Regime shifts

Thorsten Blenckner
Stockholm Resilience Centre
Stockholm University

Stockholm Resilience Centre
Research for Governance of Social-Ecological Systems
Stockholm University
A centre with: SEI Stockholm Environment Institute; The Beijer Institute of Ecological Economics
Funded by MISTRA The Swedish Foundation for Strategic Environmental Research

Structure of the talk

- Introduction
- Regime shift theory
- Test regime shifts in ecosystems
- Marine regime shifts
  - Coral reefs
  - Black Sea
  - Baltic Sea
- Baltic Sea summary in relation to other systems
- Overall conclusions

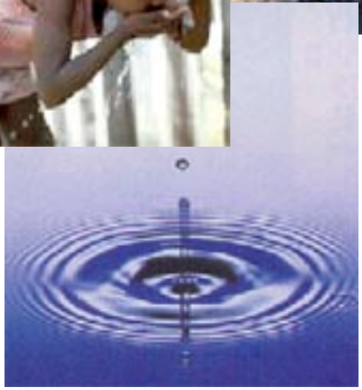




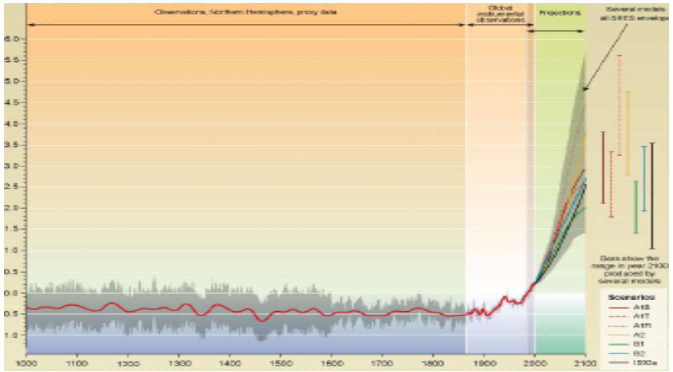




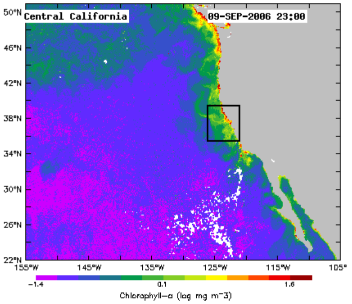




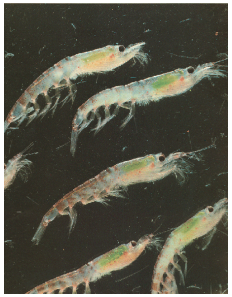
The Challenge: Sustainable Management of an Ever-Changing Planet



Observations, Northern Hemisphere, proxy data
Projections
Scenarios
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100



Central California
09-SEP-2006 23:00
50°N
46°N
42°N
38°N
34°N
30°N
26°N
22°N
155°W
145°W
135°W
125°W
115°W
105°
-1.4
0.1
1.6
Chlorophyll-a (log mg m^-3)

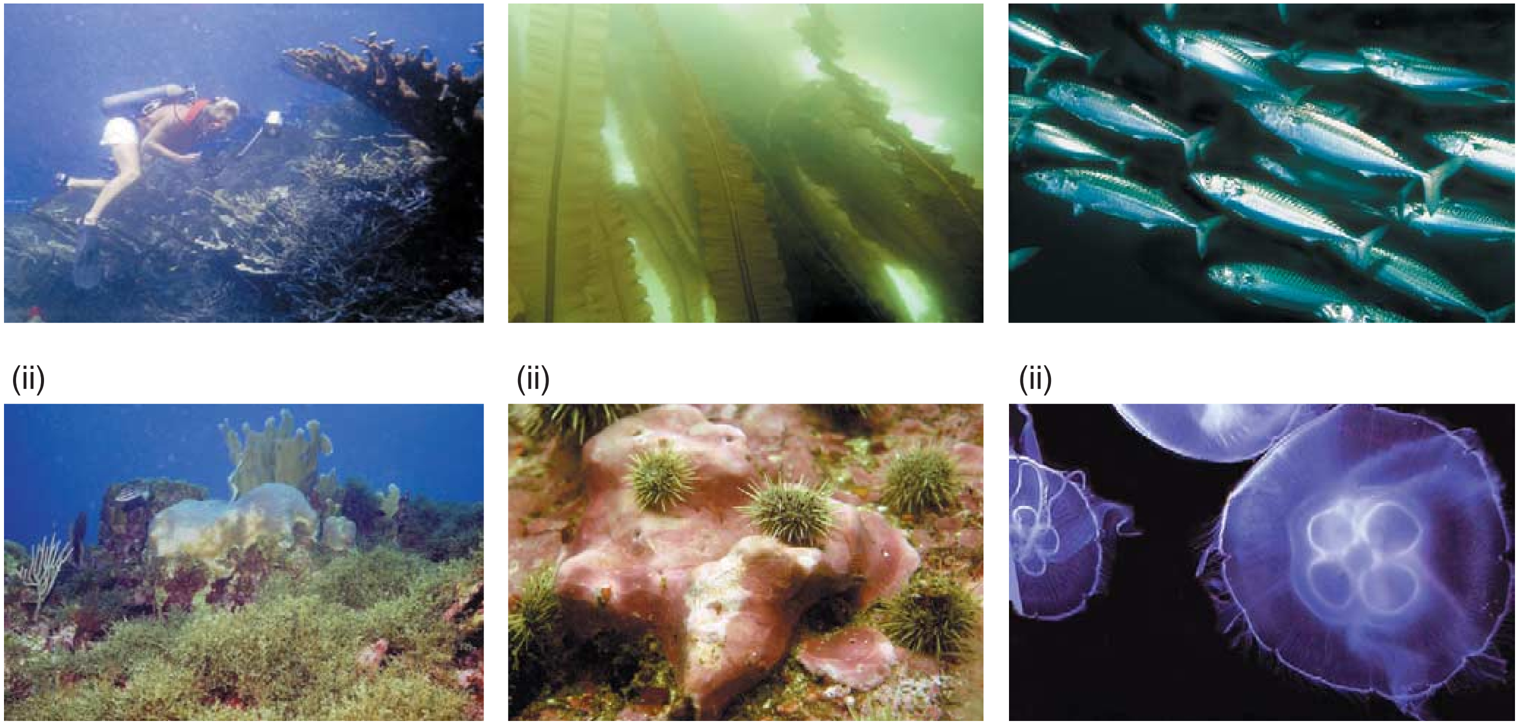


Systems can change abruptly

Coral reefs | Kelps | Black Sea

(a) (i) (b) (i) (c) (i)

