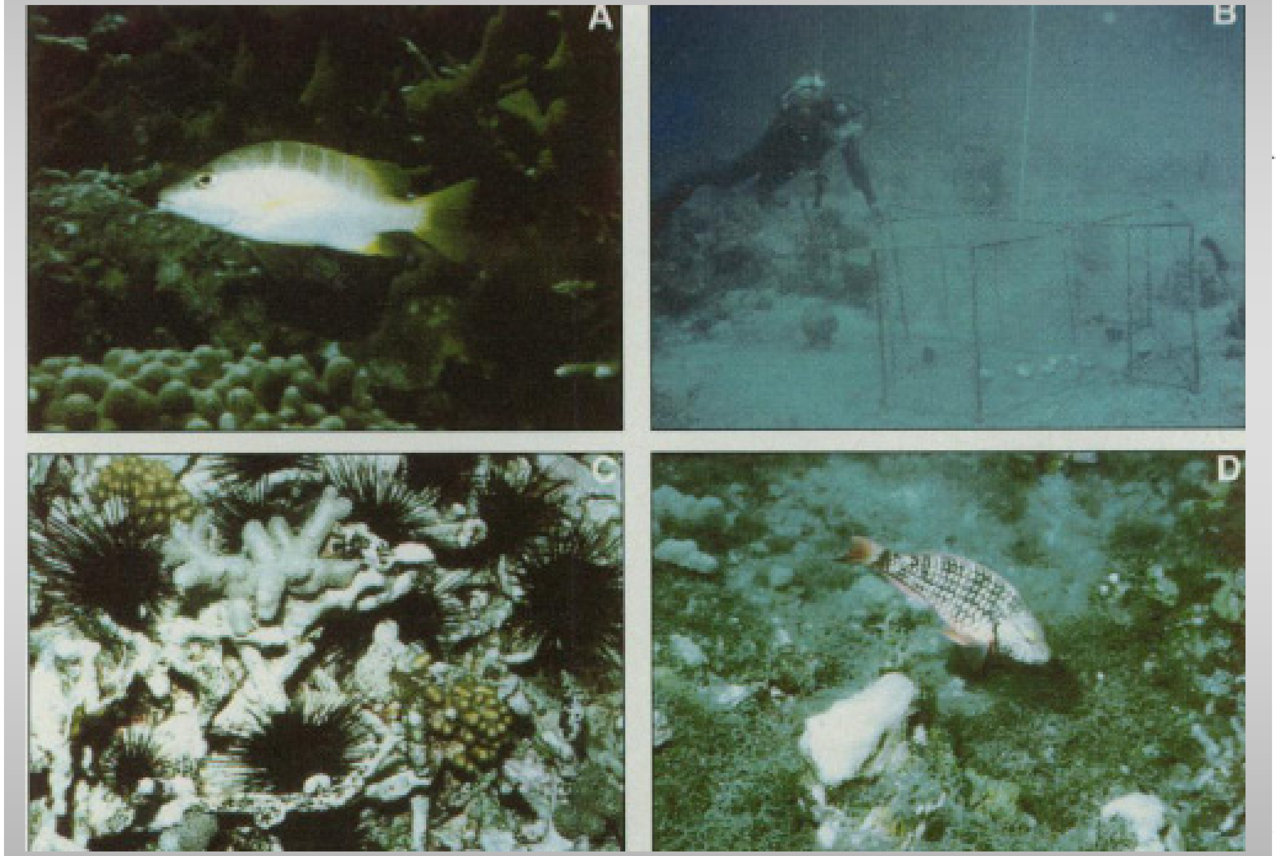
Claussen, et al (1999) *Geophysical Research Letters* **26**, 2037-2040.

Scheffer, et al. (2001). *Nature* 413: 591-596

“Simple” example



Jamaican coral reef systems



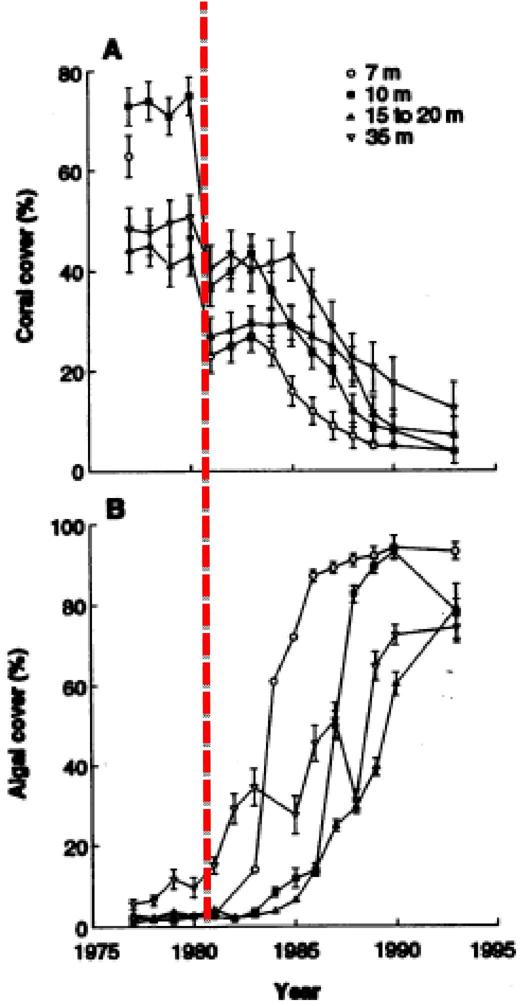


Fig. 3. Degradation of Jamaican coral reefs over the past two decades. Small-scale changes in (**A**) coral cover and in (**B**) macroalgal cover over time at four depths near Discovery Bay (*32*).

Sequence of events

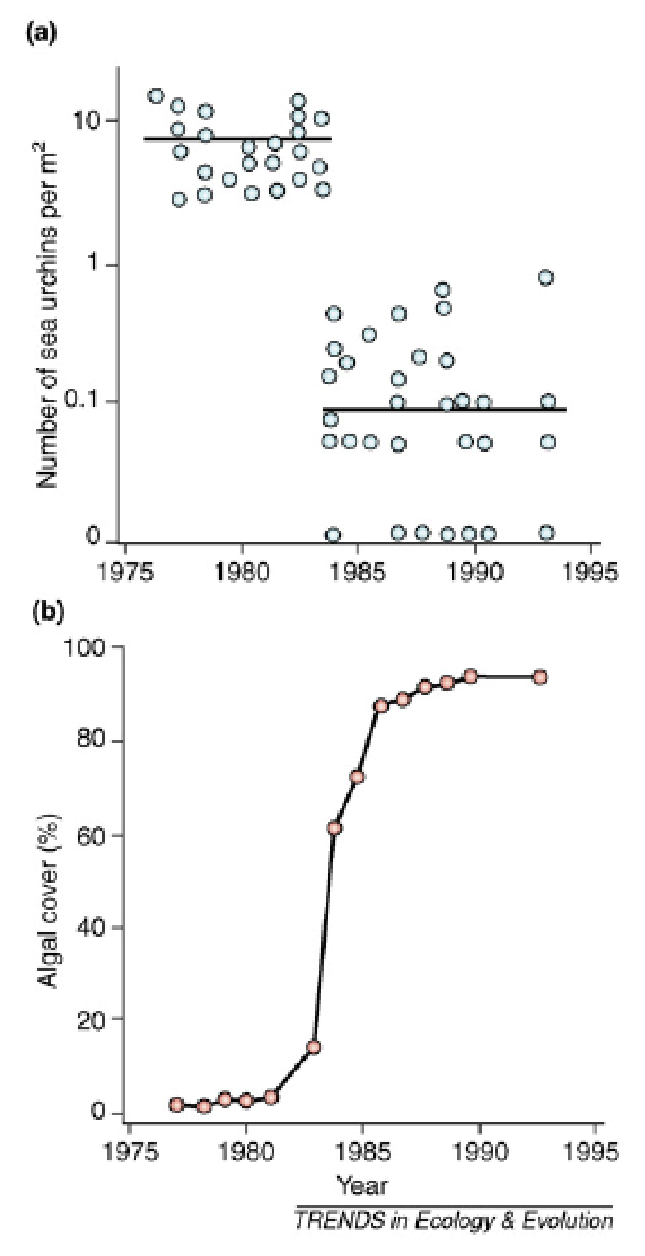
Removal of fish &
Eutrophication

Sea urchins #'s increase

Hurricane in '81
(urchins recolonized)

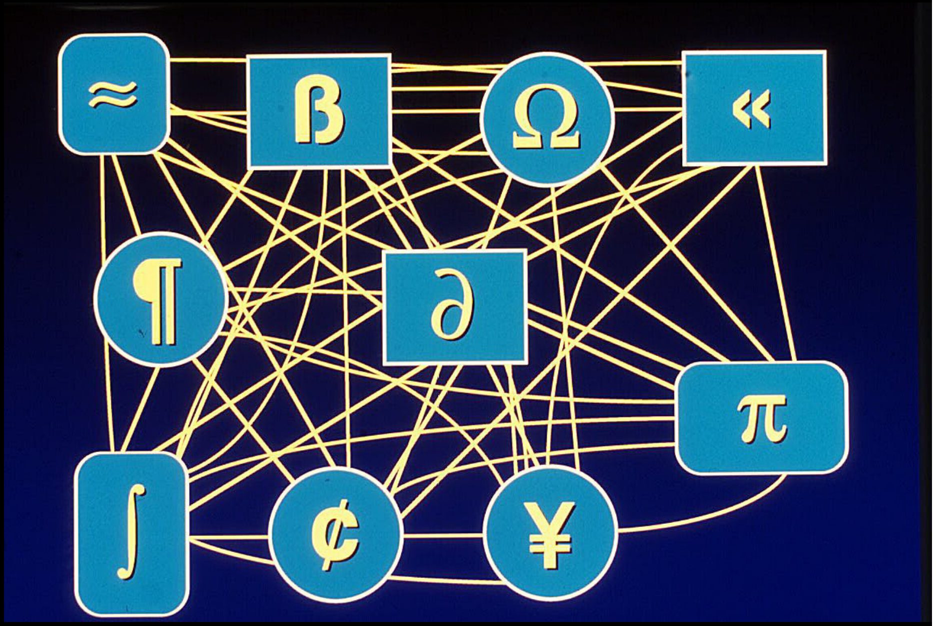
Pathogen

Fleshy brown algae took over

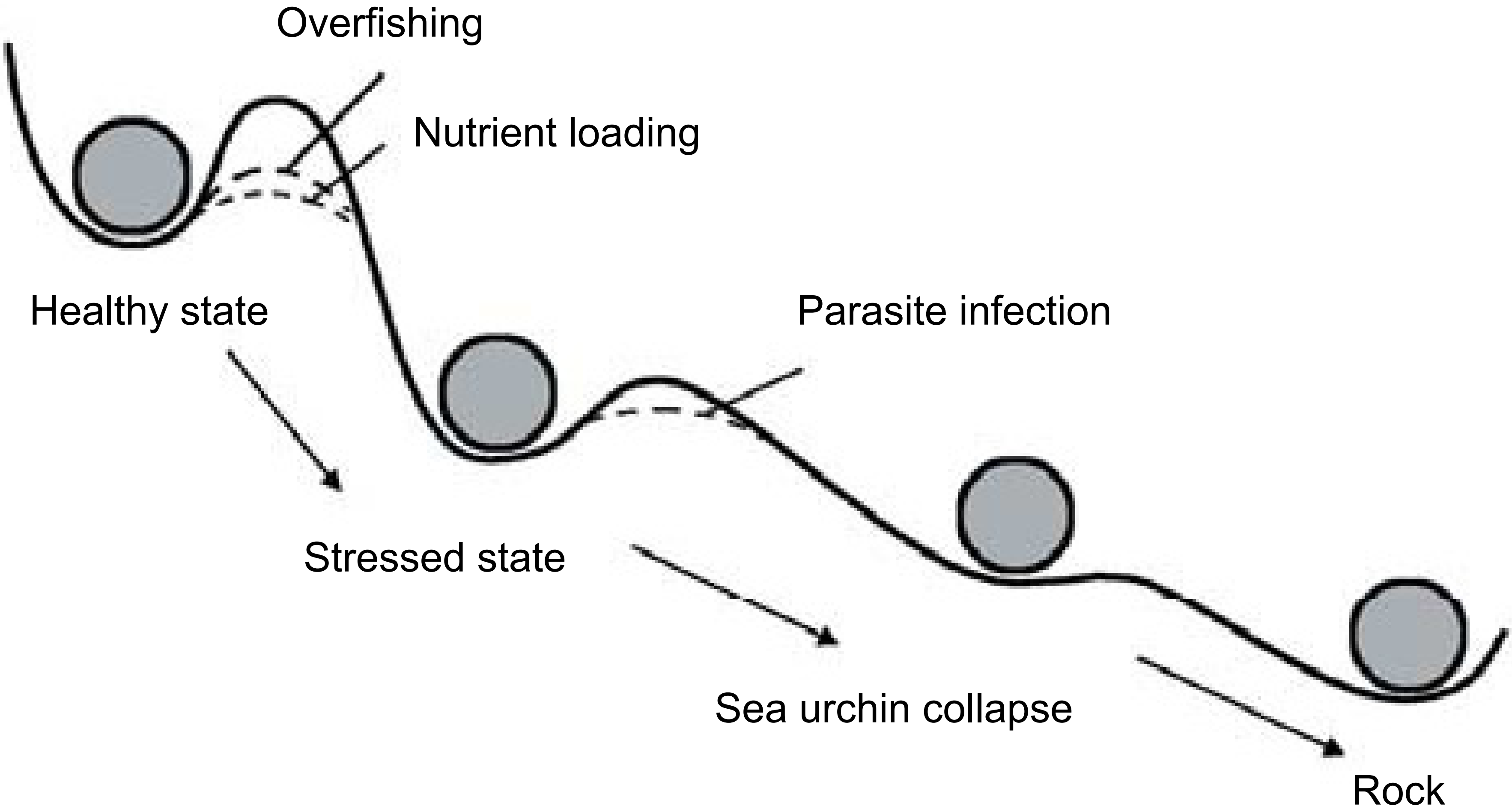


TRENDS in Ecology & Evolution

"Complicated" explanation



Loss of resilience



Overfishing

Nutrient loading

Healthy state

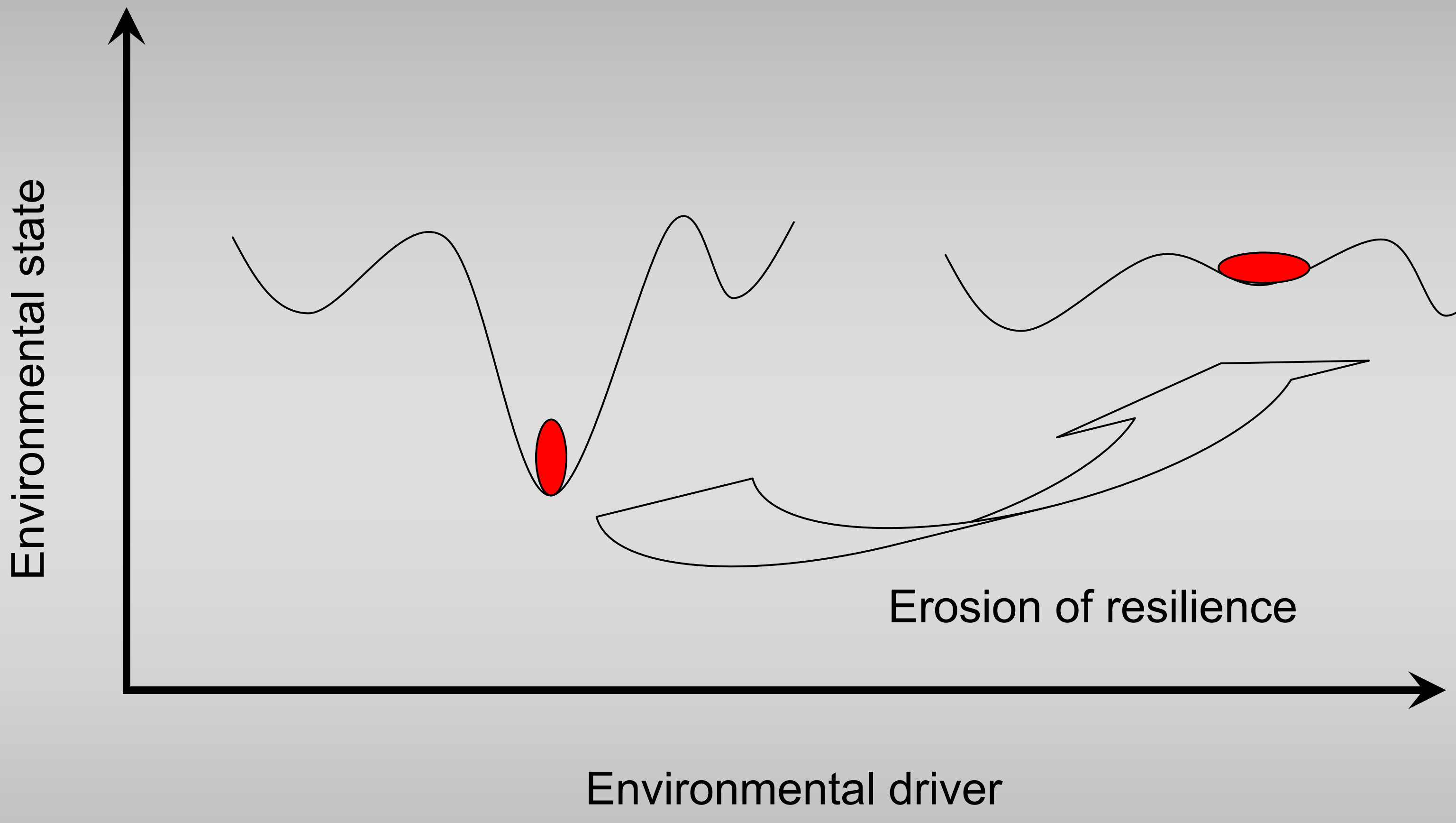
Parasite infection

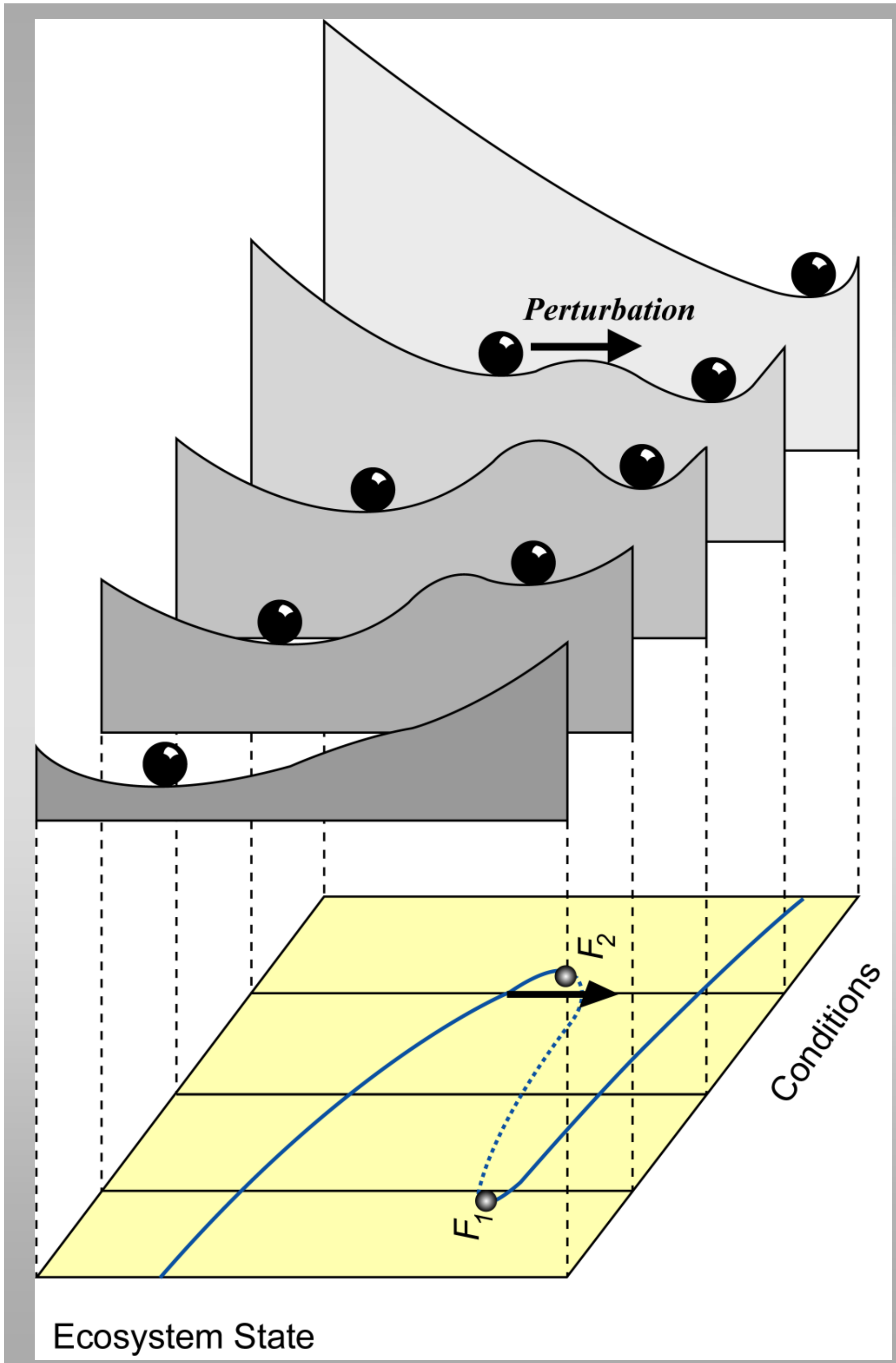
Stressed state

Sea urchin collapse

Rock

Erosion of resilience

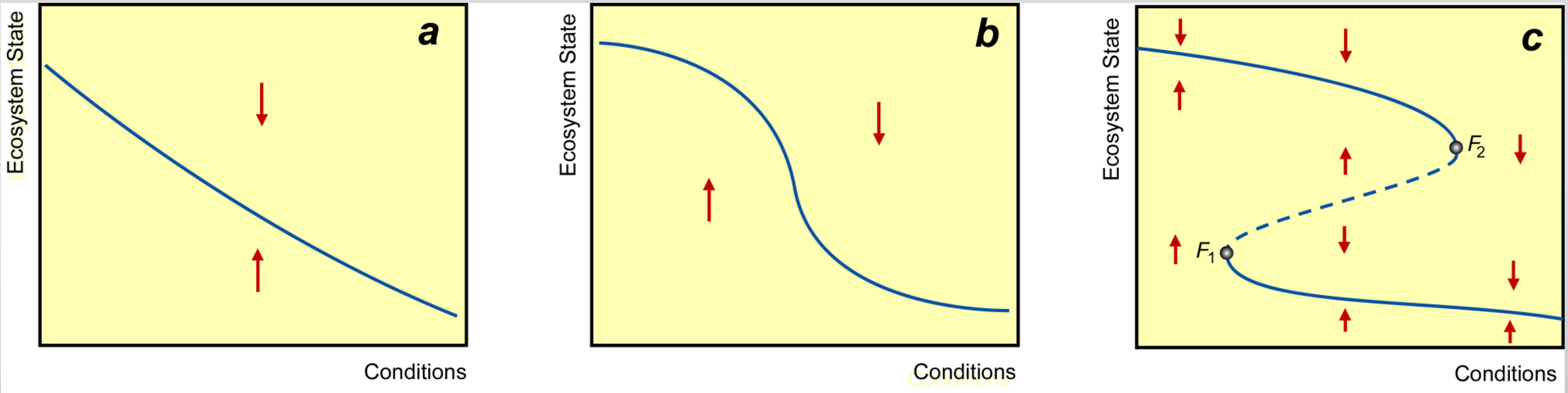




- Loss of resilience
- Irreversibility
- Triggered shifts

Scheffer et al. 2001. Nature 413:591-596.