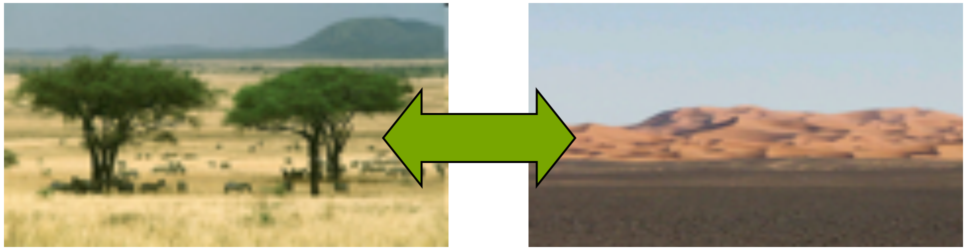
Before



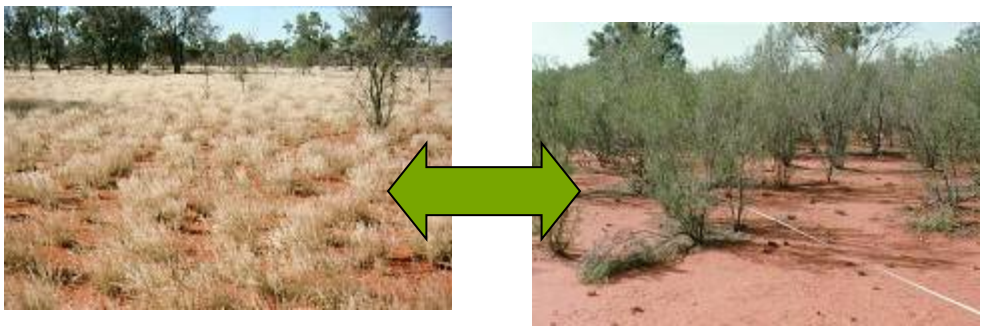
(ii) (ii) (ii)