Can we anticipate how biological and ecological systems will respond?



(a) and (b): one equilibrium state

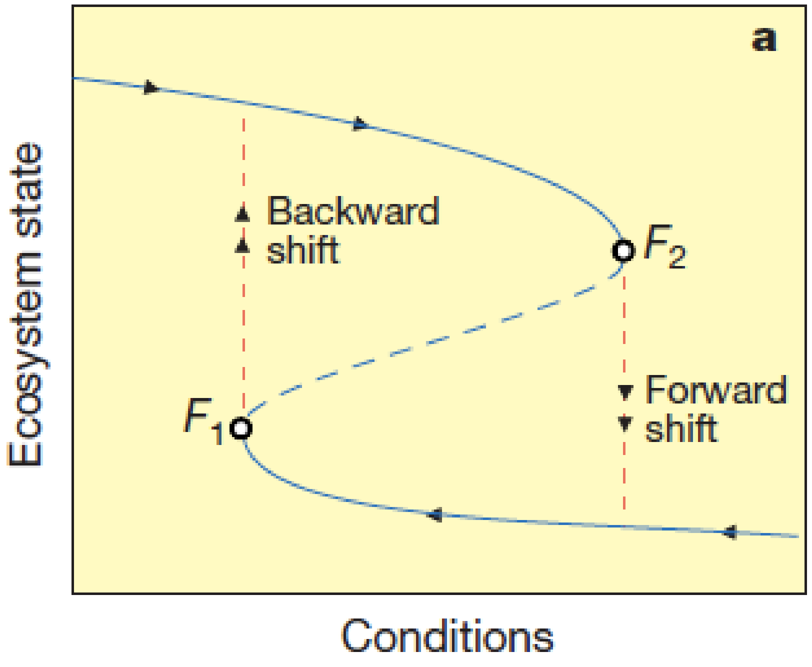
(c): three equilibrium states;
two stable, one unstable

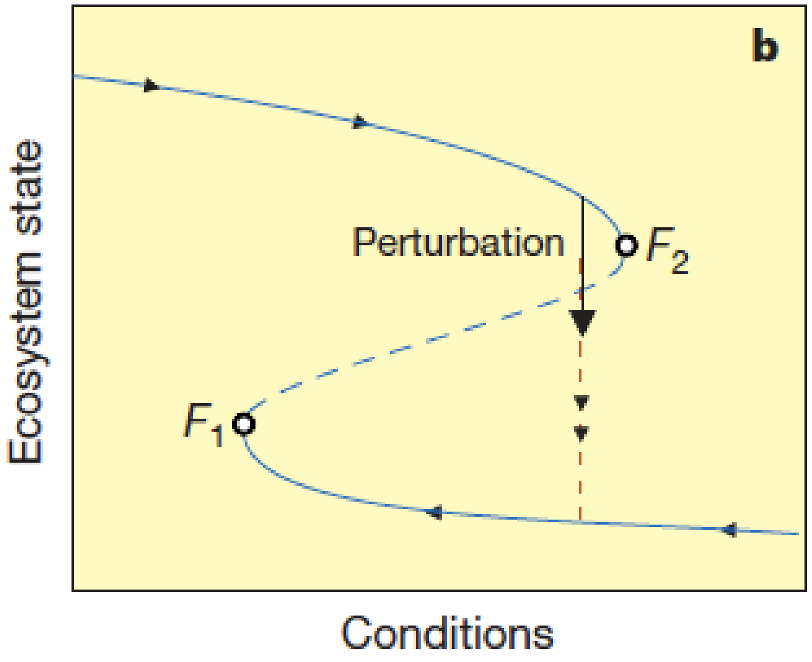
Scheffer, Carpenter, Walker, Foley and Folke 2001. NATURE

For a system on the upper branch, close to the F_2 bifurcation point, a slight incremental change may bring it beyond the bifurcation and induce a catastrophic shift to the lower alternative stable state.

A perturbation, if sufficiently large, may also induce a shift the lower alternative stable state.

Scheffer, Carpenter, Walker, Foley and Folke 2001. NATURE



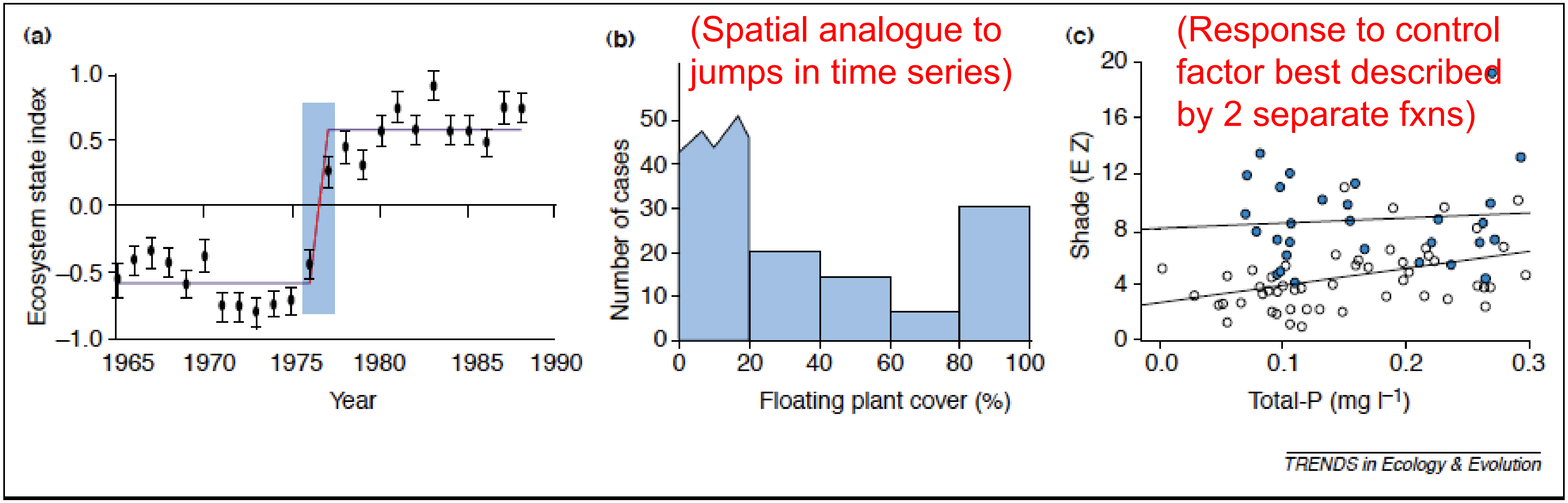


How can we demonstrate that there are alternative attractors in real ecosystems?

Shifts in
time series

Multimodal
distributions

Dual
relationships



(Spatial analogue to jumps in time series)

(Response to control factor best described by 2 separate fxns)

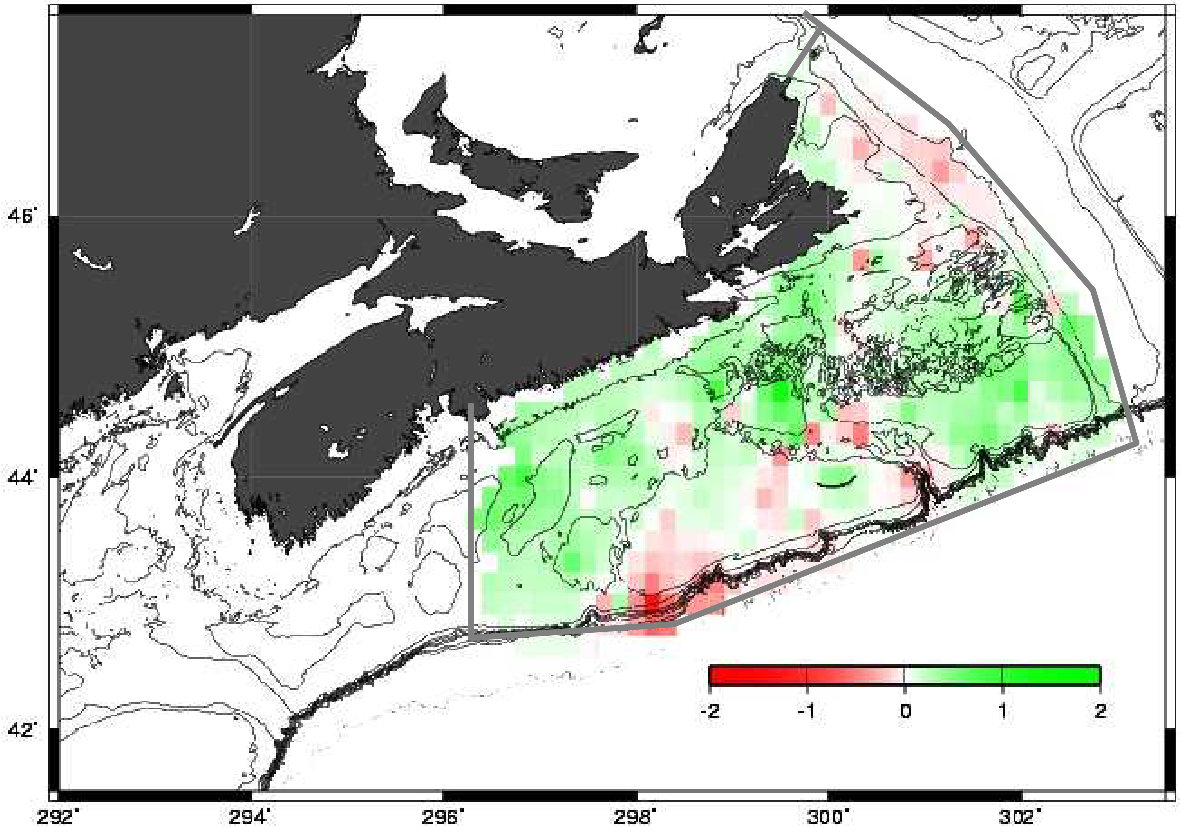
Figure 3. Three types of hints of the existence of alternative attractors from field data: (a) shift in a time series, (b) multimodal distribution of states, and (c) dual relationship to a control factor. The specific examples are (a) regime shift in the Pacific Ocean ecosystem (shaded) (modified with permission from [4]), (b) bimodal frequency distribution of free floating plants in a set of 158 Dutch ditches (modified with permission from [6]), and (c) different relationships between underwater shade and the total phosphorus concentration for shallow lakes dominated by Cyanobacteria (blue circles) and lakes dominated by other algae (open circles) (modified with permission from [62]).

Scheffer, et al. (2003) TREE.

Review of a few other oceanic examples

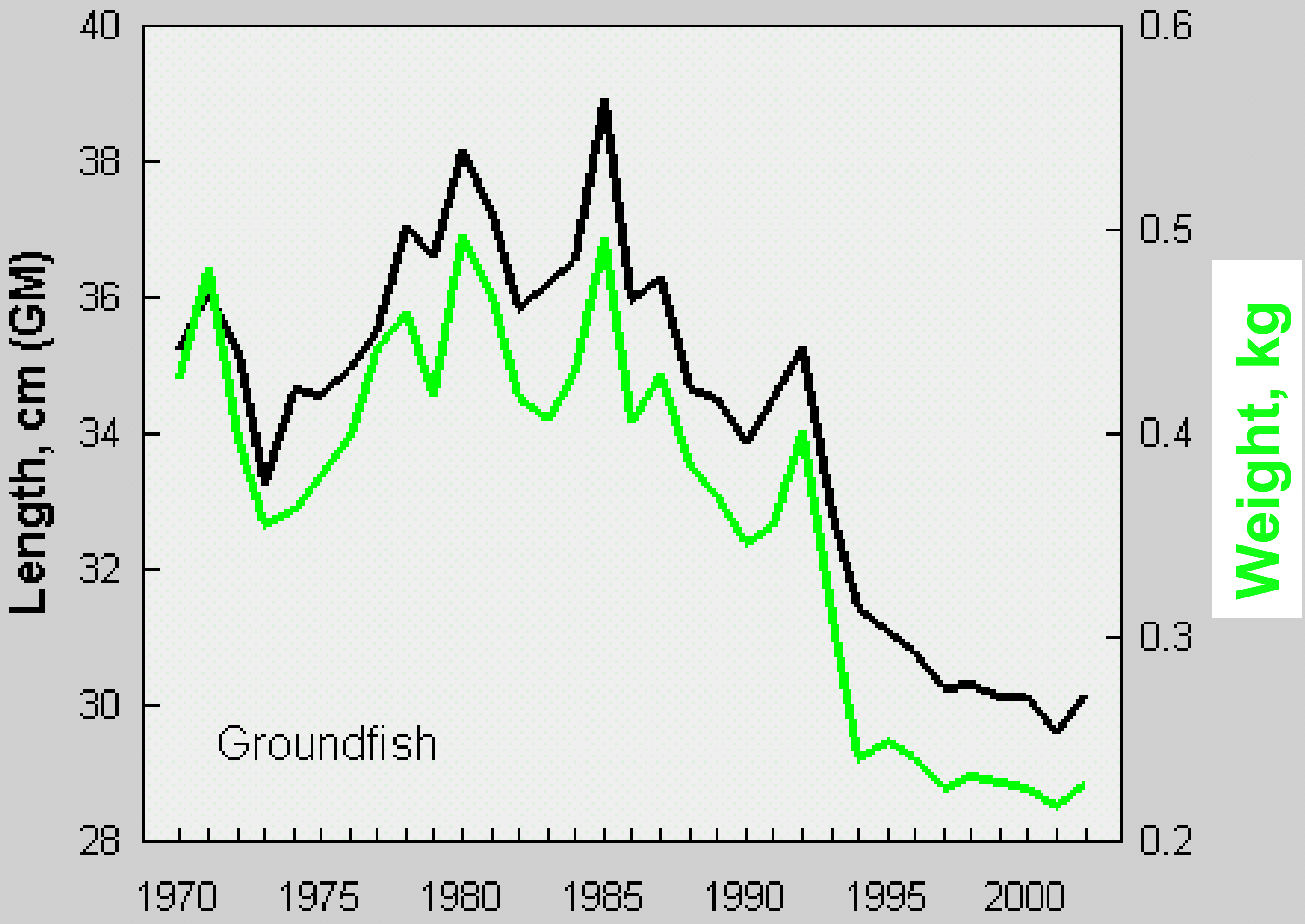
- **Scotian Shelf** – driven primarily by fishing, cascading trophic impacts
- **North Sea** – combined drivers: natural=biogeographic shift and human=fishing
- **North Pacific** – complex natural state change(s)

Fish community condition (1970-1982)



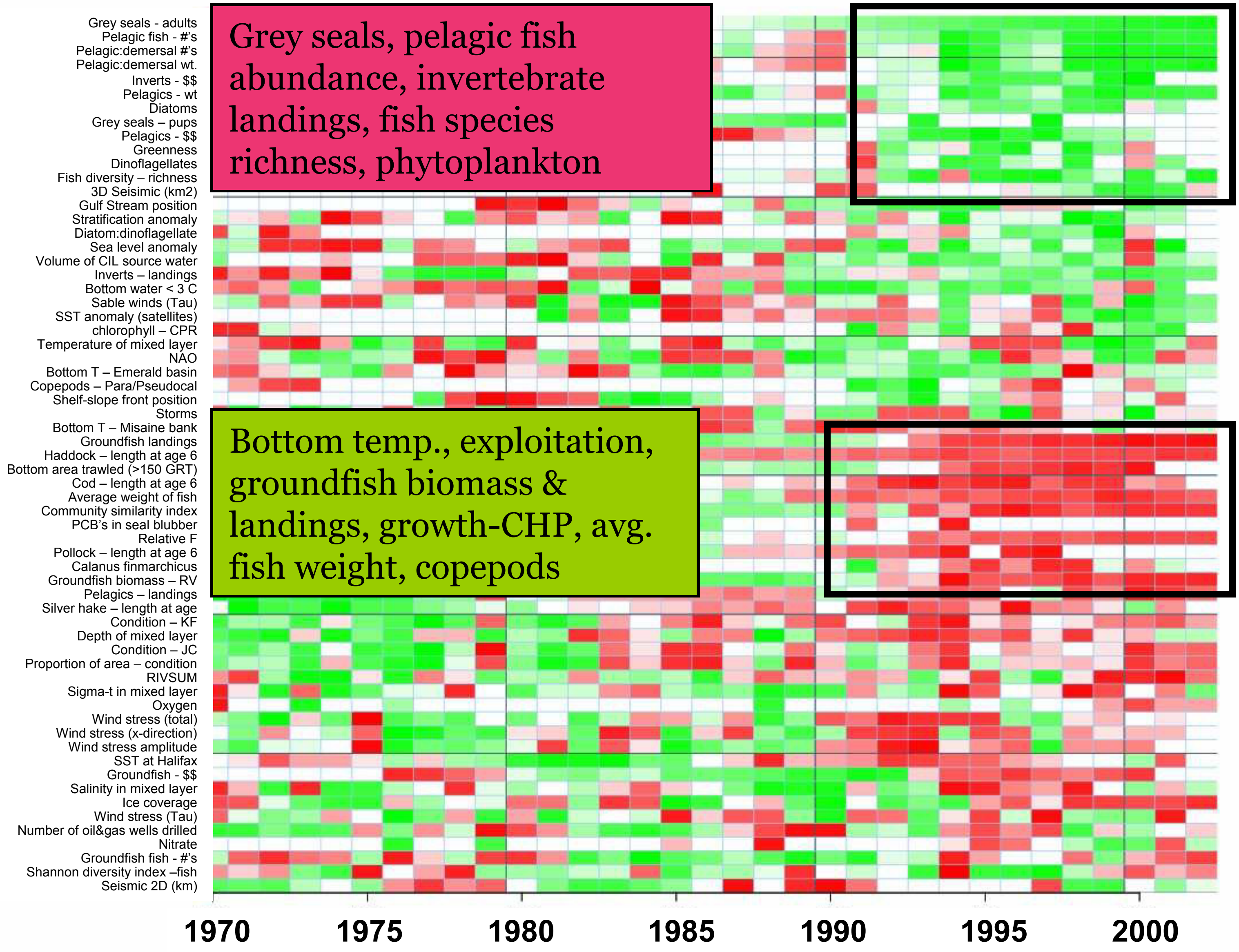
-30% +30%

Scotian Shelf **– Frank *et al.* 2005**



40
38
36
34
32
30
28
Length, cm (GM)
0.6
0.5
0.4
0.3
0.2
Weight, kg
Groundfish
1970
1975
1980
1985
1990
1995
2000

Colour display of 60+ indices for Eastern Scotian Shelf

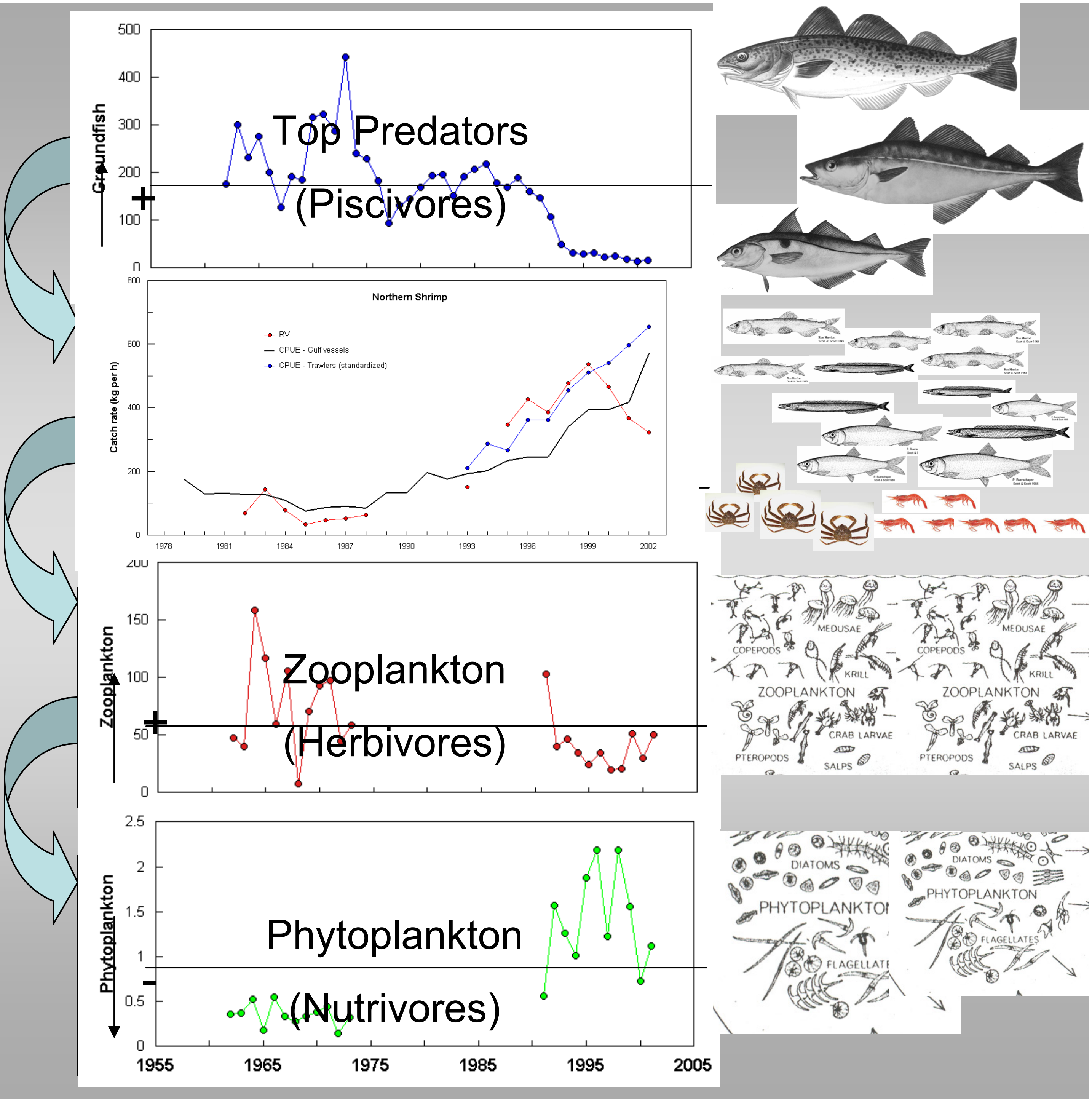


Grey seals, pelagic fish abundance, invertebrate landings, fish species richness, phytoplankton

Bottom temp., exploitation, groundfish biomass & landings, growth-CHP, avg. fish weight, copepods

Red – below average

Green – above average



Top Predators

(Piscivores)

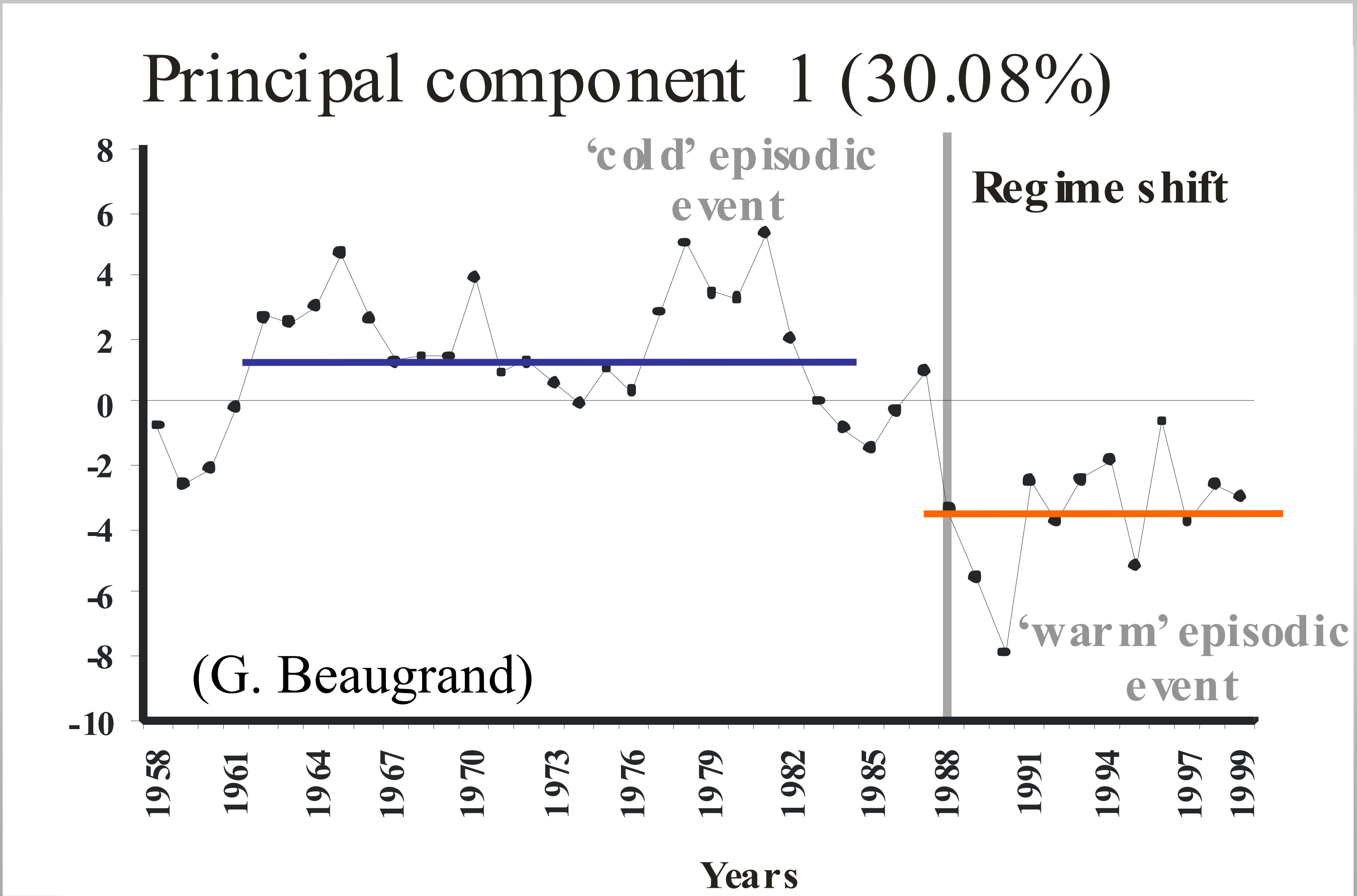
Zooplankton

(Herbivores)

Phytoplankton

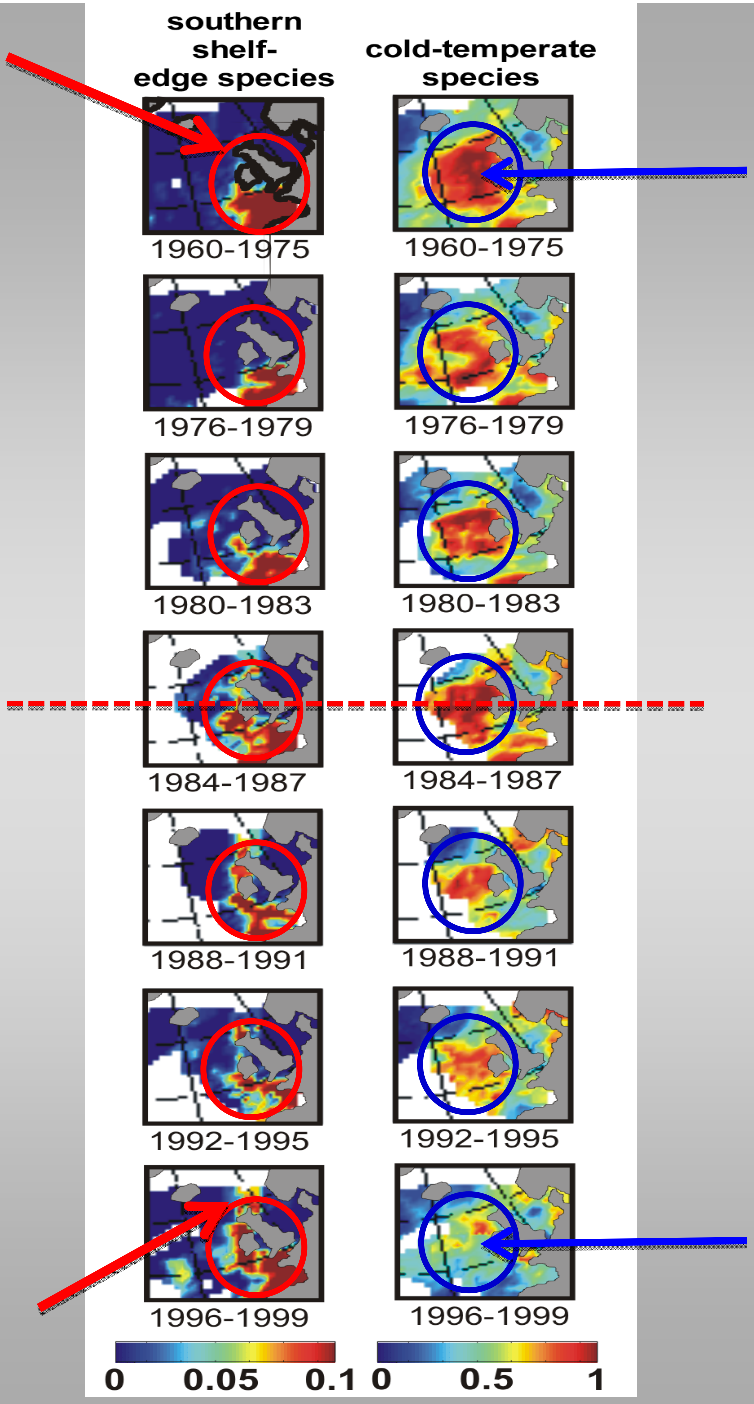
(Nutrivores)

North Sea: Long-term changes in the ecology (hydro-climate + biology)

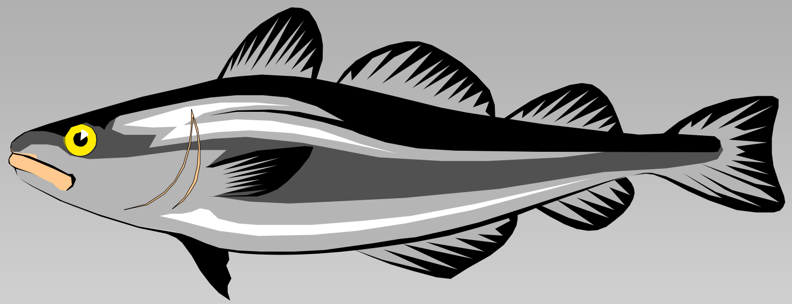


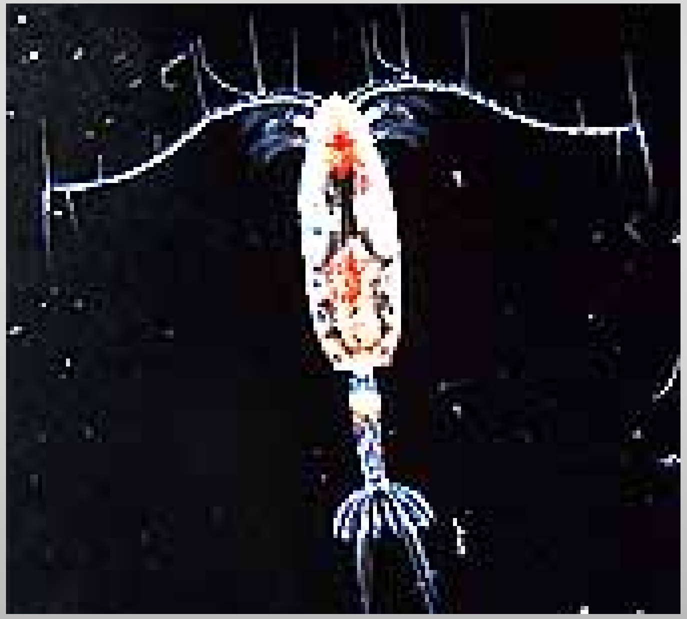
Shifts in copepod distributions in the North Atlantic:

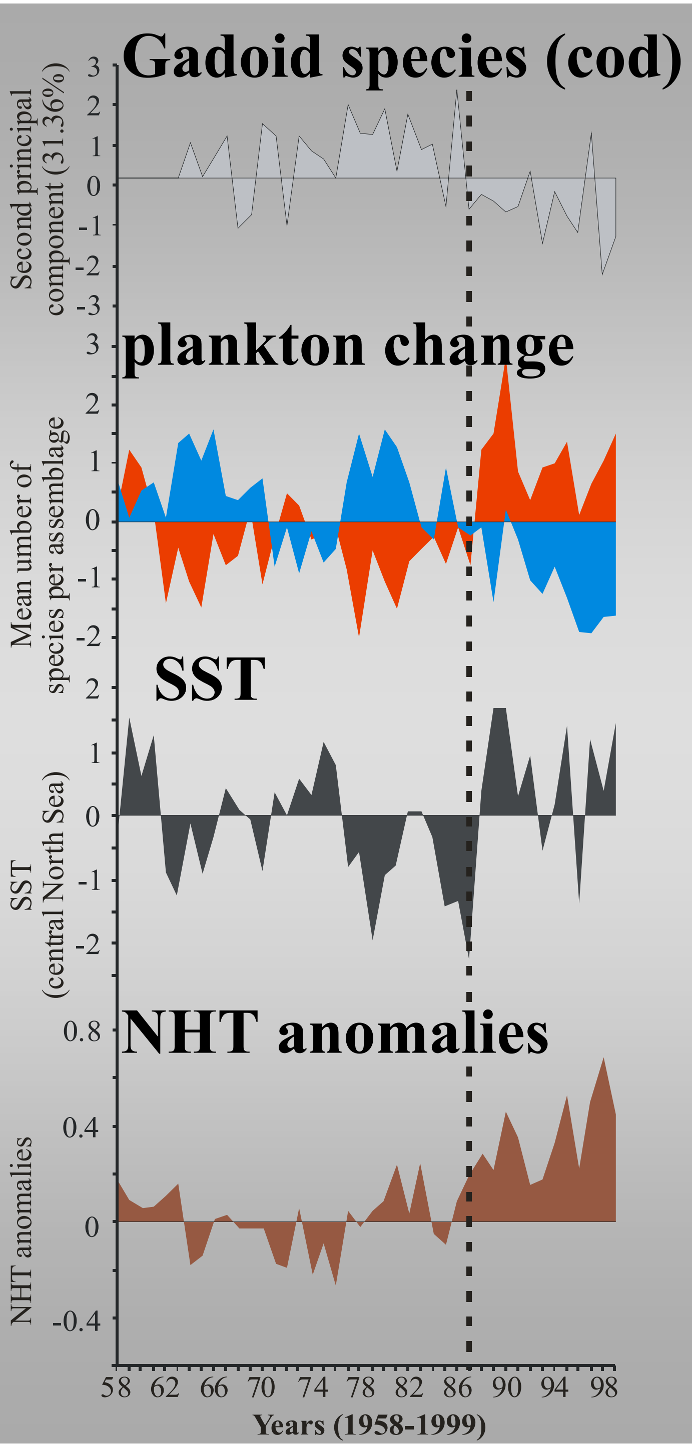
Warm-water species have extended their distribution northward by more than 10° of latitude, while cold-water species have decreased in number and extension.



(Beaugrand et al., Science, 2002)

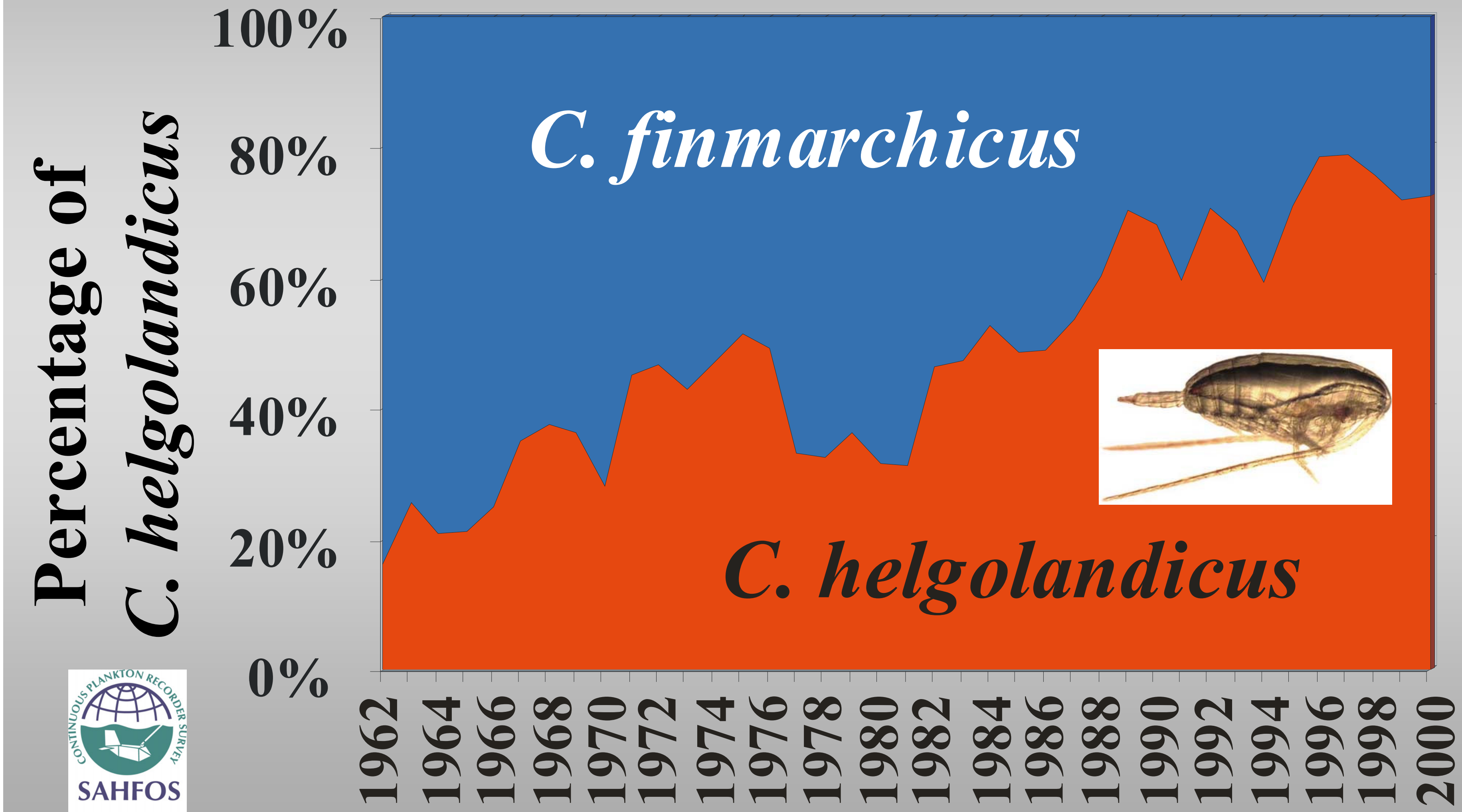






Gadoid species (cod)
Second principal component (31.36%)
3
2
1
0
-1
-2
-3
plankton change
Mean umber of species per assemblage
3
2
1
0
-1
-2
SST
SST (central North Sea)
2
1
0
-1
-2
NHT anomalies
NHT anomalies
0.8
0.4
0
-0.4
58
62
66
70
74
78
82
86
90
94
98
Years (1958-1999)

Long-term changes in the abundance of two key species in the North Sea

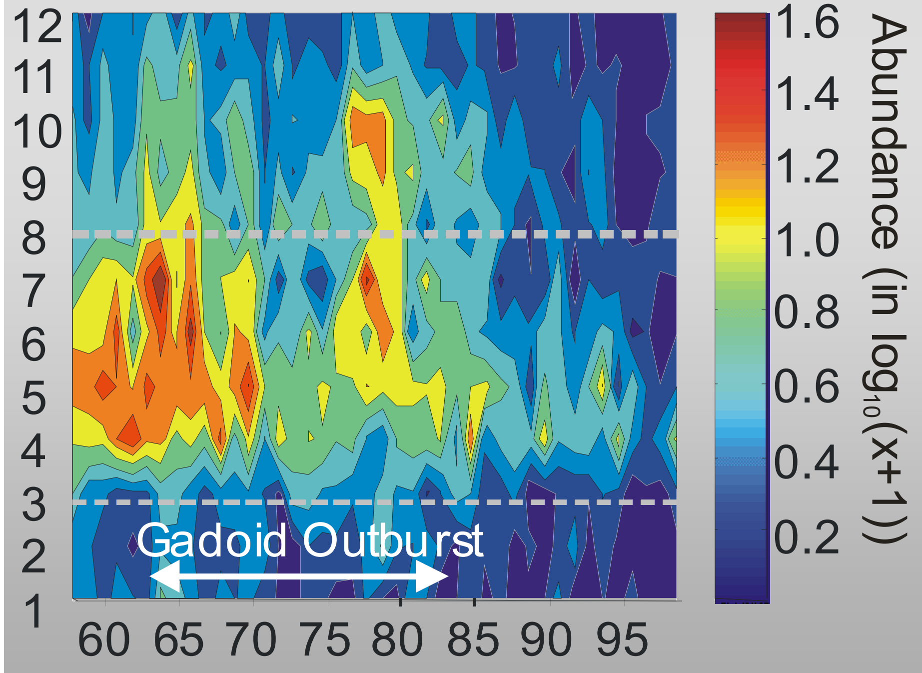


Reid et al. (2003)

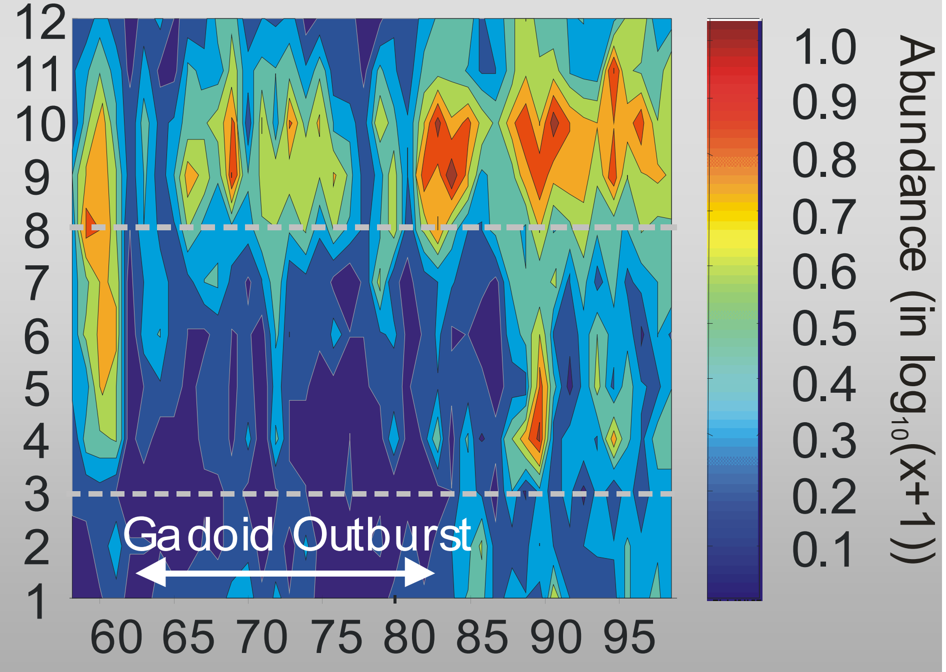
Consequences of plankton changes on higher trophic level