After

Hughes et al 2005



Savanna

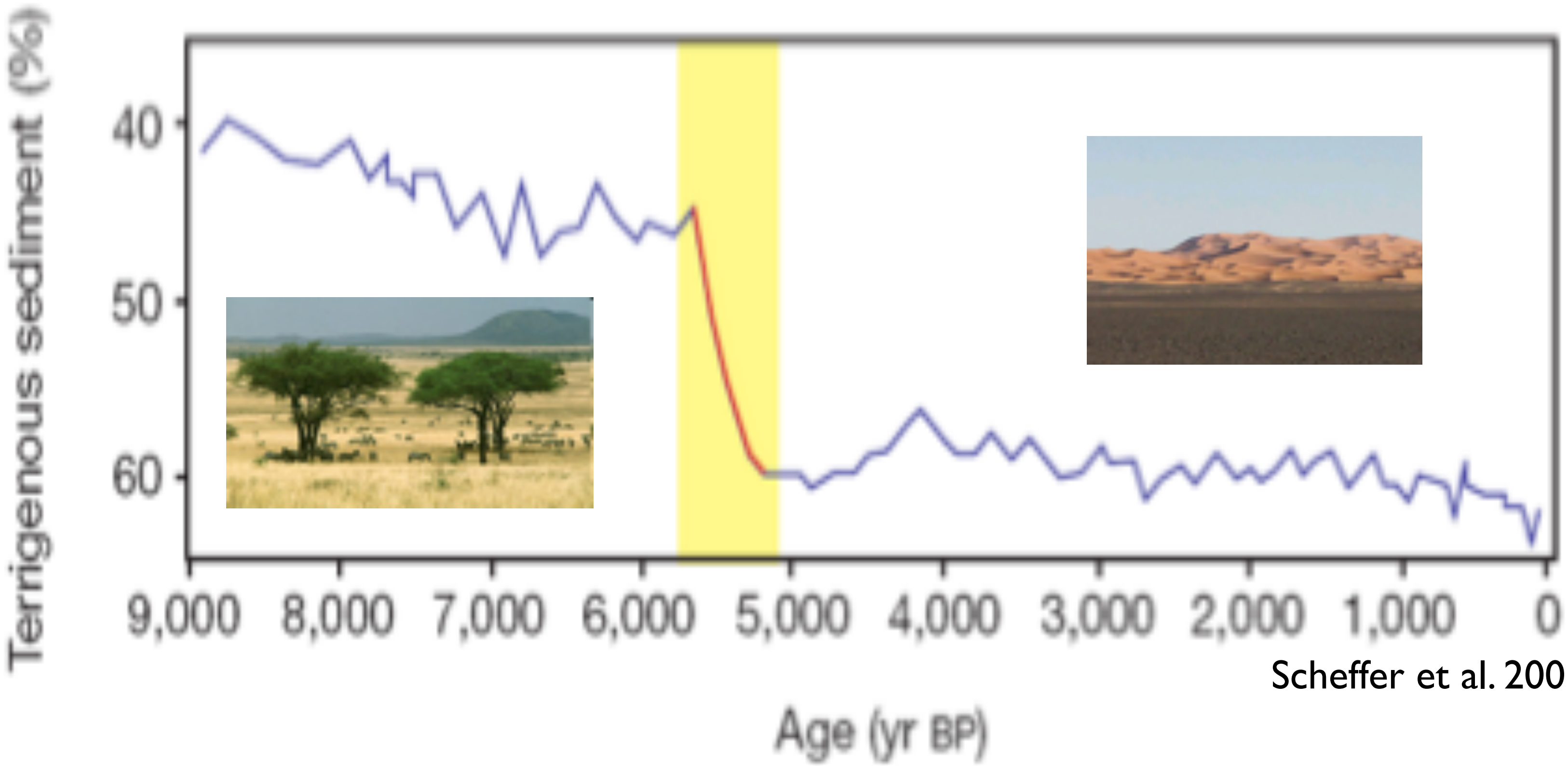


Grasslands

Tropical forests

Regime shifts can be seen empirically by jumps in time series data

Savanna to desert conditions in the Sahara



Scheffer et al. 2001 Nature

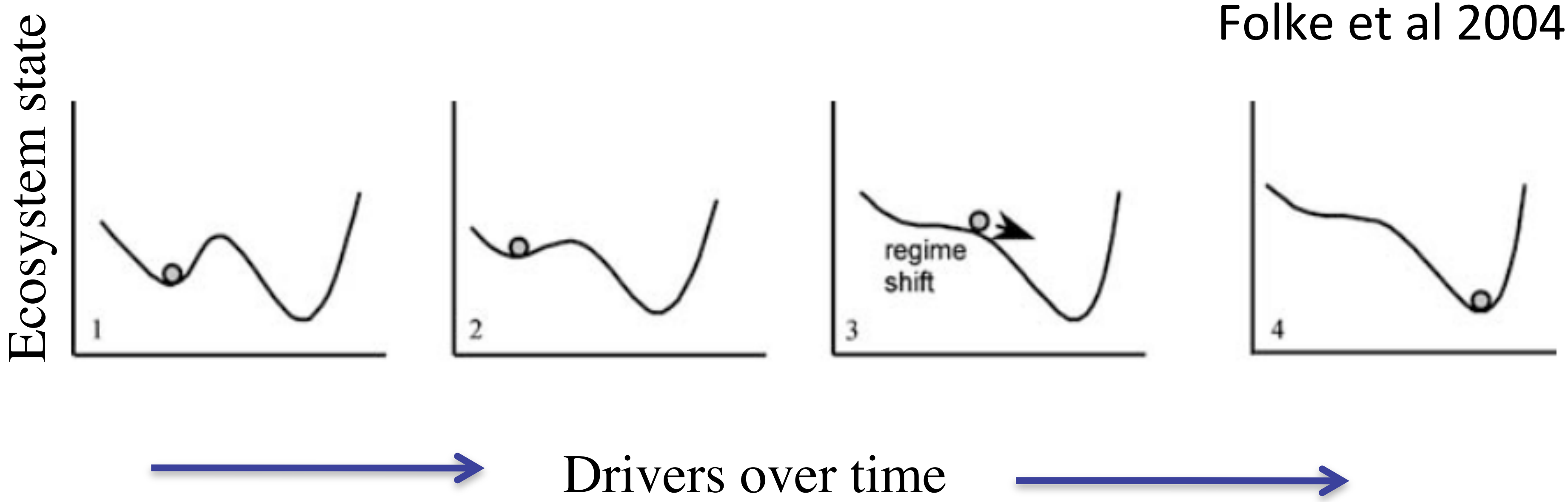
Duration of shift is rapid relative to time in each regime

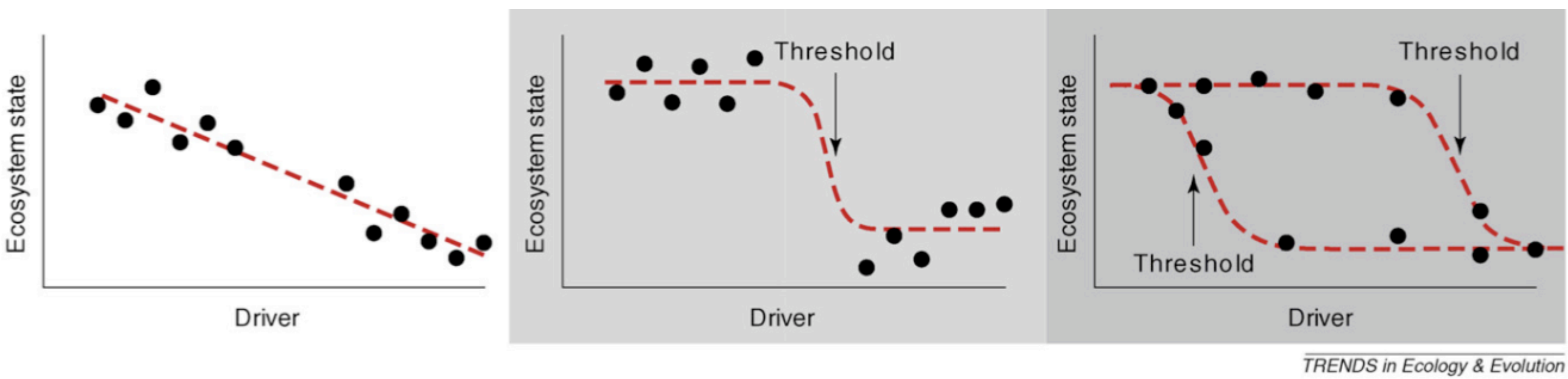
Regime shift theory

- “Sudden, large, long-lasting shifts in ecosystem structure and function”
- In ecology, is closely related to resilience.
- 1973, Holling defined resilience as the ability of a system to persist in a particular domain of attraction rather than being pushed into a different domain – i.e., the ability to withstand a regime shift.
- *alternative stable states* or *multiple equilibria*
- "the ability of a system to internally switch between different self reinforcing processes that dominate how the system functions” (Cumming & Norberg 2008)