Mismatch between the timing of calanus prey and larval cod

Abundance of C. *finmarchicus*

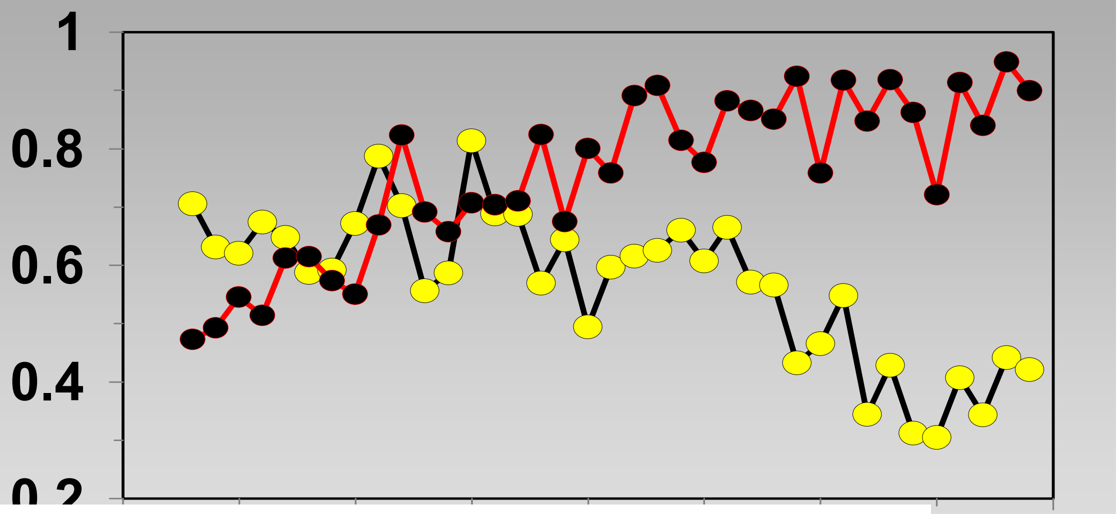


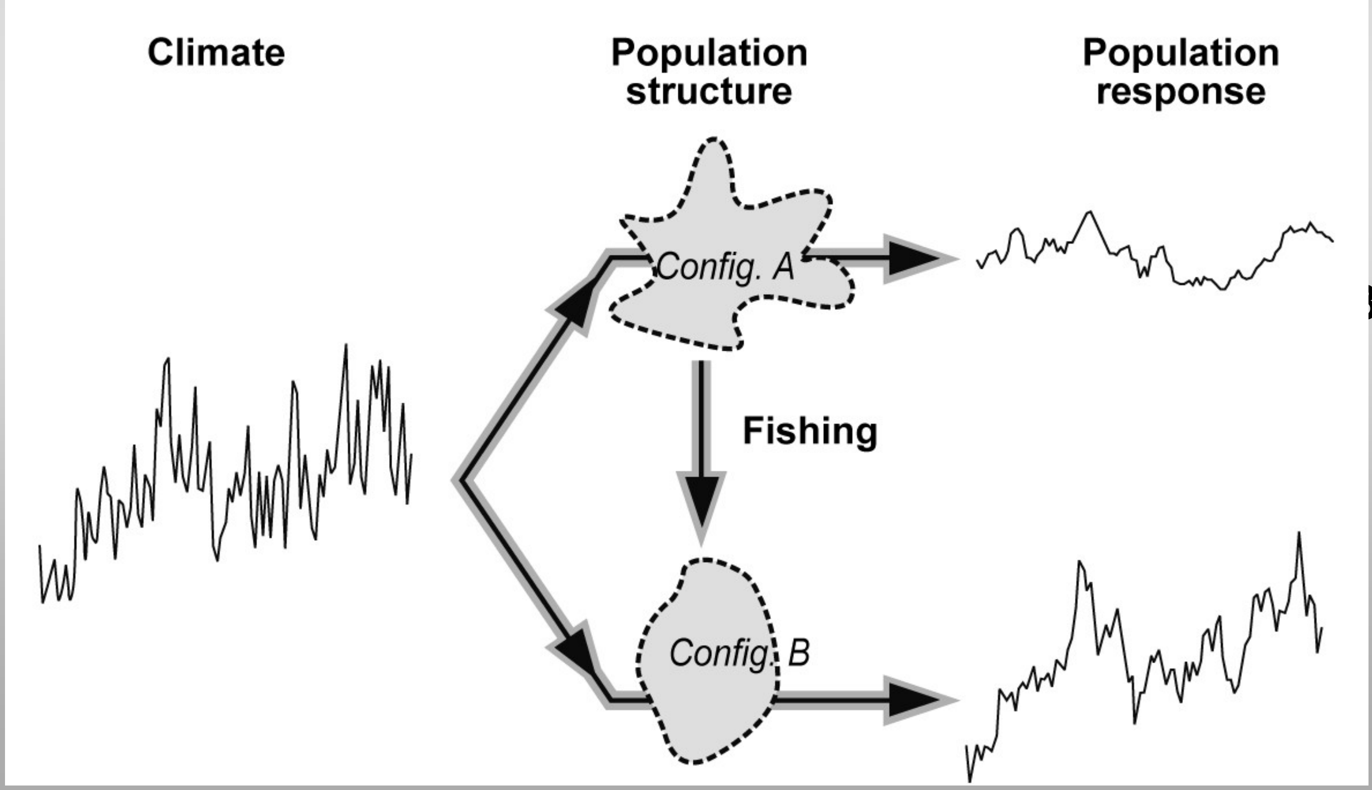
Abundance of C. *helgolandicus*



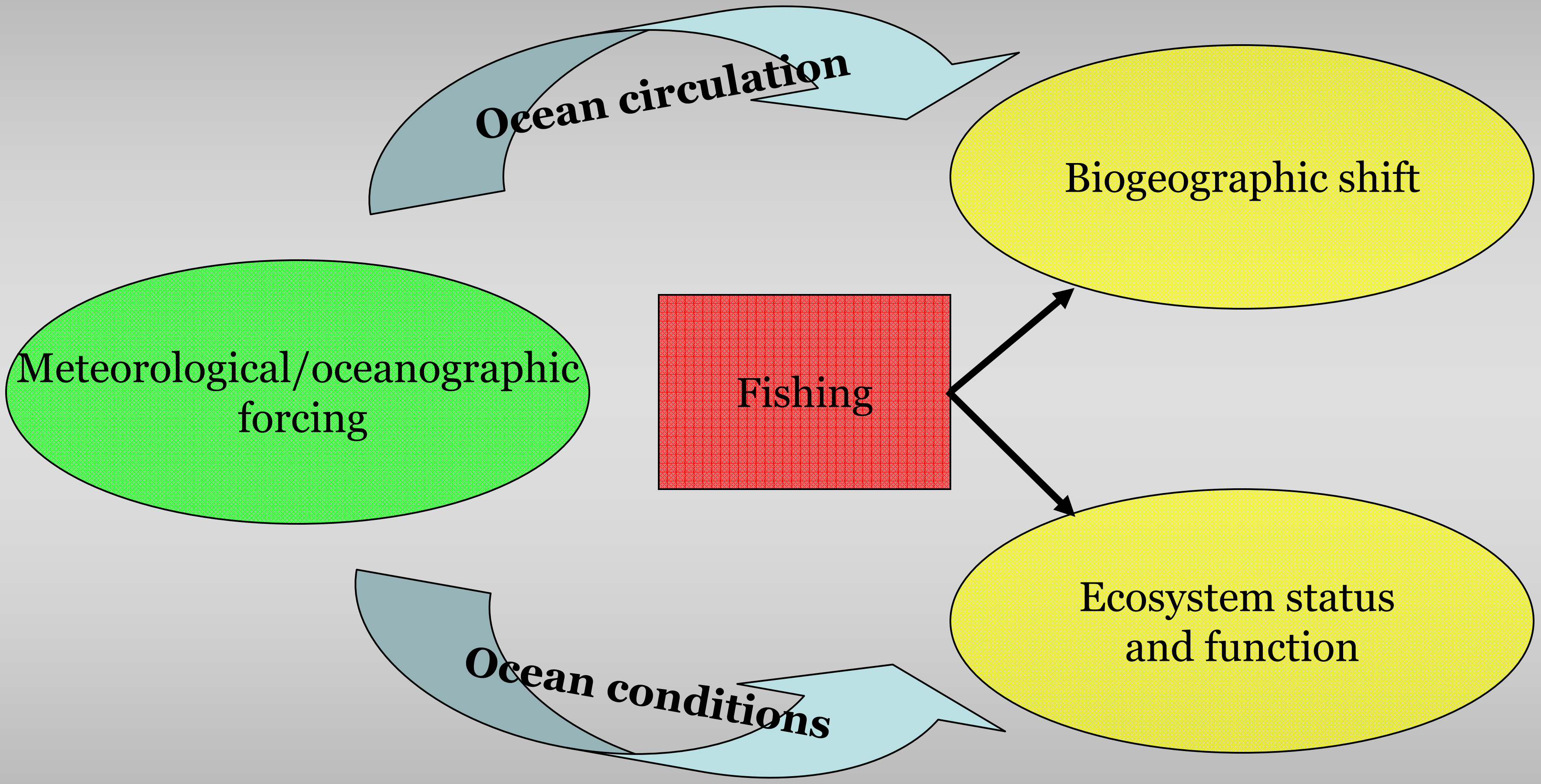
Beaugrand, et al. (2003) Nature. Vol. 426. 661-664.

But there is also an influence from fishing – how much?





North Sea - dynamics



Ocean circulation

Biogeographic shift

Meteorological/oceanographic forcing

Fishing

Ecosystem status and function

Ocean conditions

North Pacific regime shift – Hare and Mantua (2000)

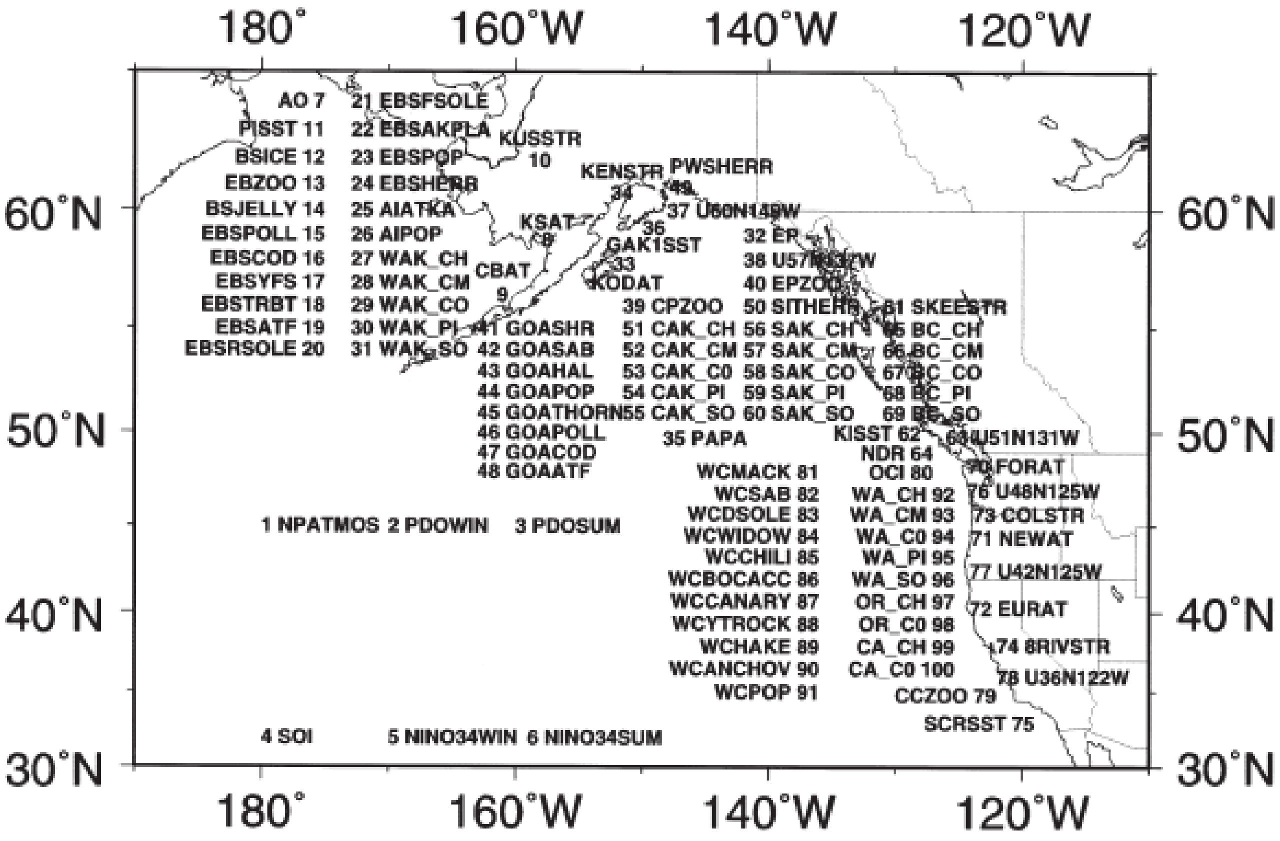
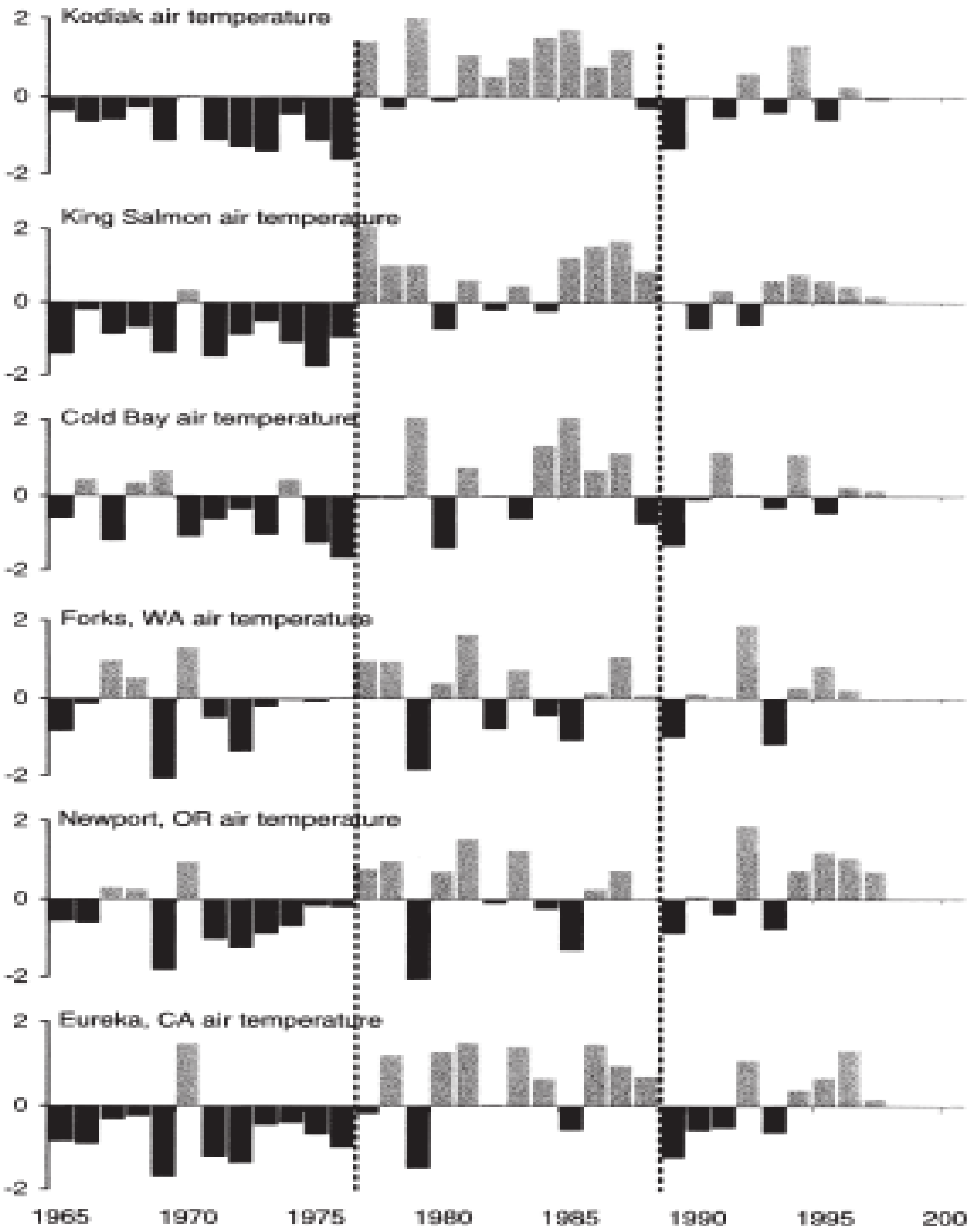


Fig. 1. Numeric and alphabetic abbreviations for the 100 time series used in this study. Geographical arrangement gives a general indication of where each variable is measured or has influence. See Table 1 for a definition of each abbreviation.

Physical forcing – air temperature - but there are dozens of other such time series



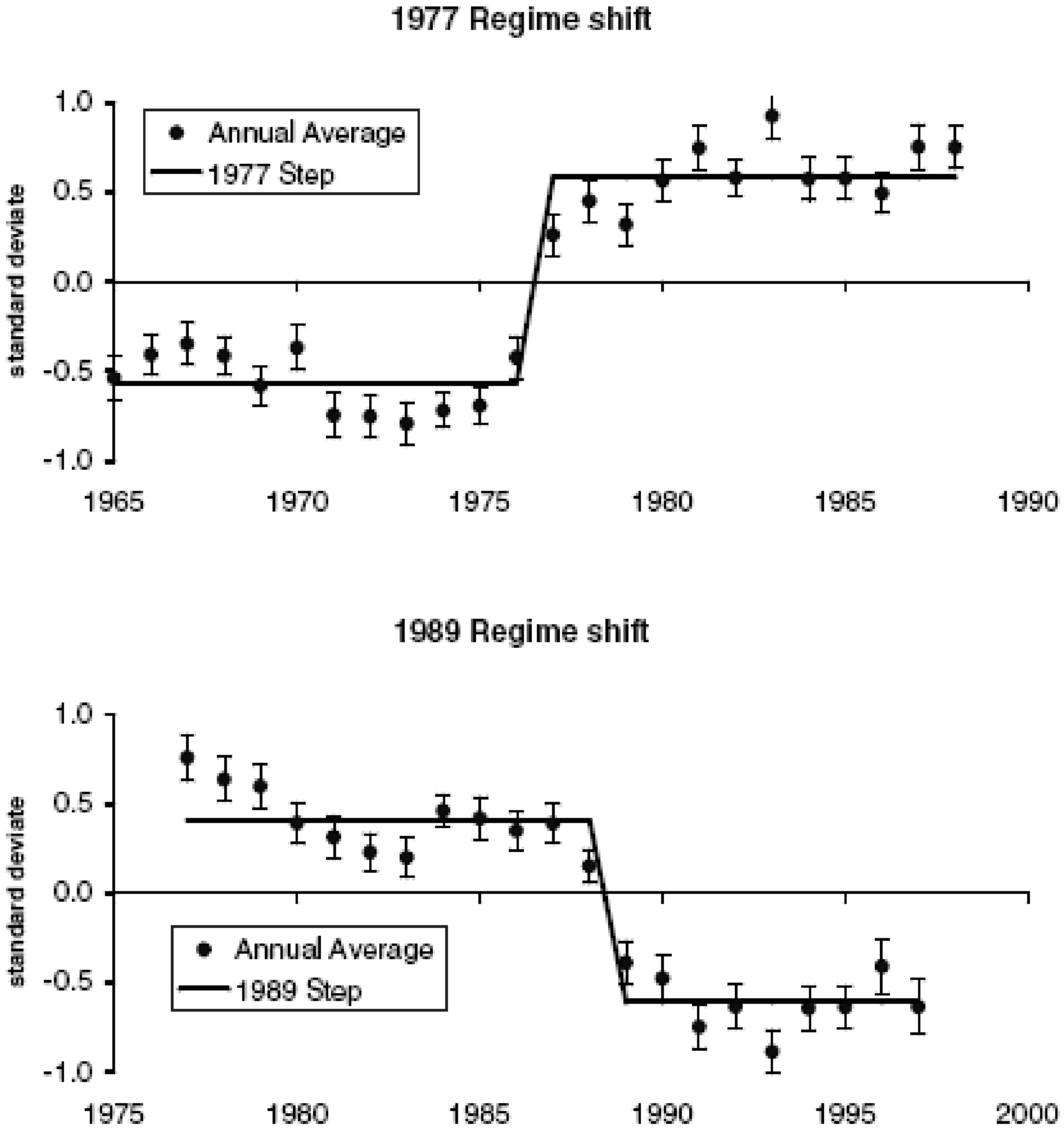


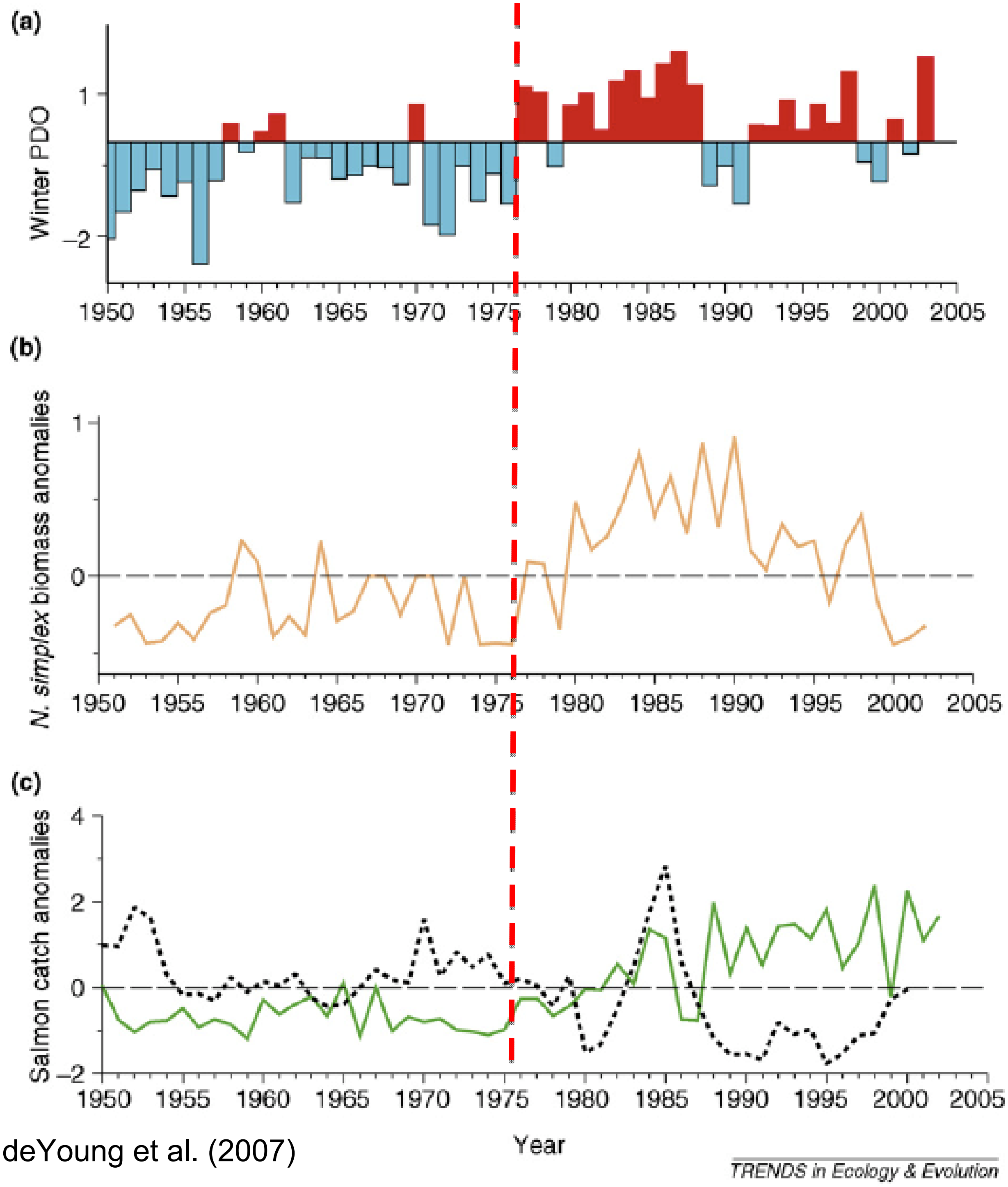
Fig. 4. Results from two regime shift analyses of a composite of the 100 environmental time series. The step passes through the mean standard deviate within each regime. The standard error of the 100 time series is illustrated for each year. After Hare and Mantua (2000).

Winter PDO

Euphausiid

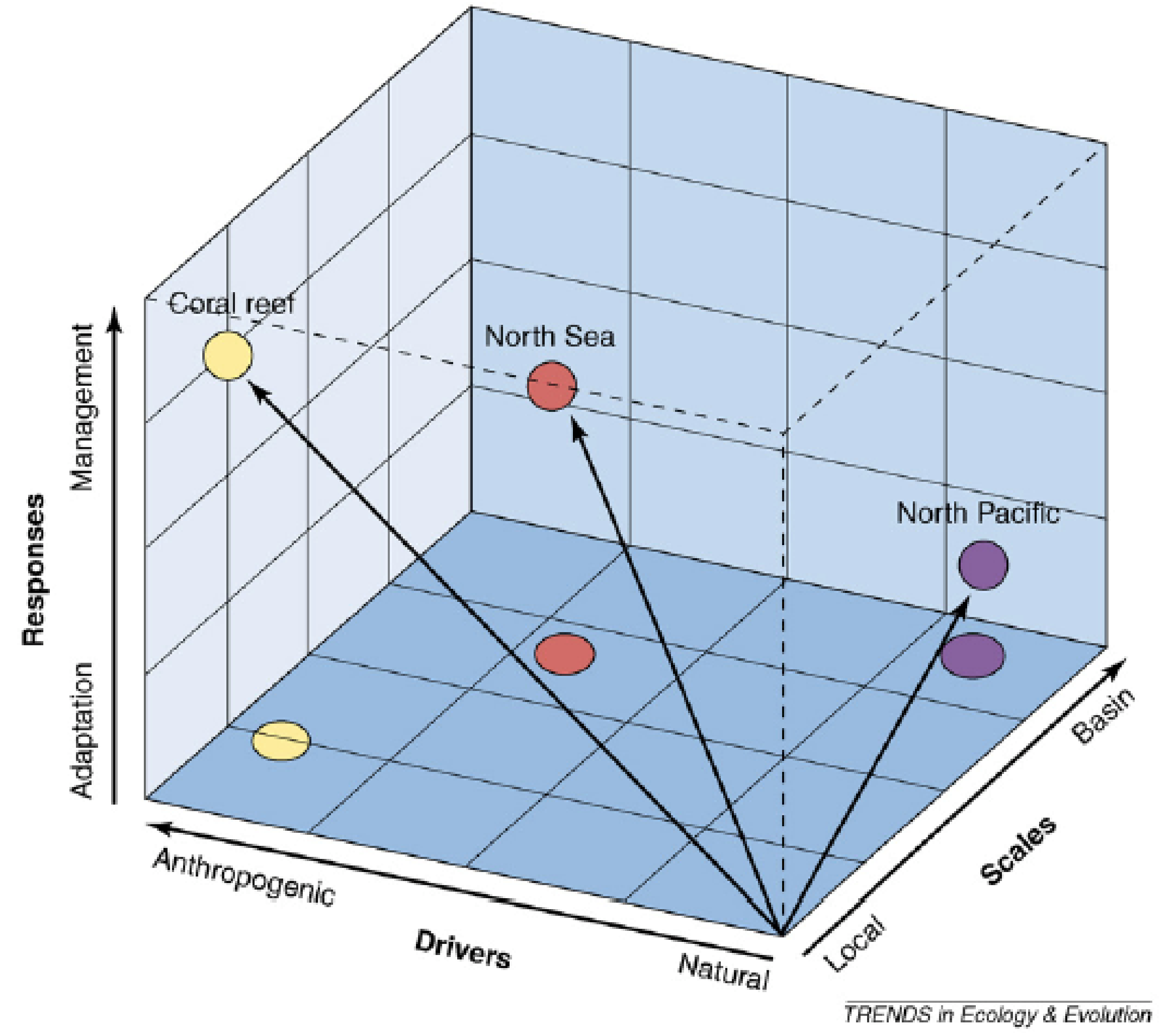
Pink salmon (solid) lagged one year

Chinook (dashed) lagged 3 years



TRENDS in Ecology & Evolution

deYoung et al. (2007)



deYoung et al. (2007)

How predictable are regime shifts?

- Coral reefs (the “simplest” case)
  - We understand the causal links
  - We can’t predict disease outbreaks

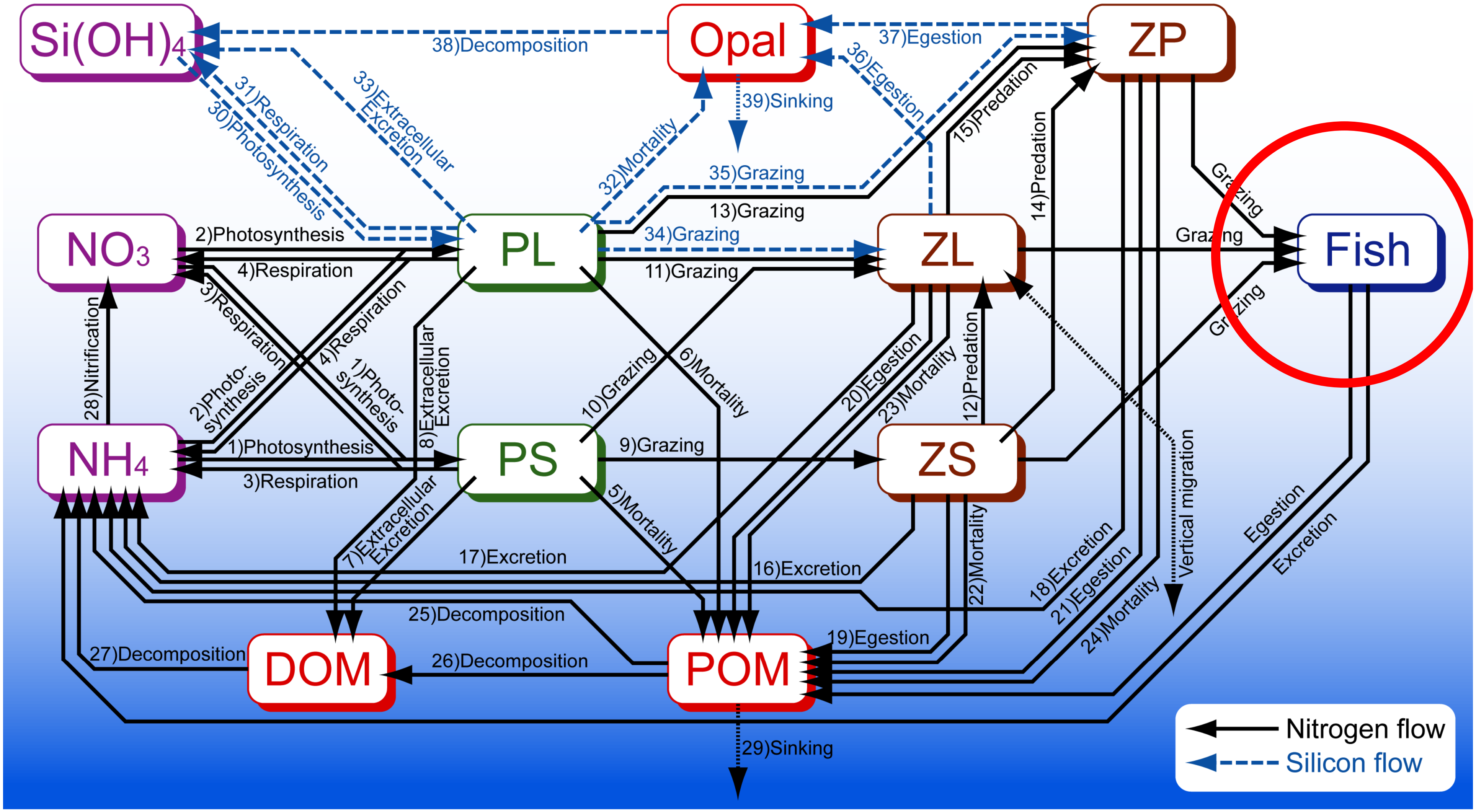
- Fishing-dominated systems
  - Although fishing can be the dominant driver, its consequences are not predictable without understanding the foodweb dynamics
  - Shifts may not be easily reversible

- North Pacific
  - We have not been able to separate drivers or where different states are occurring
  - Accurate prediction not currently possible

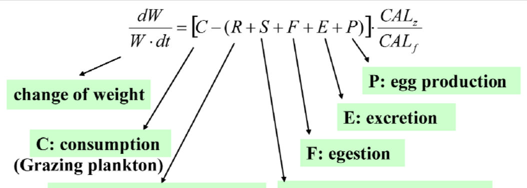
Can we model regime shifts?

Example North Pacific model
Yamanaka, Rose, Werner *et al. Ecological Modelling, 2007.*

NEMURO.FISH

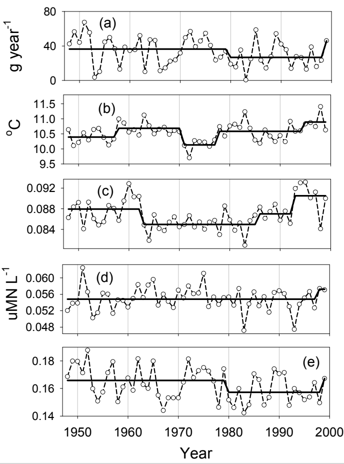

Si(OH)4
Opal
ZP
38)Decomposition
37)Egestion
36)Egestion
33)Extracellular Excretion
31)Respiration
30)Photosynthesis
39)Sinking
32)Mortality
35)Grazing
15)Predation
14)Predation
13)Grazing
Grazing
NO3
2)Photosynthesis
PL
34)Grazing
ZL
Grazing
Fish
4)Respiration
11)Grazing
3)Respiration
4)Respiration
2)Photo-synthesis
1)Photo-synthesis
8)Extracellular Excretion
10)Grazing
6)Mortality
20)Egestion
23)Mortality
12)Predation
Grazing
28)Nitrification
NH4
1)Photosynthesis
PS
9)Grazing
ZS
Vertical migration
3)Respiration
7)Extracellular Excretion
5)Mortality
Egestion
Excretion
17)Excretion
16)Excretion
22)Mortality
18)Excretion
21)Egestion
24)Mortality
25)Decomposition
19)Egestion
27)Decomposition
DOM
26)Decomposition
POM
29)Sinking
Nitrogen flow
Silicon flow

Nemuro Pacific herring model



$$\frac{dW}{W \cdot dt} = \left[C - (R + S + F + E + P)\right] \cdot \frac{CAL_z}{CAL_f}$$

Time series output



Zooplankton and temperature time series

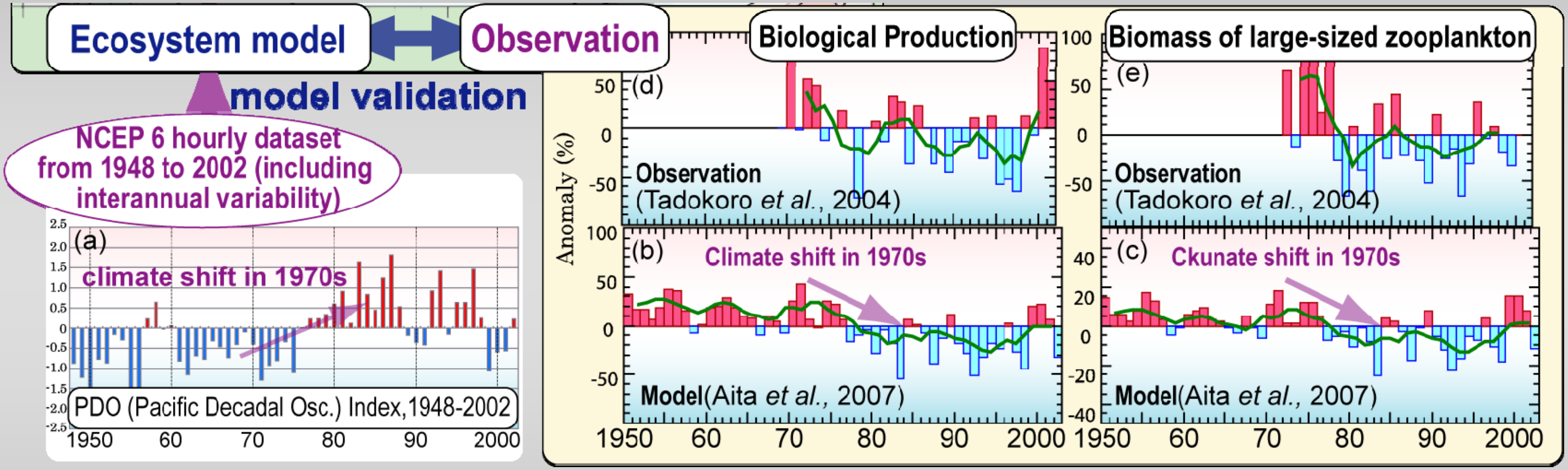
COCO – Tokyo 3-D Nemuro

Validation

Observations- Biological and Physical

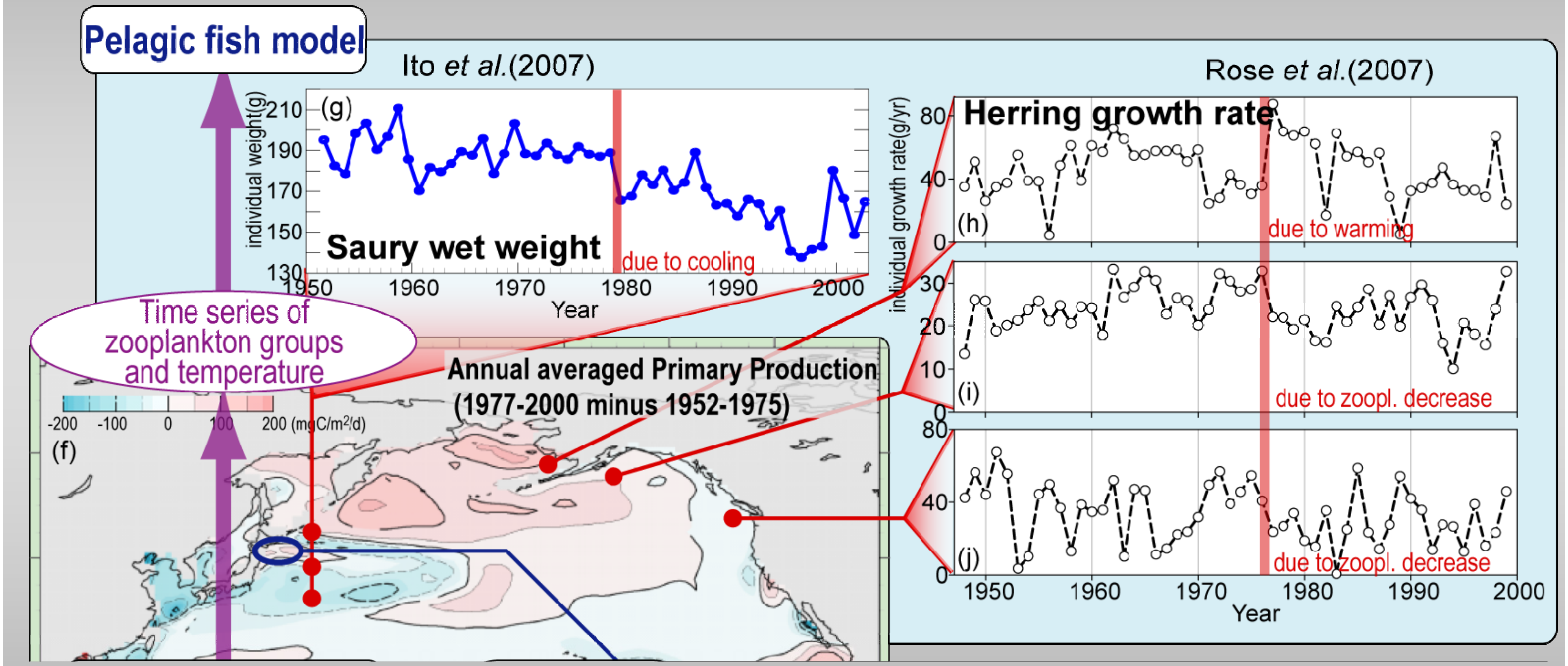
NCEP 6 hourly data
1948-2002
(includes interannual variability)

Modeled the basin-scale response in physics and lower trophic levels…



… and forced the upper trophic levels…

Obtained “shifts” in weights of individual fish at various locations in the North Pacific…



Pelagic fish model

Time series of zooplankton groups and temperature

Ito *et al.*(2007)

Rose *et al.*(2007)

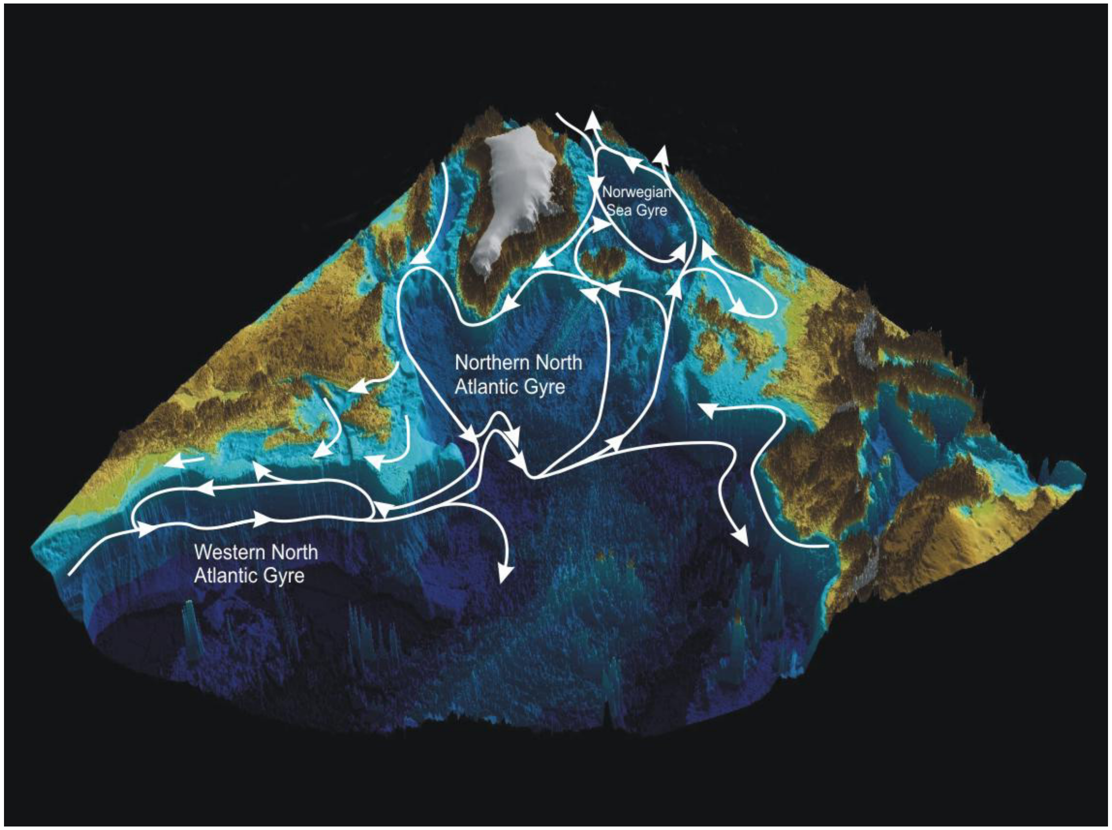
Summary

- Clear evidence for regime shifts in the ocean
- More regime shifts are likely – decreased resilience
- Limited data, systemic complexity, range of different structures
- Need sustained monitoring, experimental work, models, etc.

BASIN: Basin-scale Analysis, Synthesis, and Integration.

Resolving the impact of climatic processes on
ecosystems of the North Atlantic
basin and shelf seas.

BASIN is an initiative to develop a joint EU/North American ocean ecosystem research program.



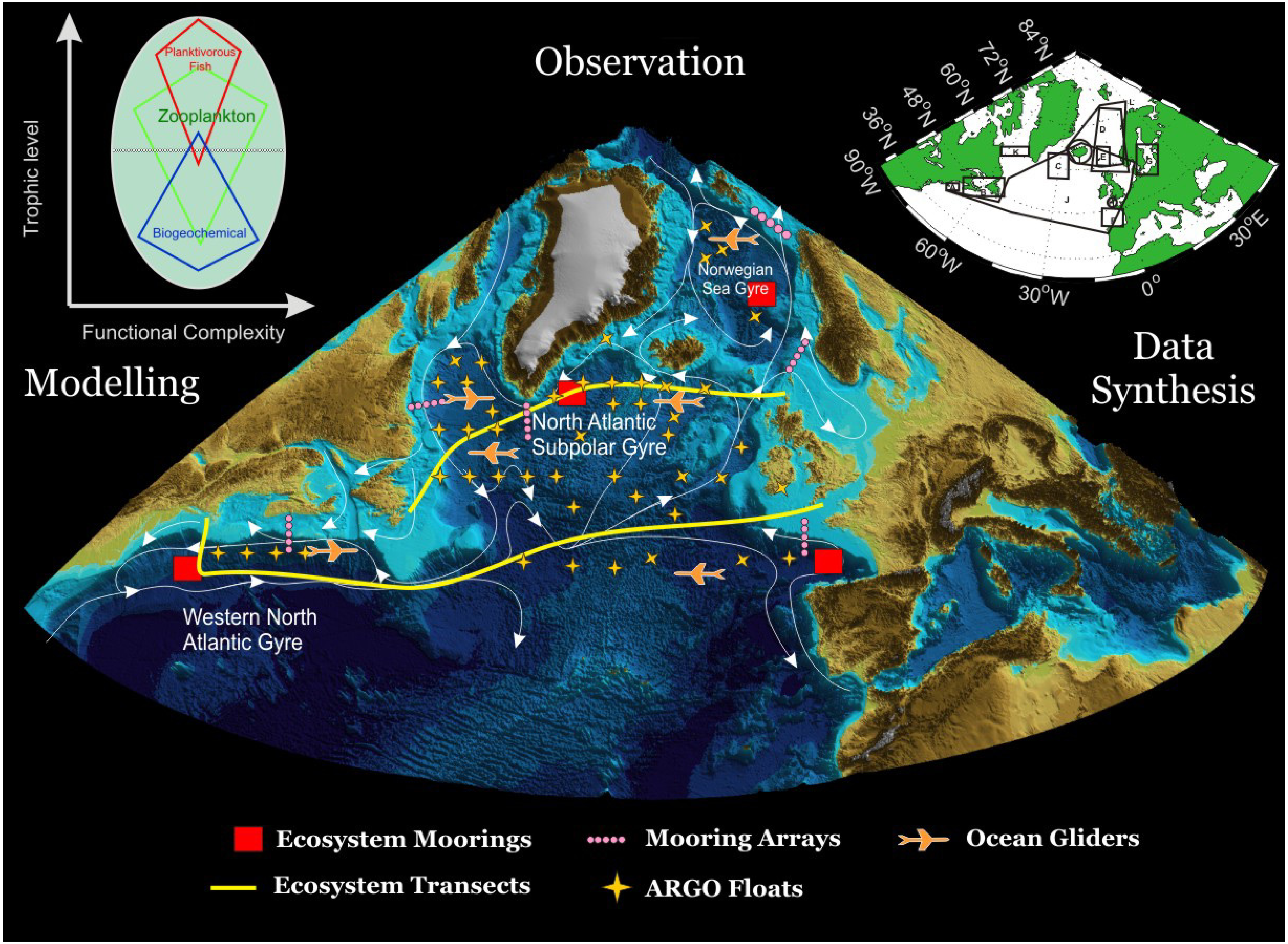
Biological consequences expected under climatic warming Or changes in water mass structure.