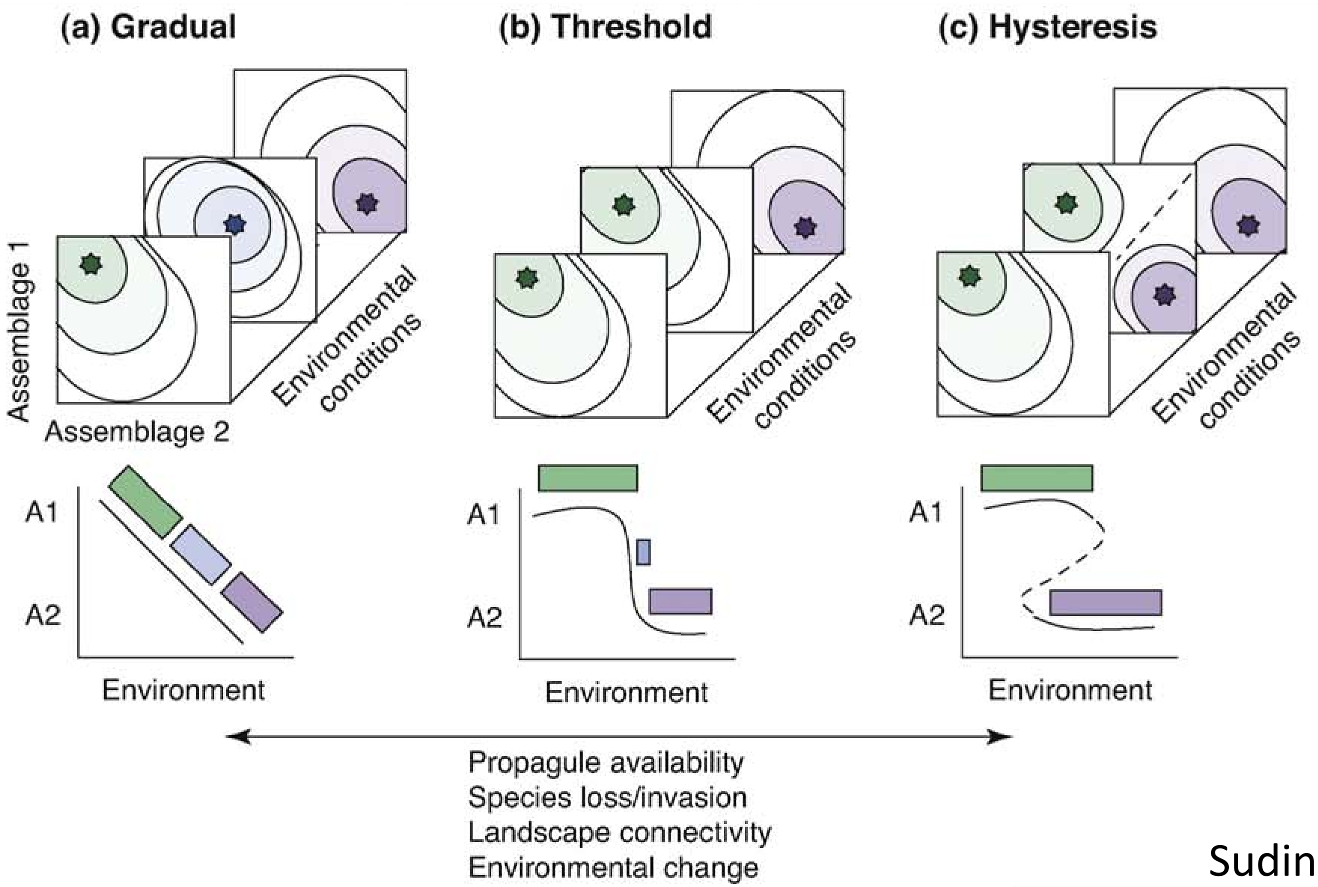
Concept: Regime shifts

Folke et al 2004





Strengths of Feedbacks
Gradual, threshold, hysteresis
Locked regime states ?

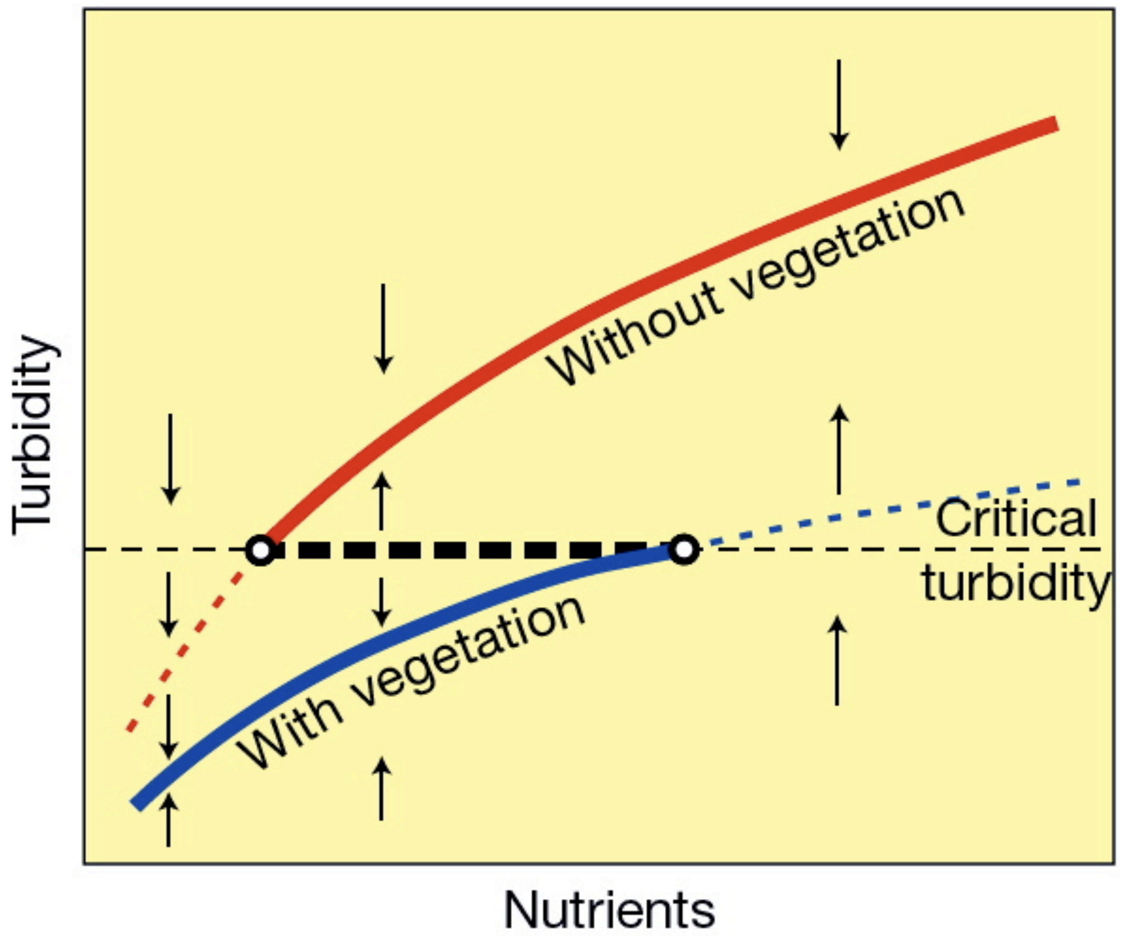


Suding & Hobbs 2009

Can we find this in real ecosystems ?