- Changes in the range and spatial distribution of species.
- Shifts in the location of biogeographical boundaries, provinces, and biomes.
- Change in the phenology of species (e.g. earlier reproductive season).
- Modification in dominance (e.g. a key species can be replaced by another one).
- Change in diversity.
- Change in other key functional attributes for marine ecosystems.
- Change in structure and dynamics of ecosystem with possible regime shifts.

Expected Result: Major impact for marine exploited resources and biogeochemical processes (e.g. sequestration of CO_2 by the ocean).

Research Goals

- Integrate and synthesize existing basin-wide data sets from previous programs in Europe and North America,
- Improve the current state of the art in bio-physical modelling,
- Develop hindcast modelling studies to understand the observed historical variability of the North Atlantic ecosystem,
- Construct scenarios of possible ecosystem changes in response to future climate variability,
- Identify data gaps that limit process understanding and contribute to uncertainty in model results,
- Specify new data needed to assess the performance of forecasts,
- Provide relevant information to resource managers and decision makers.


Observation
Modelling
Data Synthesis
Trophic level
Functional Complexity
Planktivorous Fish
Zooplankton
Biogeochemical
84°N
72°N
60°N
48°N
36°N
90°W
60°W
30°W
0°
30°E
Norwegian Sea Gyre
North Atlantic Subpolar Gyre
Western North Atlantic Gyre
🟥 Ecosystem Moorings
Mooring Arrays
Ocean Gliders
Ecosystem Transects
ARGO Floats

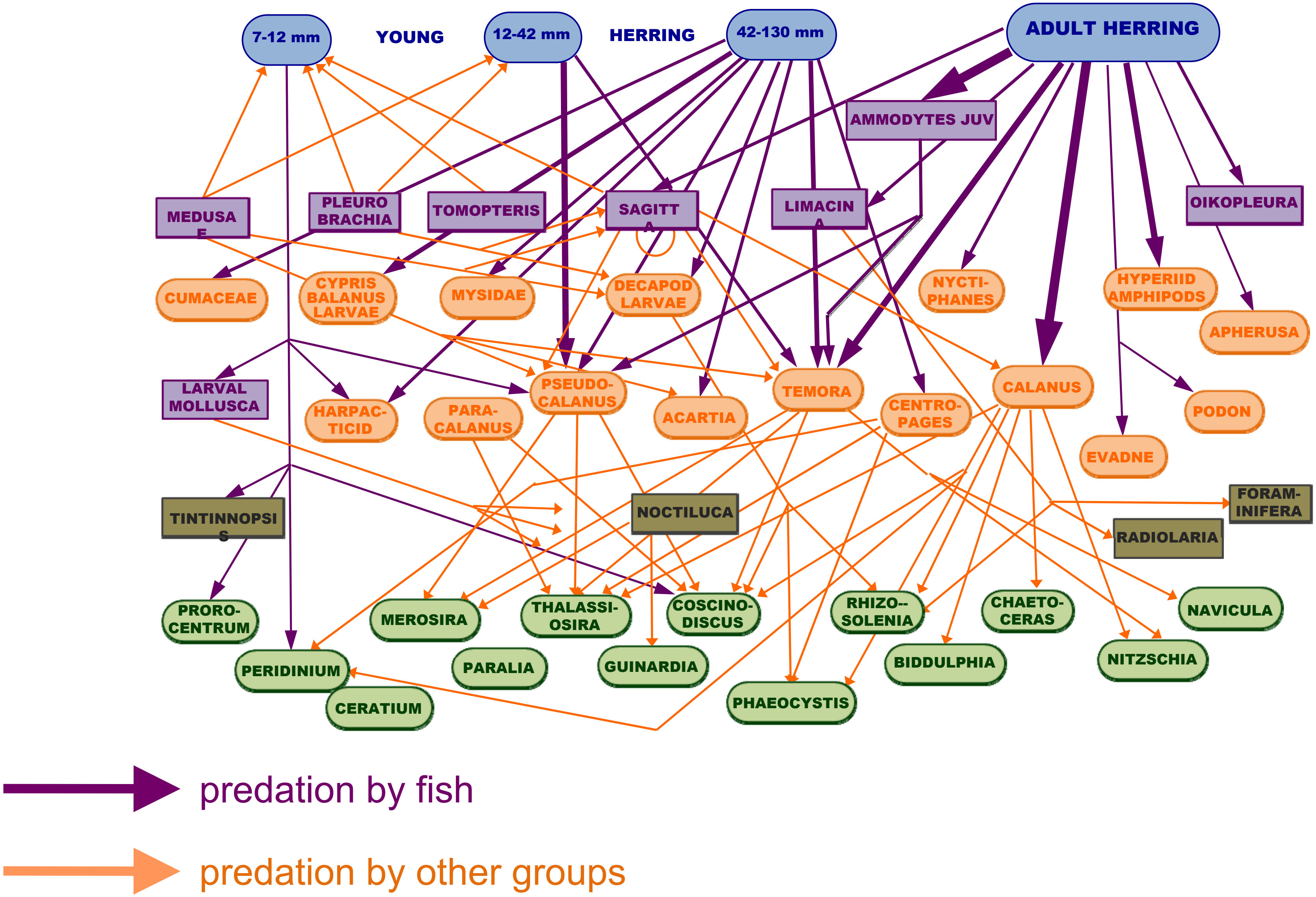
Coleen Moloney

What did we learn about marine food webs during the GLOBEC era?

We learnt that...

1. marine food webs are special

Food web supporting herring in the North Sea

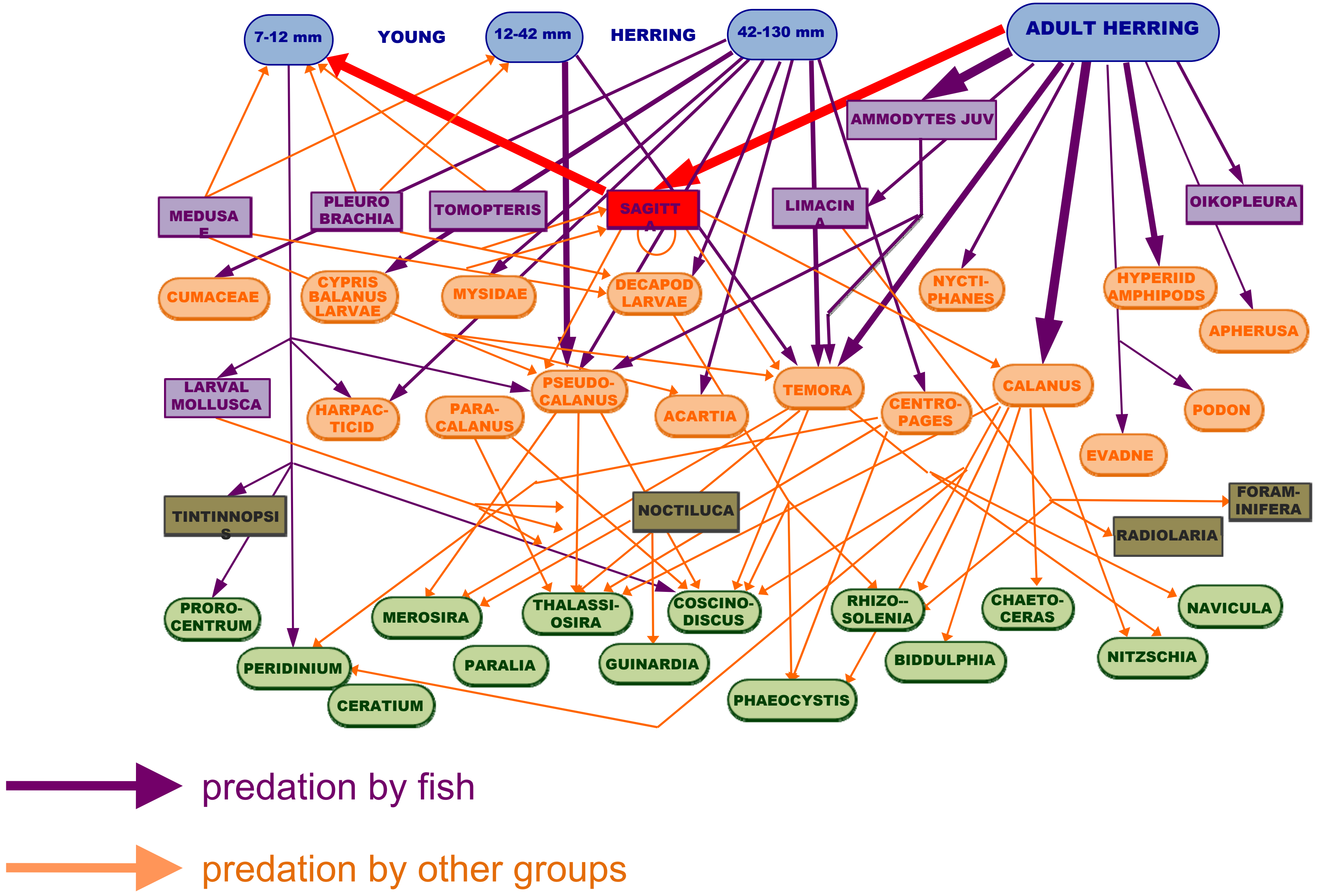


predation by fish

predation by other groups

Hardy (1924), adapted from Elton (1927)

Food web supporting herring in the North Sea


7-12 mm
YOUNG
12-42 mm
HERRING
42-130 mm
ADULT HERRING
AMMODYTES JUV
MEDUSAE
PLEUROBRACHIA
TOMOPTERIS
SAGITTA
LIMACINA
OIKOPLEURA
CUMACEAE
CYPRIS BALANUS LARVAE
MYSIDAE
DECAPOD LARVAE
NYCTIPHANES
HYPERIID AMPHIPODS
APHERUSA
LARVAL MOLLUSCA
HARPACTICID
PARACALANUS
PSEUDOCALANUS
ACARTIA
TEMORA
CENTROPAGES
CALANUS
PODON
EVADNE
TINTINNOPSIS
NOCTILUCA
FORAMINIFERA
RADIOLARIA
PROROCENTRUM
MEROSIRA
THALASSIOSIRA
COSCINODISCUS
RHIZOSOLENIA
CHAETOCERAS
NAVICULA
PERIDINIUM
PARALIA
GUINARDIA
BIDDULPHIA
NITZSCHIA
CERATIUM
PHAEOCYSTIS

predation by fish

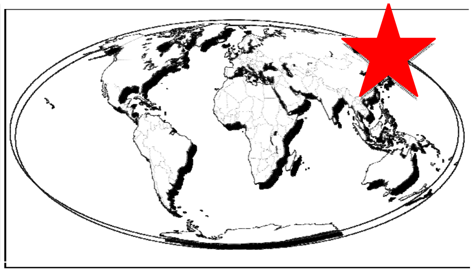
predation by other groups

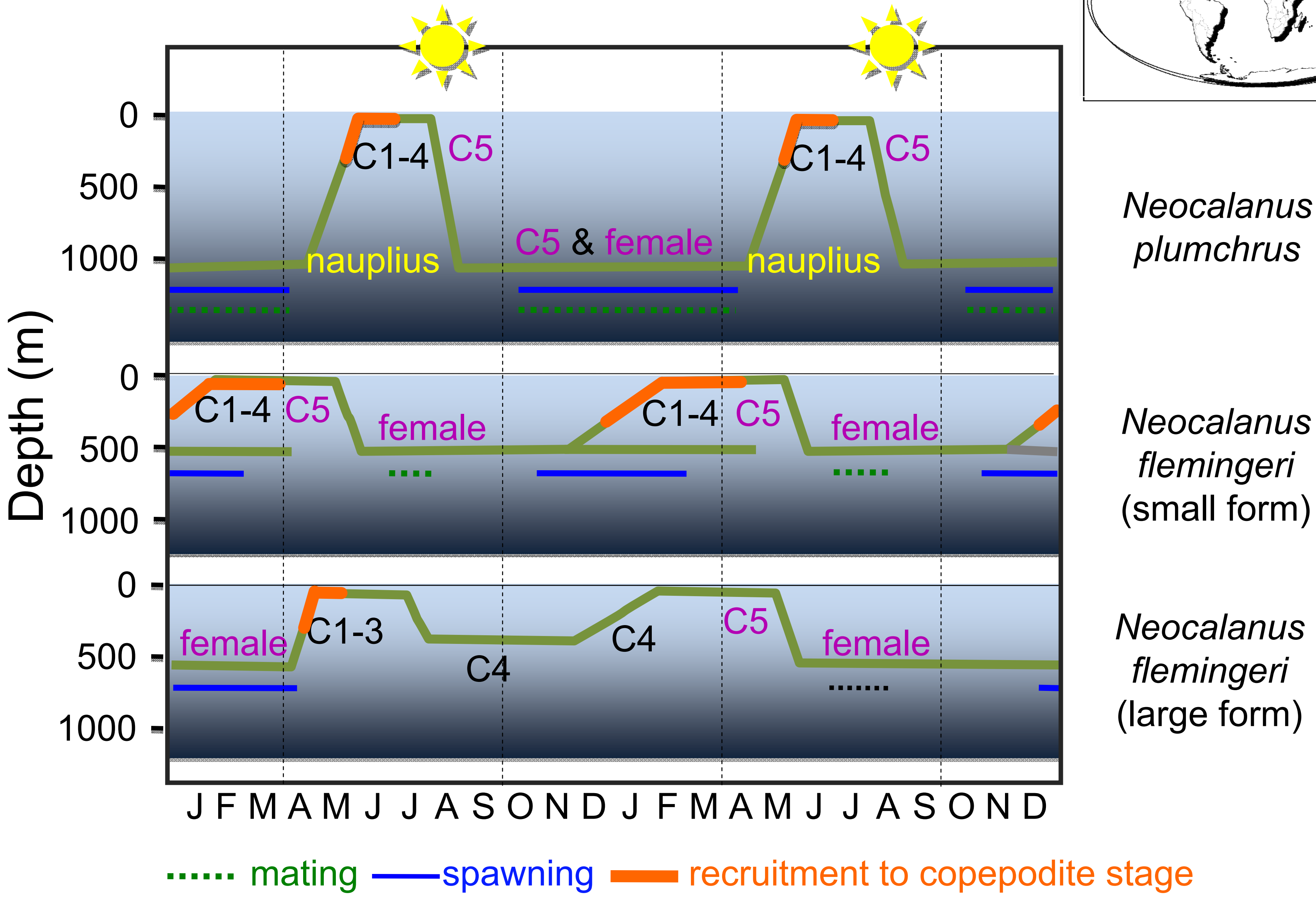
Hardy (1924), adapted from Elton (1927)

We learnt that...

1. marine food webs are special
2. population-level processes are important in food web dynamics (target-species approach)

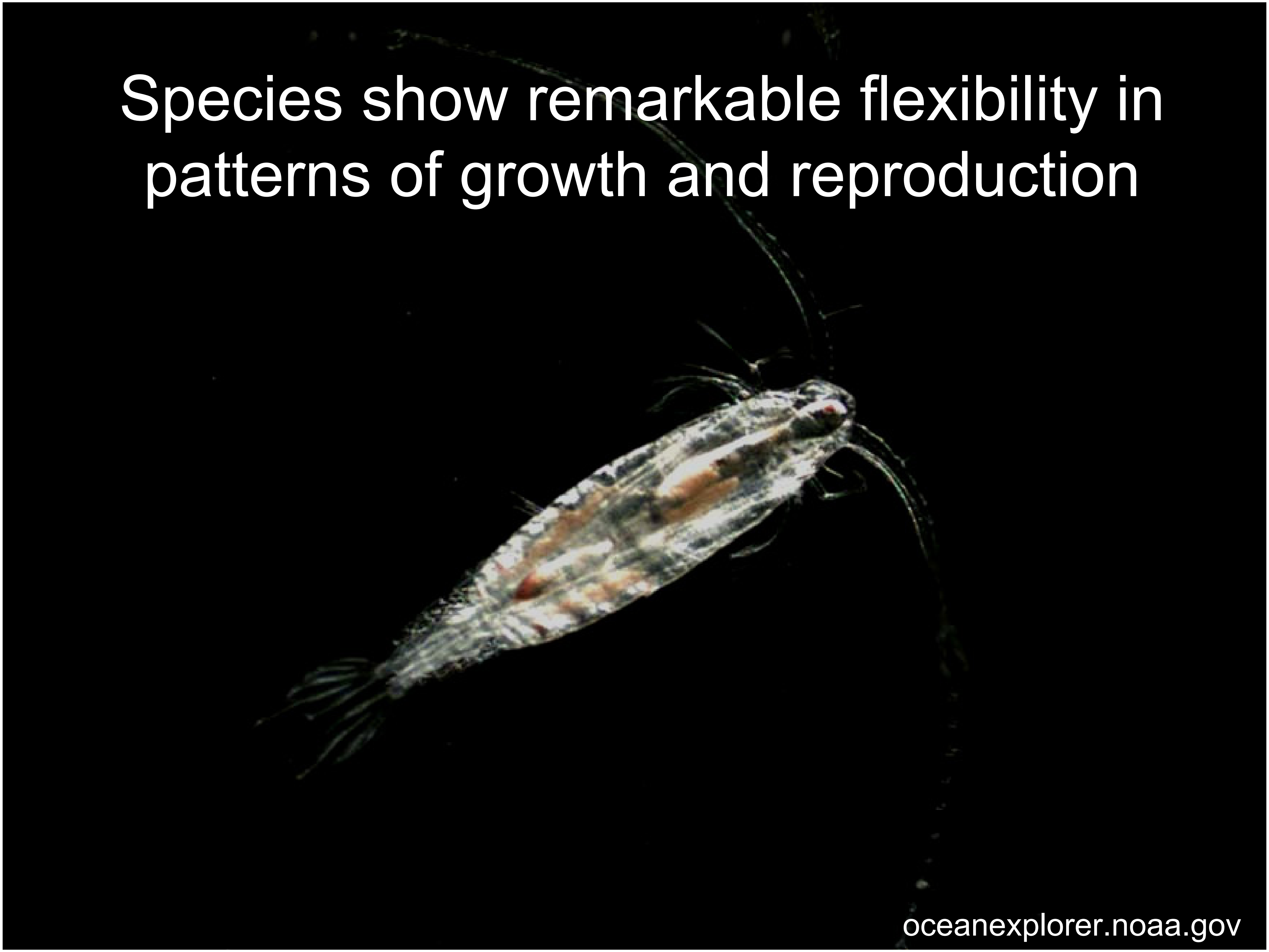
Population-level processes: adaptability





modified from Tsuda *et al.* (1999) *Mar. Biol.* 135: 533

Species show remarkable flexibility in patterns of growth and reproduction



oceanexplorer.noaa.gov

We learnt that...

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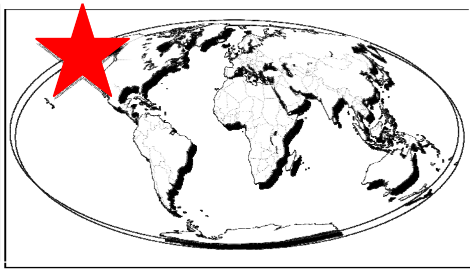
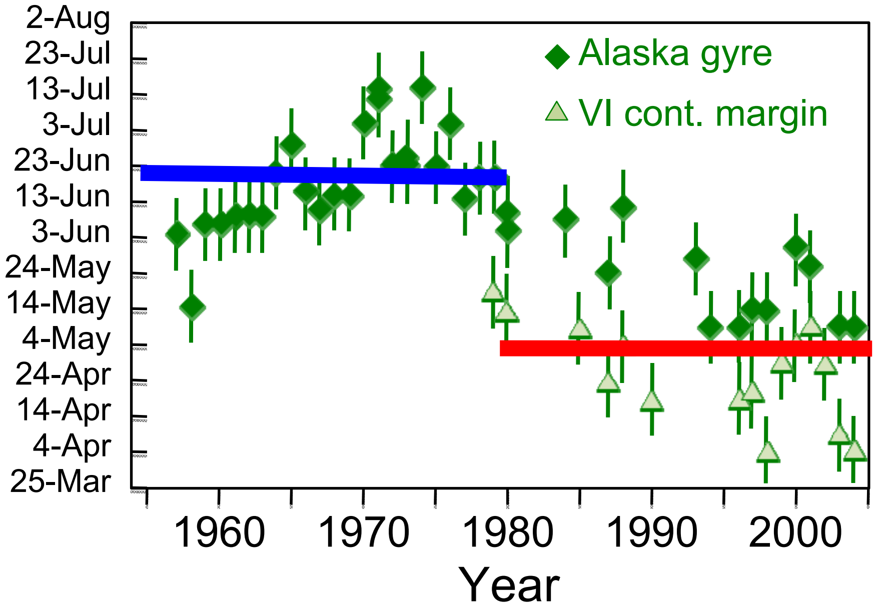
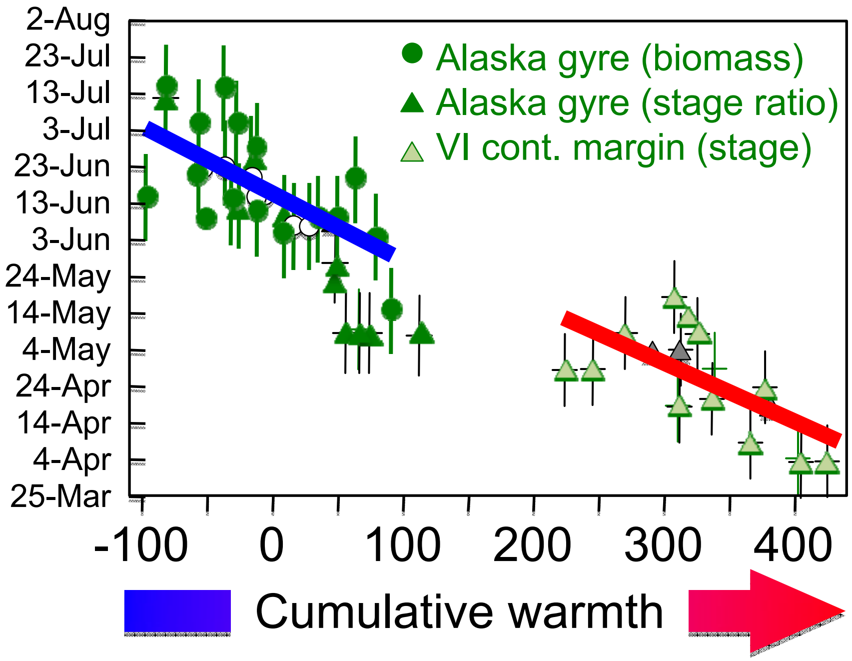
2. population-level processes are important in food web dynamics (target-species approach)
3. long time series allow(ed) patterns to be identified (and processes inferred)

Changes in seasonal timing: pattern to process



Dates at which *Neocalanus plumchrus* reaches its annual biomass maximum





warm water = early biomass peak

Mackas *et al.* (1998) Can. J. Fish. Aquat. Sci. 55: 1878; Mackas *et al.* (2007) *Prog. Oceanogr.* 75: 223

Changes in timing have unknown effects through the food web

oceanexplorer.noaa.gov

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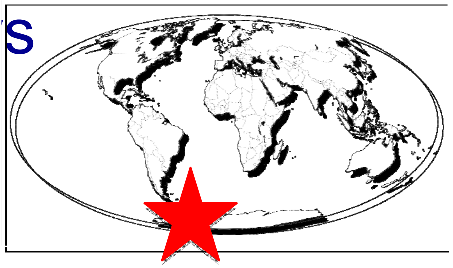
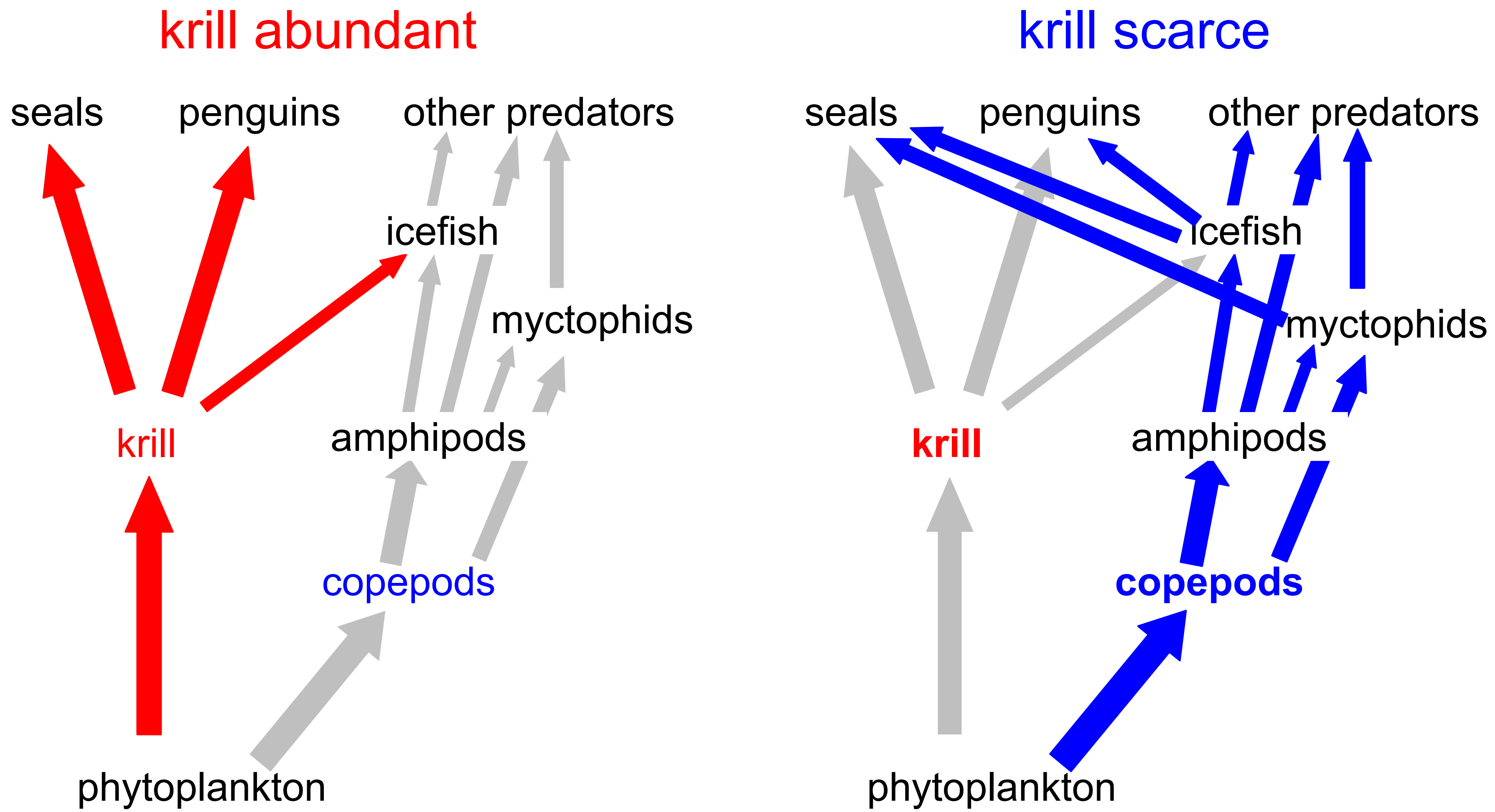
3. long time series allow(ed) patterns to be identified (and processes inferred)
4. food web structure varies on different scales

Changes in structure: alternative food web pathways



Scotia Sea



krill abundant

seals
penguins
other predators
icefish
myctophids
krill
amphipods
copepods
phytoplankton

krill scarce

seals
penguins
other predators
icefish
myctophids
krill
amphipods
copepods
phytoplankton

Murphy *et al.* (2007) *Phil. Trans. R. Soc. B* 362: 113

Changes in structure: regime shifts

Regions for which ecosystem regime shifts have been documented

Jarre and Shannon (*in press*) GLOBEC synthesis

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Food web dynamics: trophic controls

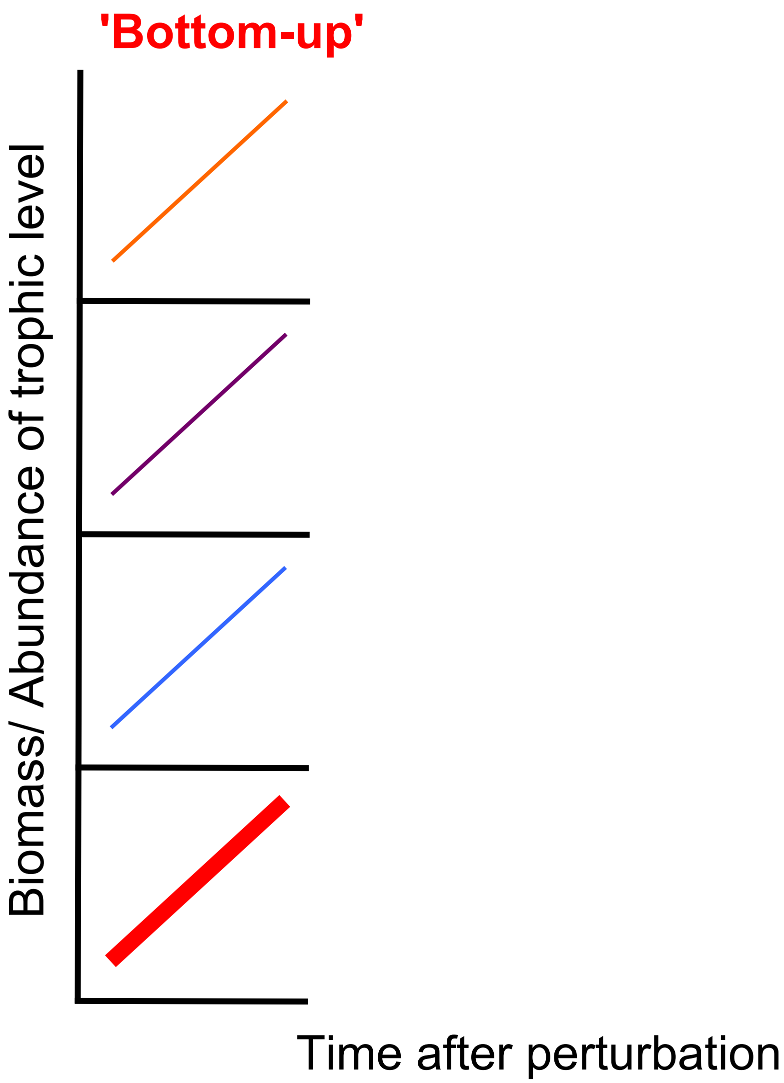
Trophic level
(taxa)

IV
Top Predator
(large fish)

III
Level 1 Predator
(small fish)

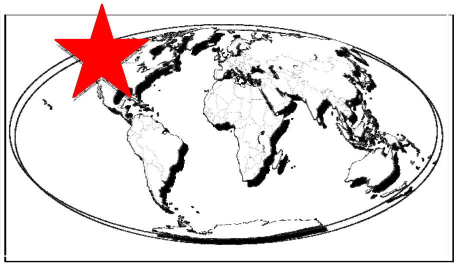
II
Herbivore
(copepod)

I
Primary producer
(phytoplankton)



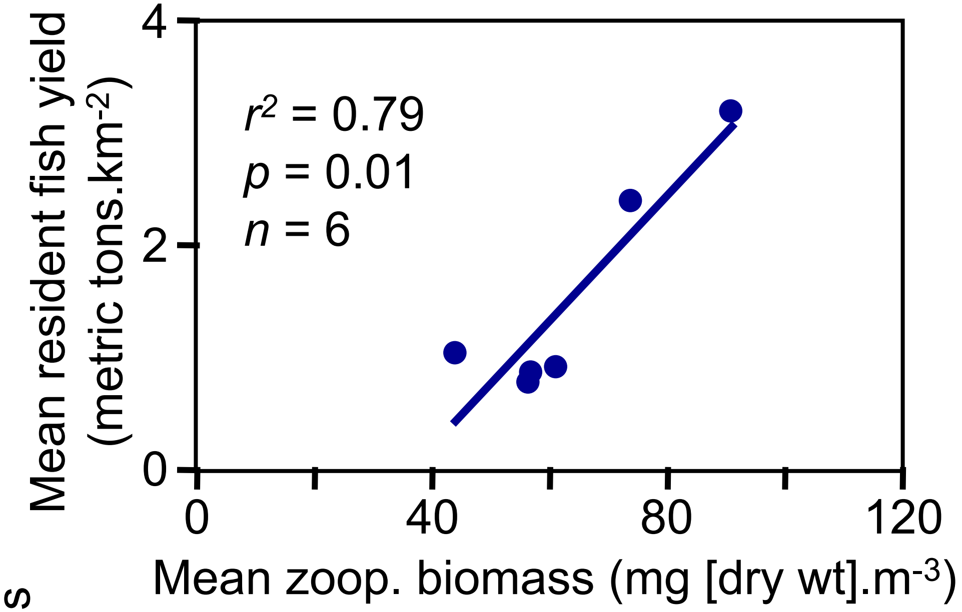
Mackas (in press, GLOBEC synthesis), based on Cury *et al.* (2001) and McQueen *et al.* (1986)

Bottom-up trophic control

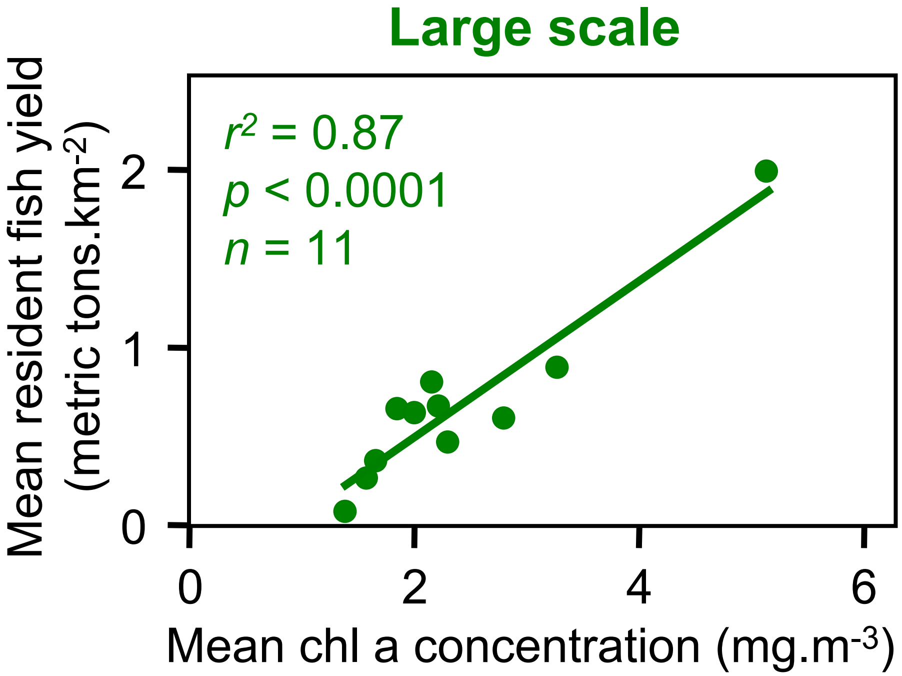


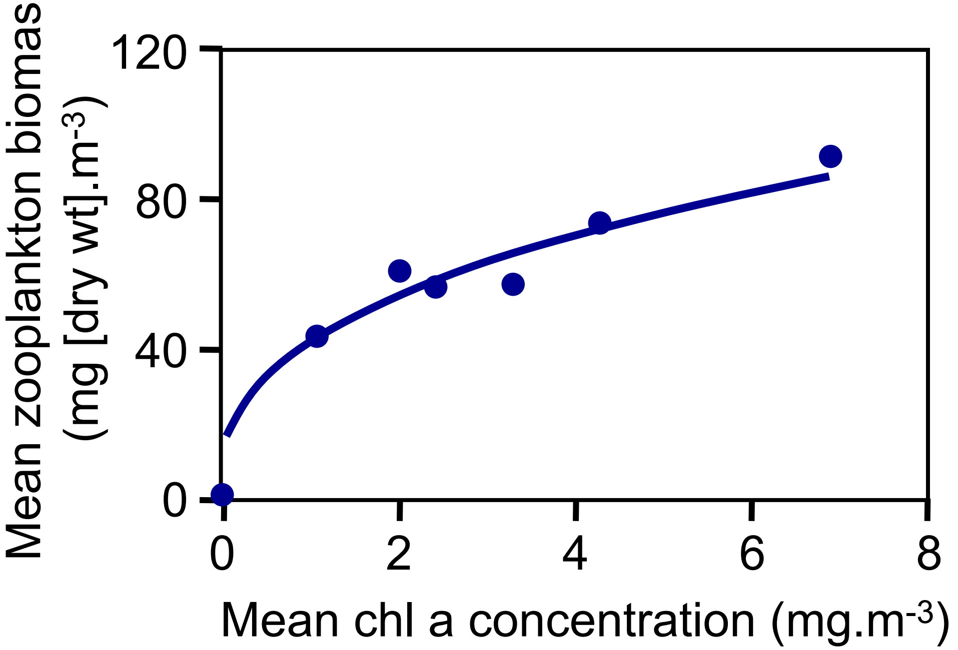
Continental margin areas, NE Pacific

Small scale



Large scale





Ware and Thompson (2005) *Science* 308: 1280-1284

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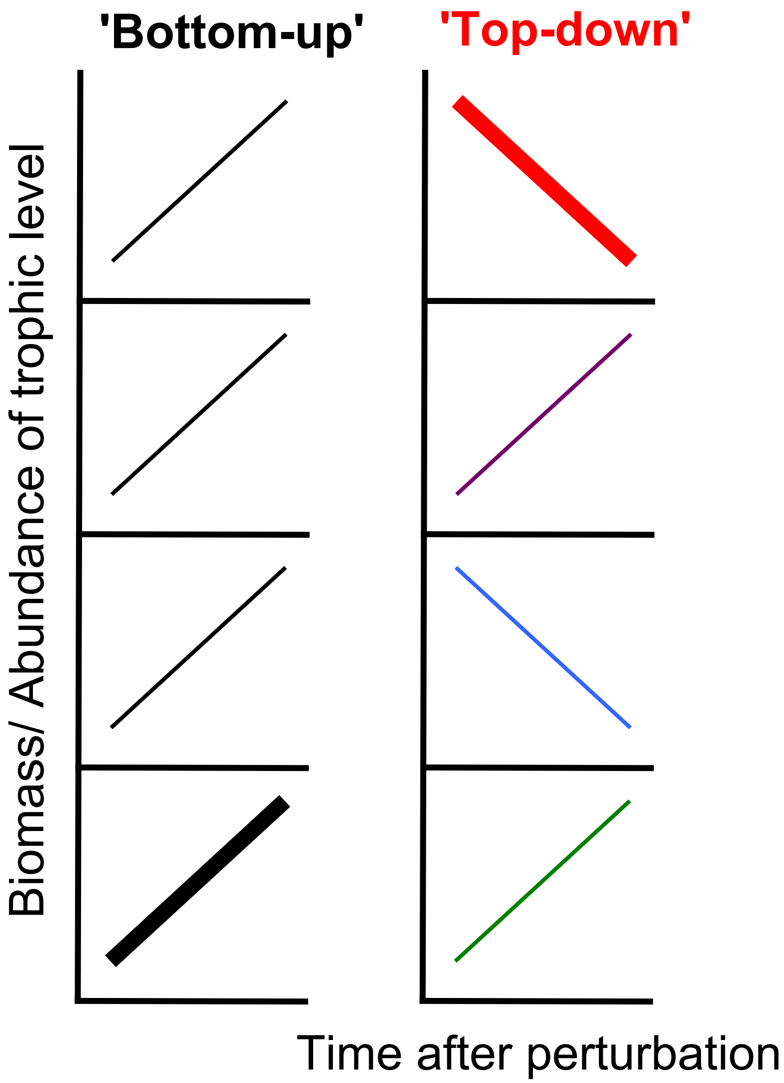
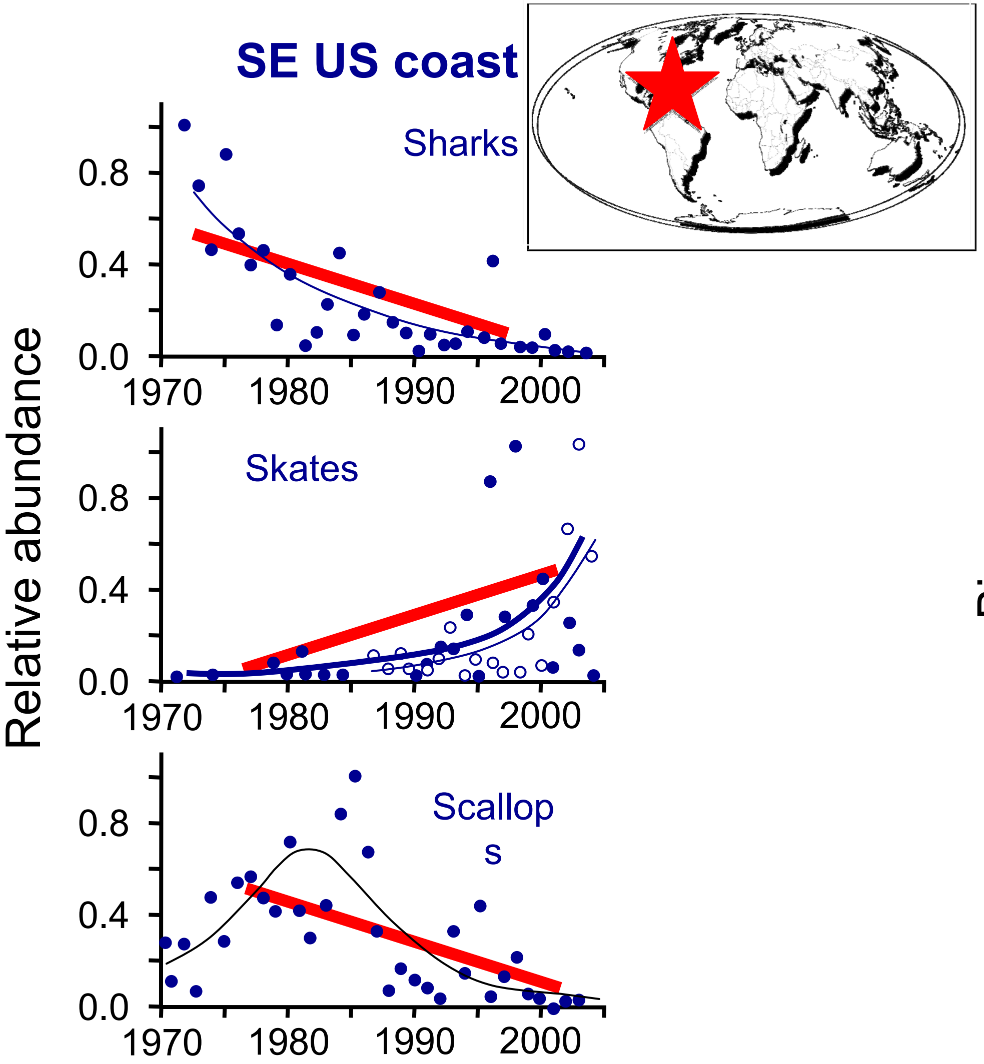


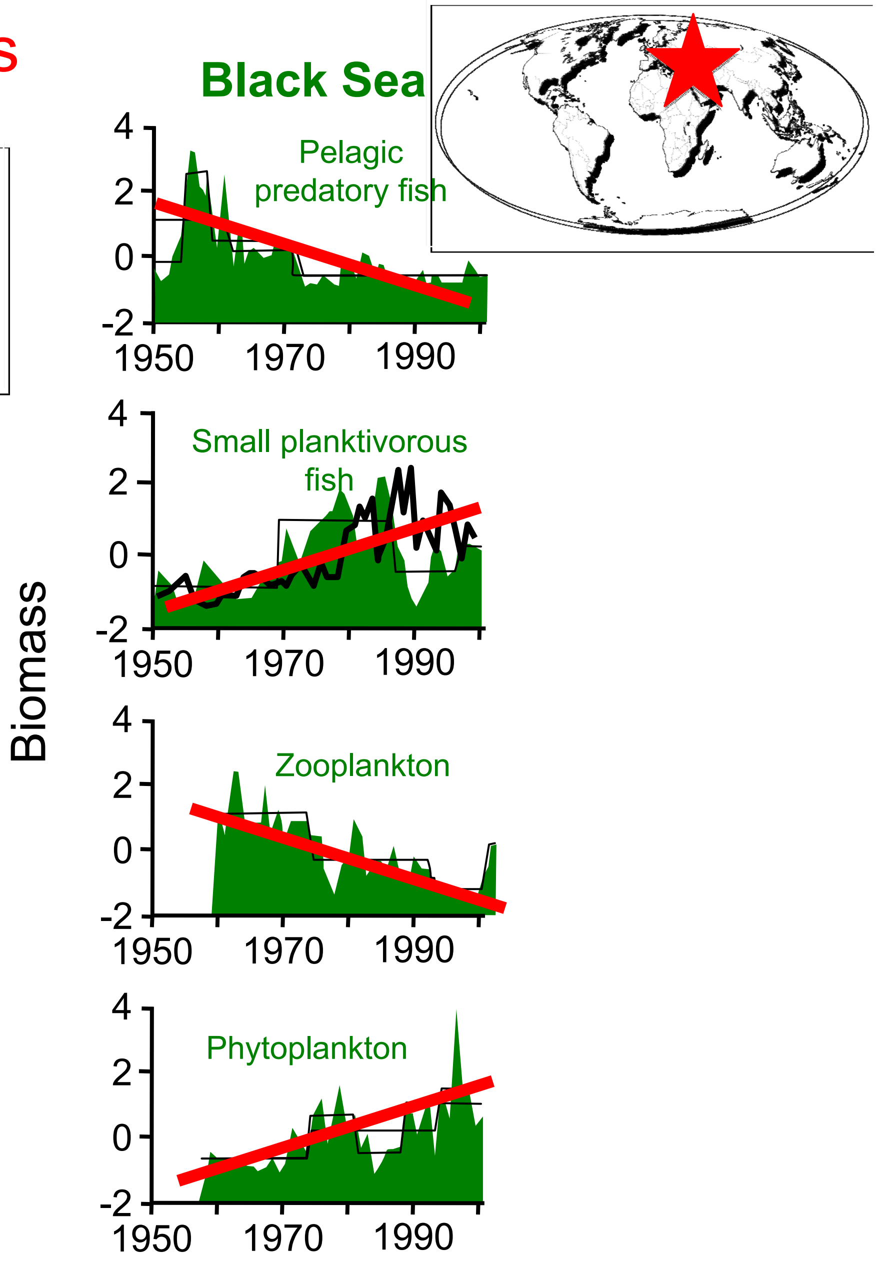
trophic
cascades

Mackas (in press, GLOBEC synthesis), based on Cury *et al.* (2001) and McQueen *et al.* (1986)