Lake Eutrophication I

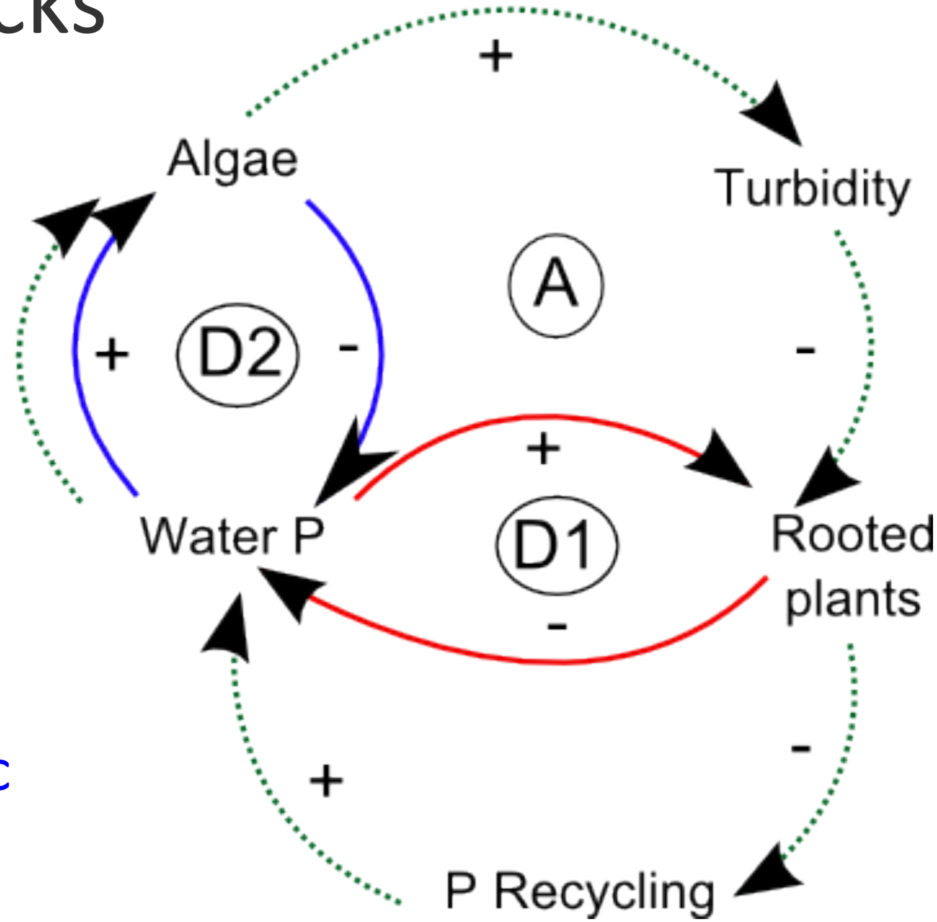
Ecosystem State



Scheffer et al 2001

Lake Eutrophication II

Feedbacks



Dominant feedback in clear water regime

Dominant feedback in turbid regime

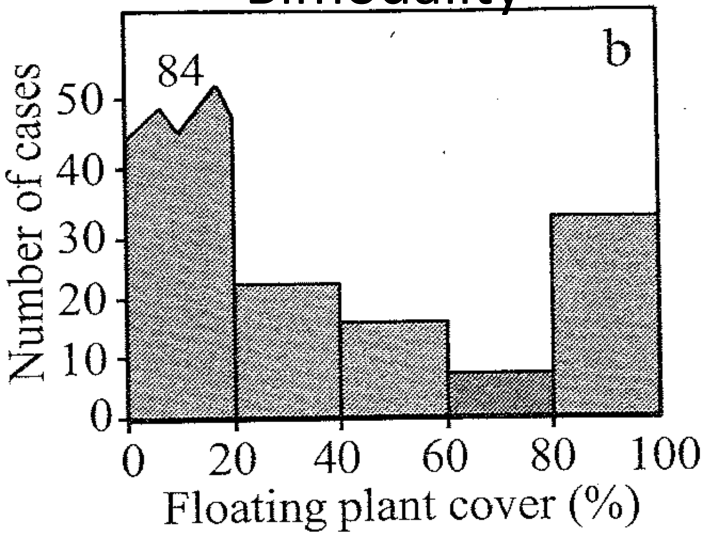
Amplifying feedback that reinforces turbid regime

Competition between benthic vs. pelagic positive feedbacks

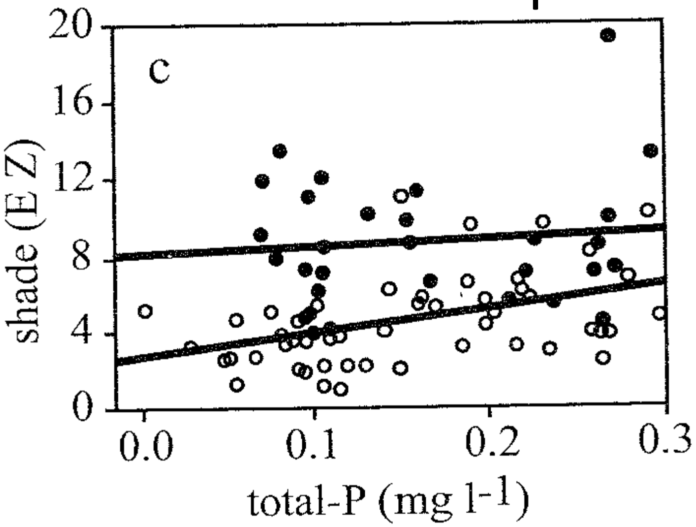
(Bennett et al 2005; Biggs et al 2012)

Lake Eutrophication III

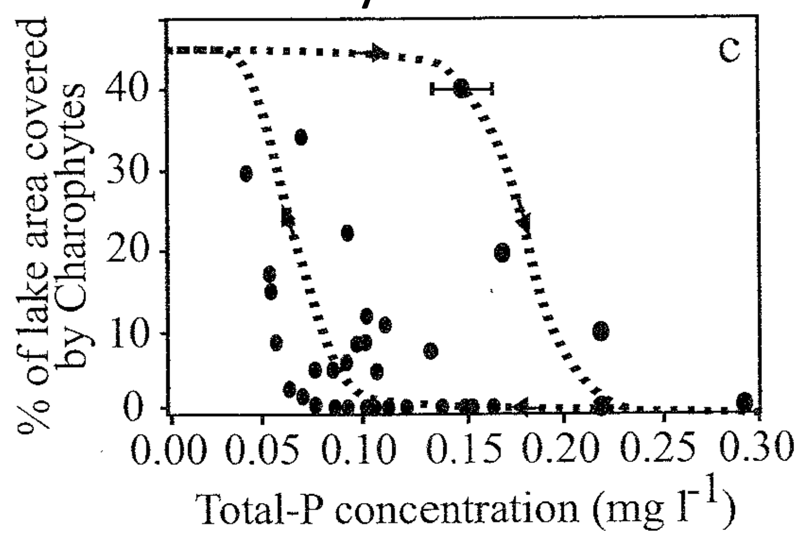
Bimodality



Diff. relationship



Hysteresis



Scheffer 2009

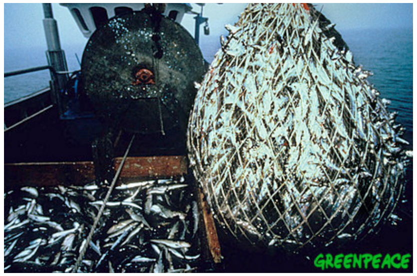
What about marine systems ?