Top-down control – trophic cascades

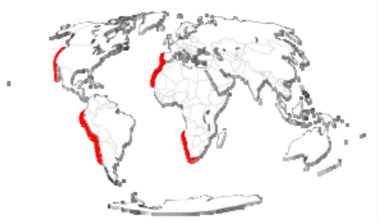


Myers *et al.* (2008)
Science 315: 1846-1850



Daskalov *et al.* (2007)
PNAS 104: 10518-10523

Food web dynamics: trophic controls



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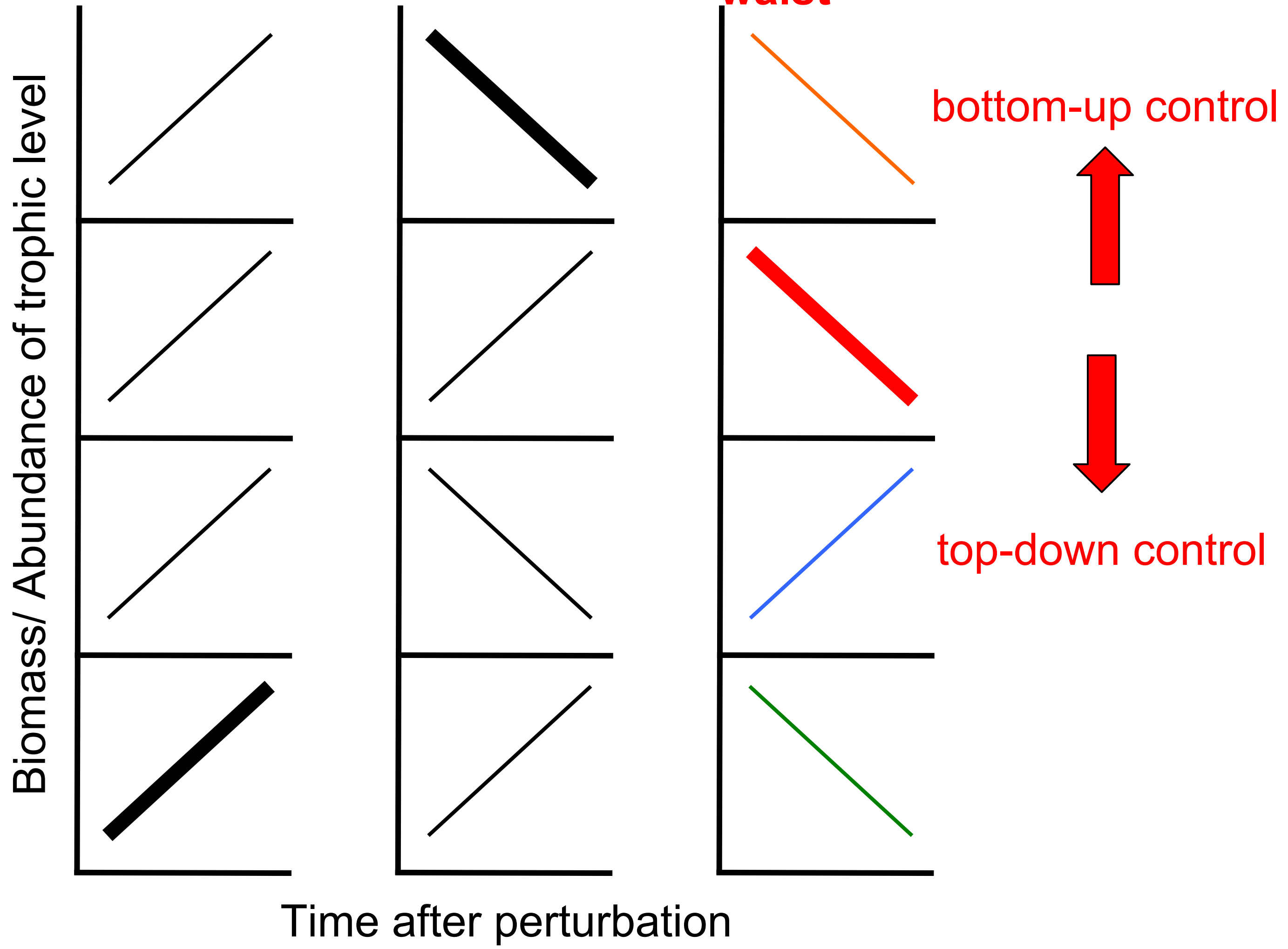
Primary producer
(phytoplankton)

'Bottom-up' **'Top-down'** **'Wasp-waist'**



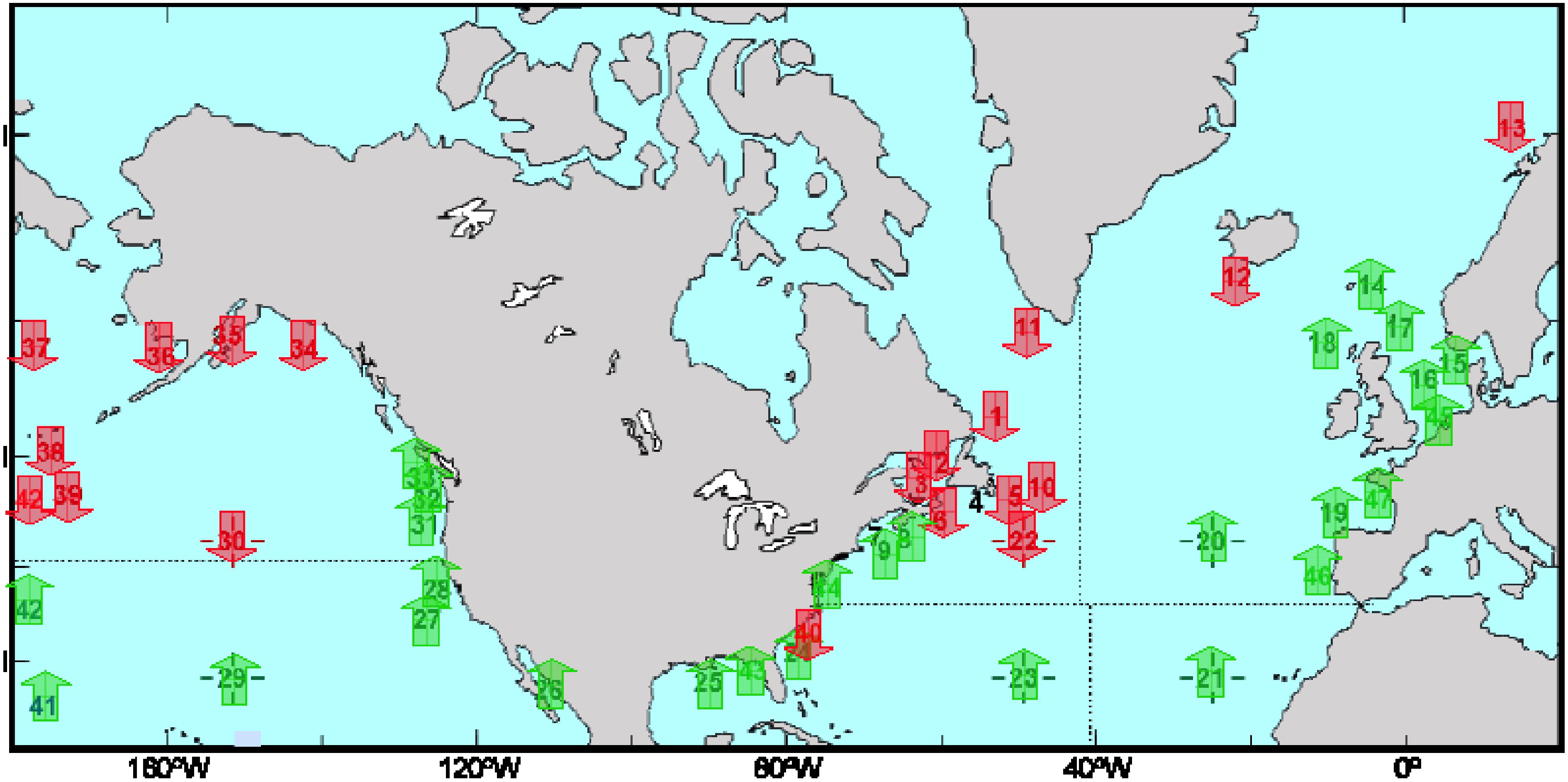
Mackas (in press, GLOBEC synthesis), based on Cury *et al.* (2001) and McQueen *et al.* (1986)

Trophic controls are situation-dependent

- they vary in space...

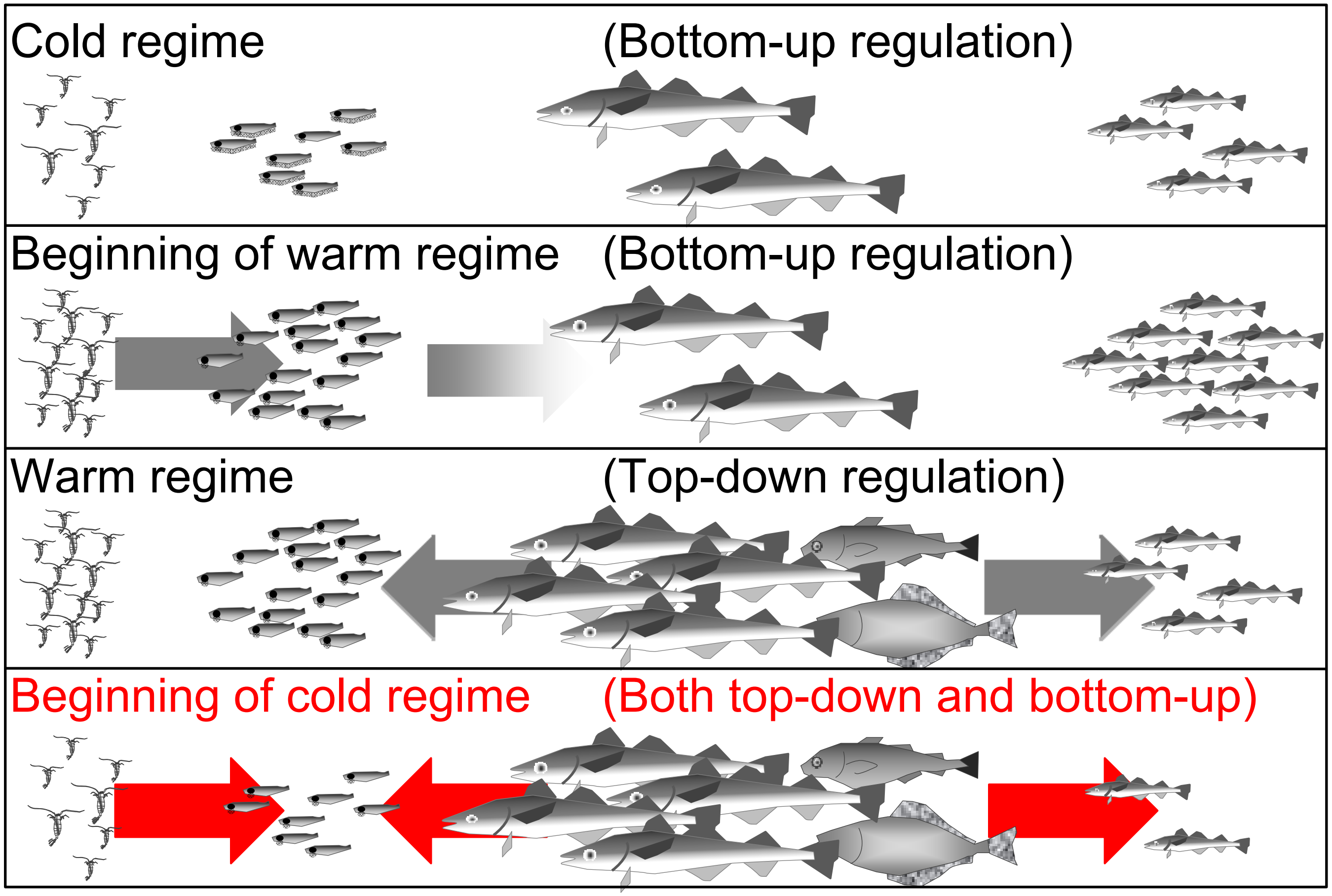
- and they vary in time...

Latitutudinal gradient in trophic controls
Analysis of 47 systems



Frank (pers. comm.), Frank *et al.* (2006). Ecol. Letters 9: 1096-1105.

Oscillating control – Bering Sea



Zooplankton

Larval survival

Abundance of piscivorous fish

Juvenile recruits

Hunt *et al.* (2002). *Deep-Sea Res. II* 49: 5821-5853

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3. long time series allow(ed) patterns to be identified (and processes inferred)
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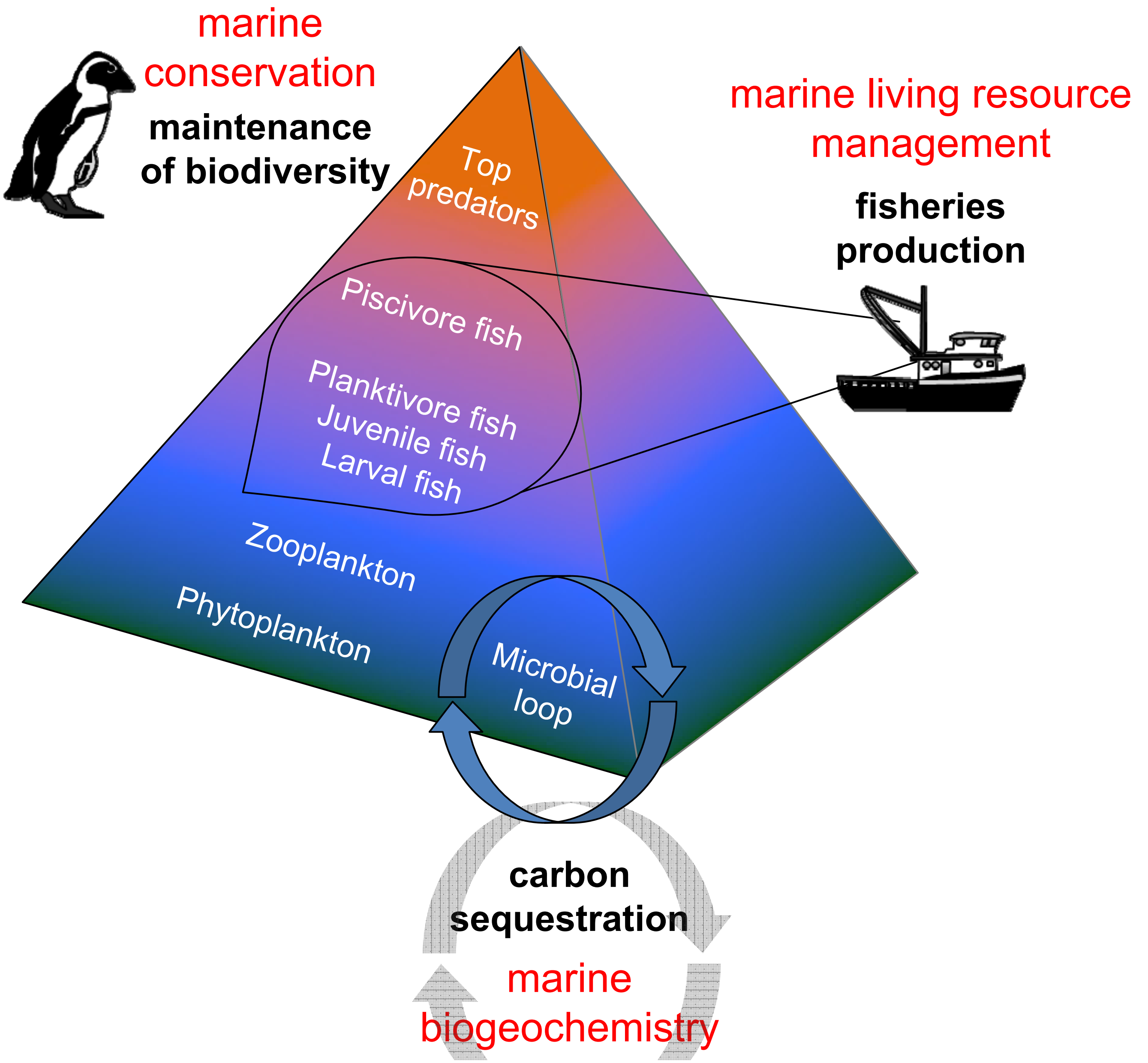
5. food web dynamics vary among regions
6. food webs should be understood from end to end

Why study marine food webs end to end?



marine conservation

maintenance of biodiversity

marine living resource management

fisheries production

carbon sequestration

marine biogeochemistry

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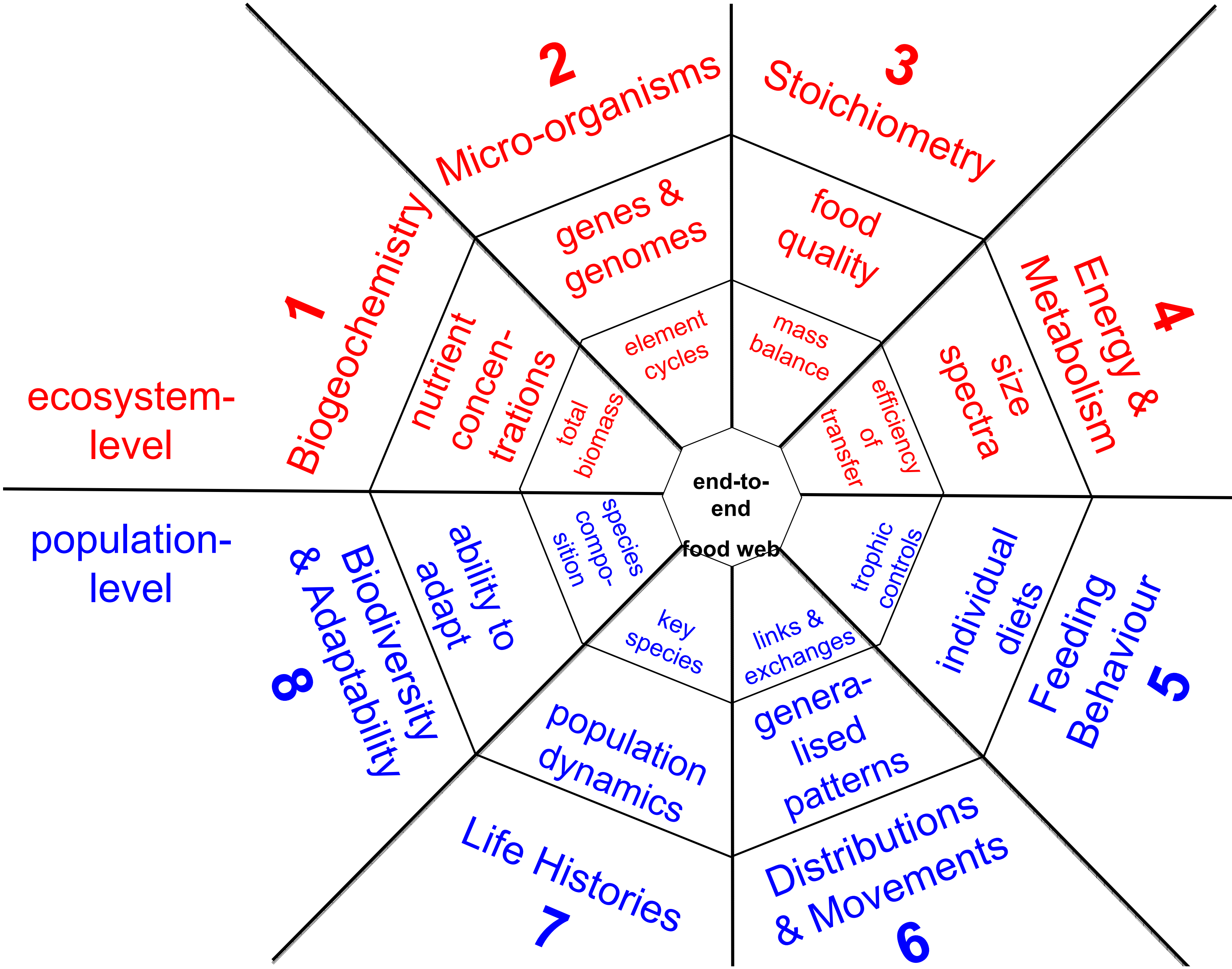
4. food webs can change from one state to another
5. food web dynamics vary among regions
6. food webs should be understood from end to end
7. innovation is needed to deal with the complexity of marine food webs

Research framework for end-to-end food webs



ecosystem-level

1 Biogeochemistry

nutrient concentrations

total biomass

2 Micro-organisms

genes & genomes

element cycles

3 Stoichiometry

food quality

mass balance

4 Energy & Metabolism

size spectra

efficiency of transfer

end-to-end food web

population-level

5 Feeding Behaviour

individual diets

trophic controls

6 Distributions & Movements

generalised patterns

links & exchanges

7 Life Histories

population dynamics

key species

8 Biodiversity & Adaptability

ability to adapt

species composition

Moloney, St John *et al.* (submitted)

	North Pacific		Coral - Jamaica		North Sea	
	Drivers	**Response**	**Drivers**	**Response**	**Drivers**	**Response**
	Complex physical climate (AO, PDO, ENSO)	Zooplankton to fish and mammals	Fishing Eutrophication	Species composition (urchins-algae-coral)	Oceanic (circulation temperature) atmospheric (NAO), fishing	Phytoplankton to fish
Time scale	Shift – 1-5 years Persistence – 10-20 years	Shift: 1-5 years Regime: > 10 years	Parasite (Trigger) – 1-2 years Erosion of resilience (10 year)	Shift – 1-2 years Persistence – > 20 years	Shift 1-5 years (NAO) Oceanic persistence – 10 years Erosion of resilience – > 10 years - fishing	Shift – 1-5 years Regime: > 10 years
Spatial scale	10,000 km (basin)	1,000 -2,000 km (regional)	10-100 km	10-100 km	1000 km (fishing, oceanic) to 10,000 km (atmospheric)	1000-2000 km (extends beyond North Sea)
Detect	2 years	3-5 years	< 1 year	1-2 years	2 years	2-5 years
Predict	Little skill	Following from detection	Erosion fishing impact is predictable Trigger – no	Probabilistic	Little skill, Erosion - fishing impact is predictable	Following from detection
Manage	Not possible	Fishing management after detection - adaptation	Marine management of resilience and trigger >> prevention	Marine management - rehabilitation (?)	Climate – not possible Fishing - prevention	Fishing management after detection - adaptation