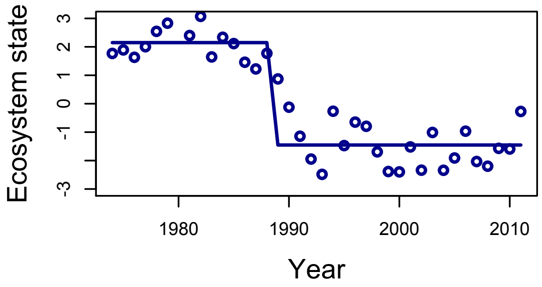
Reported regime shifts in marine systems

- Black Sea (Daskalos et al 2002, 2007)
- North Sea (Weijerman et al. 2005, Alheit et al. 2005, Reid et al 2001, Beaugrand et al. 2003, 2008, Beaugrand 2004, Llope et al 2009)
- North West Atlantic / Scotian Shelf (Frank et al 2005, 2006,2007)
- North Pacific (Hare & Mantua 2000, Wooster & Zhang 2004)
- Baltic Sea (Möllmann et al 2000, 2005, 2008a, 2009, Casini et al 2008,2009; Österblom et al 2007, Alheit et al 2007)
- ……….
- => disruptive changes in ecosystem services, i.e., fisheries productivity
- => extensive fluctuations of harvested fish stocks

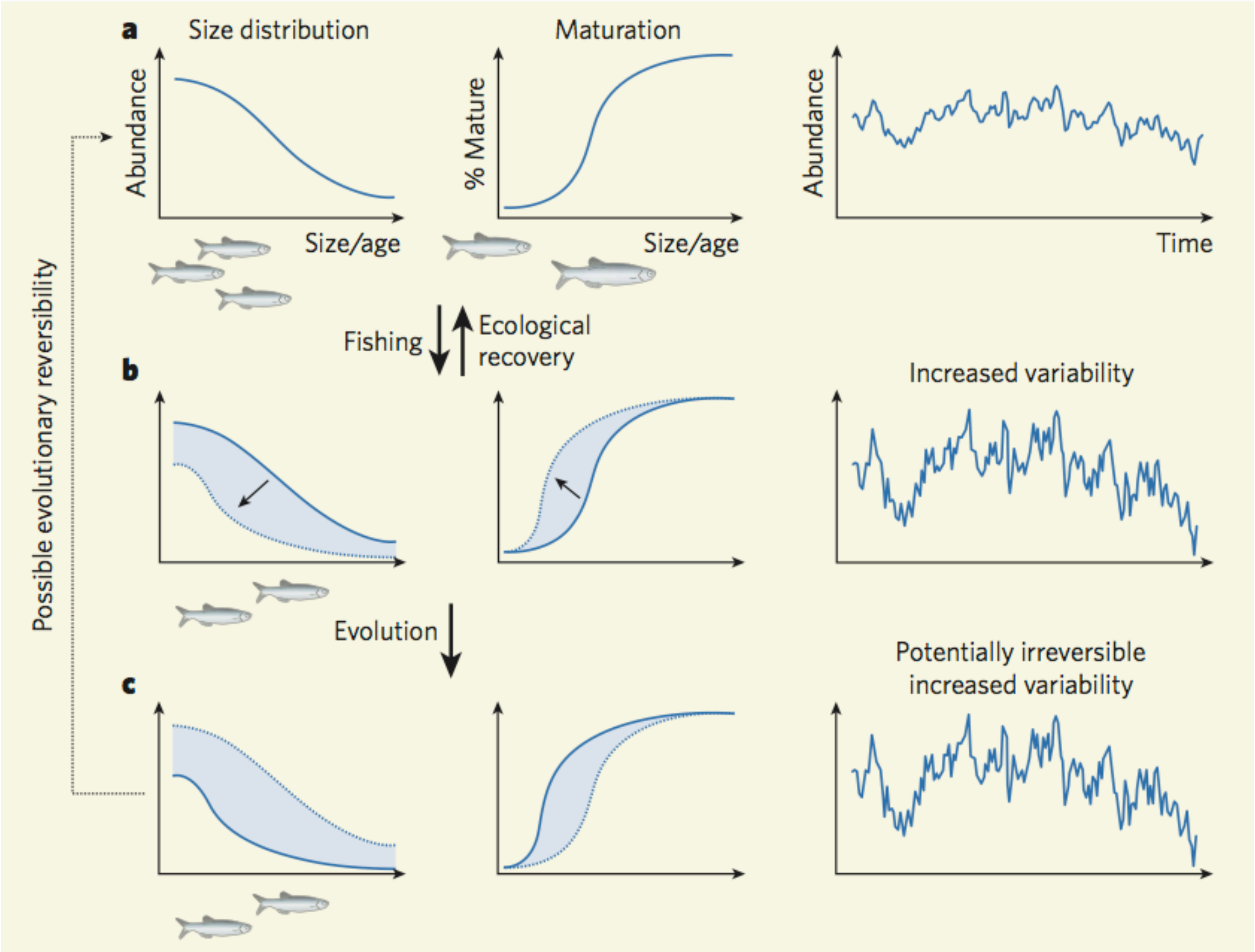
Drivers of regime shifts in marine systems

- fisheries
- climate change
- eutrophication
- non-native species invasion
- etc..
- *interaction* of those…

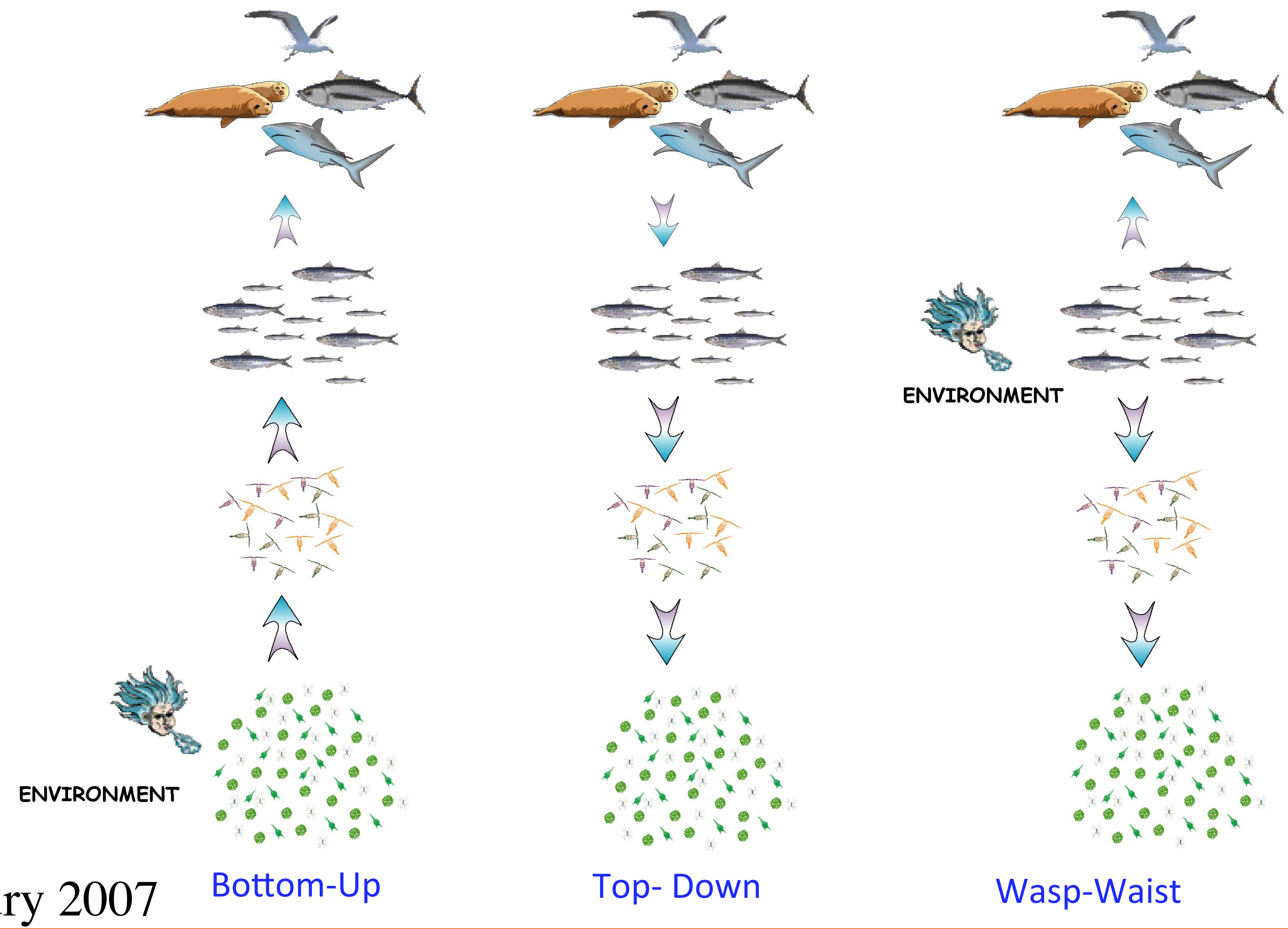



Why fishing magnifies fluctuations in fish abundance



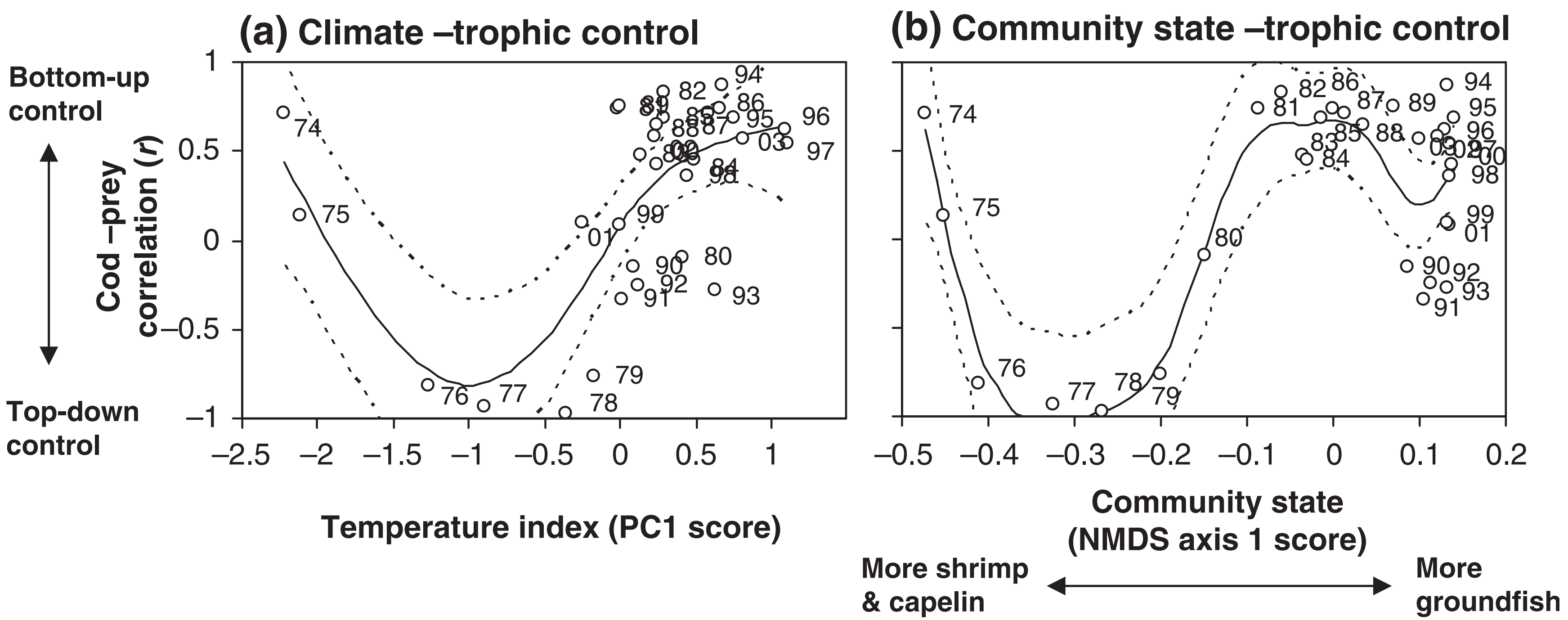
Stenseth & Rouyer 2008, based on Anderson et al 2008

Flow of energy in marine systems



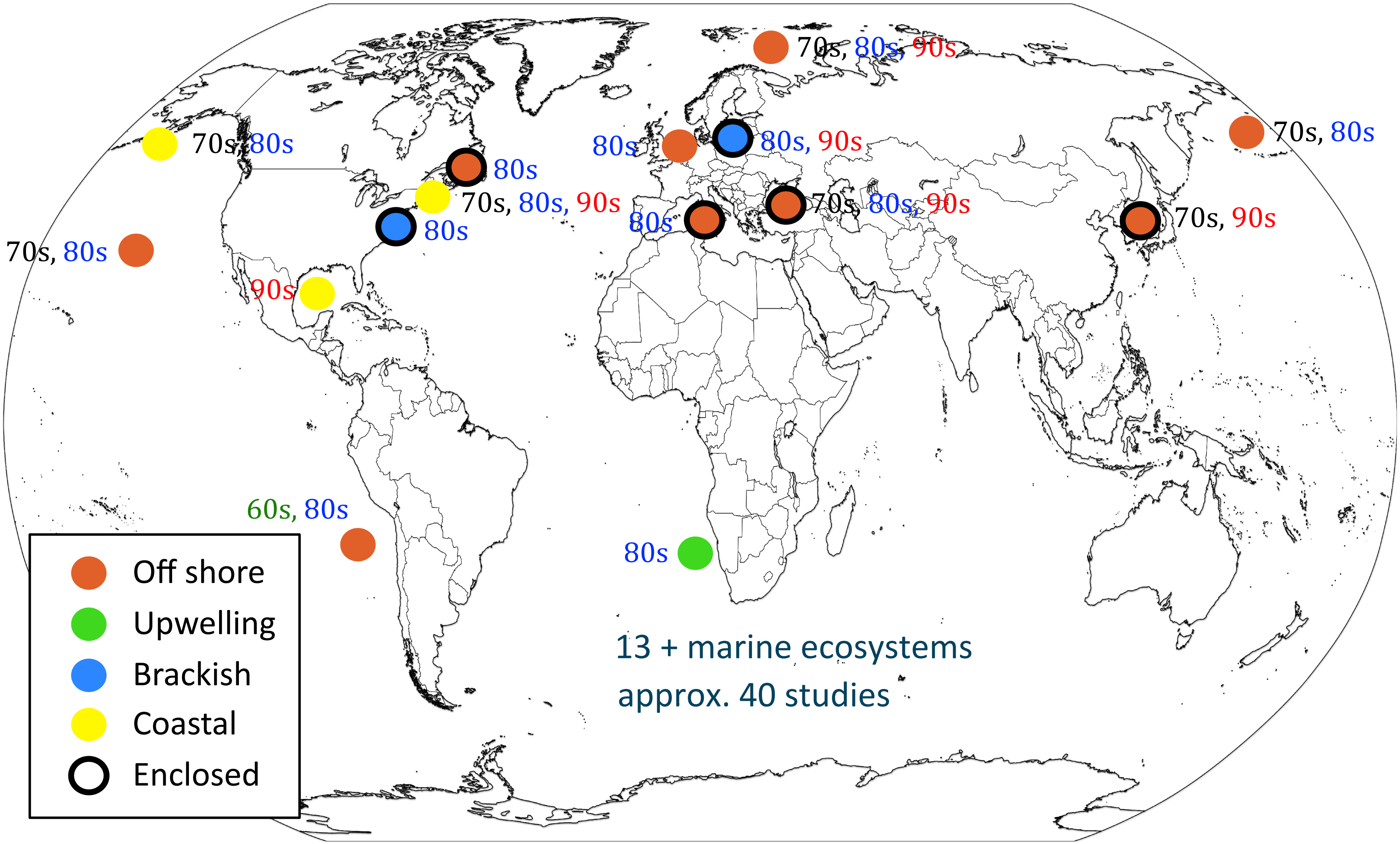
Cury 2007

Changes bottom up – top down dynamics



Litzow & Ciannelli et al 2007

Regime shifts in marine systems

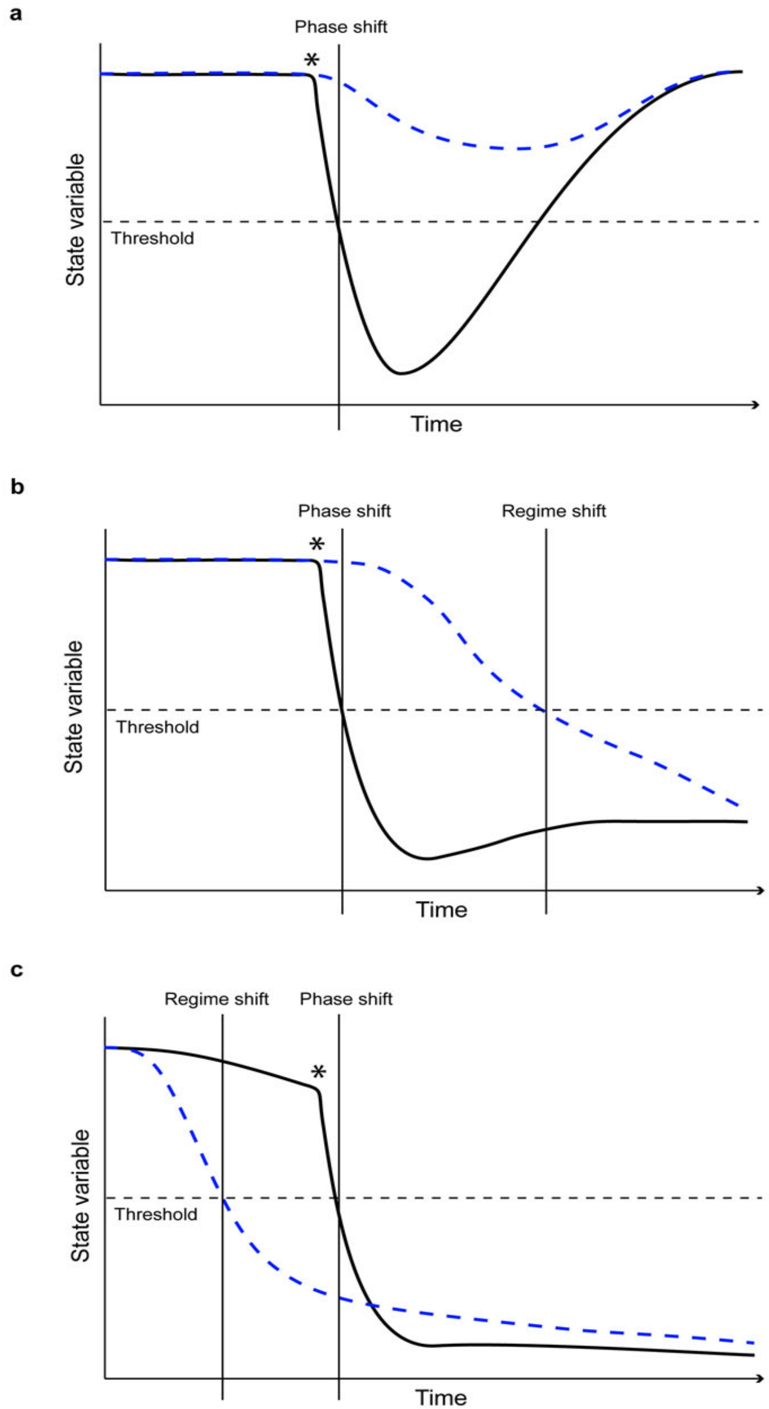


Blenckner & Niiranen 2012

Some more detailed examples:

- Coral reefs ("recovery" potential)
- Black Sea (eutrophication + fishing)
- Baltic Sea

Coral reefs



*: pulse perturbation
solid line: community structure
blue-dotted: key-process (state variable)

a) Recovery

b) Regime shift following disturbance

c) ”Cryptic” regime shift before disturbance (e.g. the Caribbean story)

Nyström *et al.* 2009 (Coral Reefs)

Jamaica –
the archetypical example of a coral reef regime shift

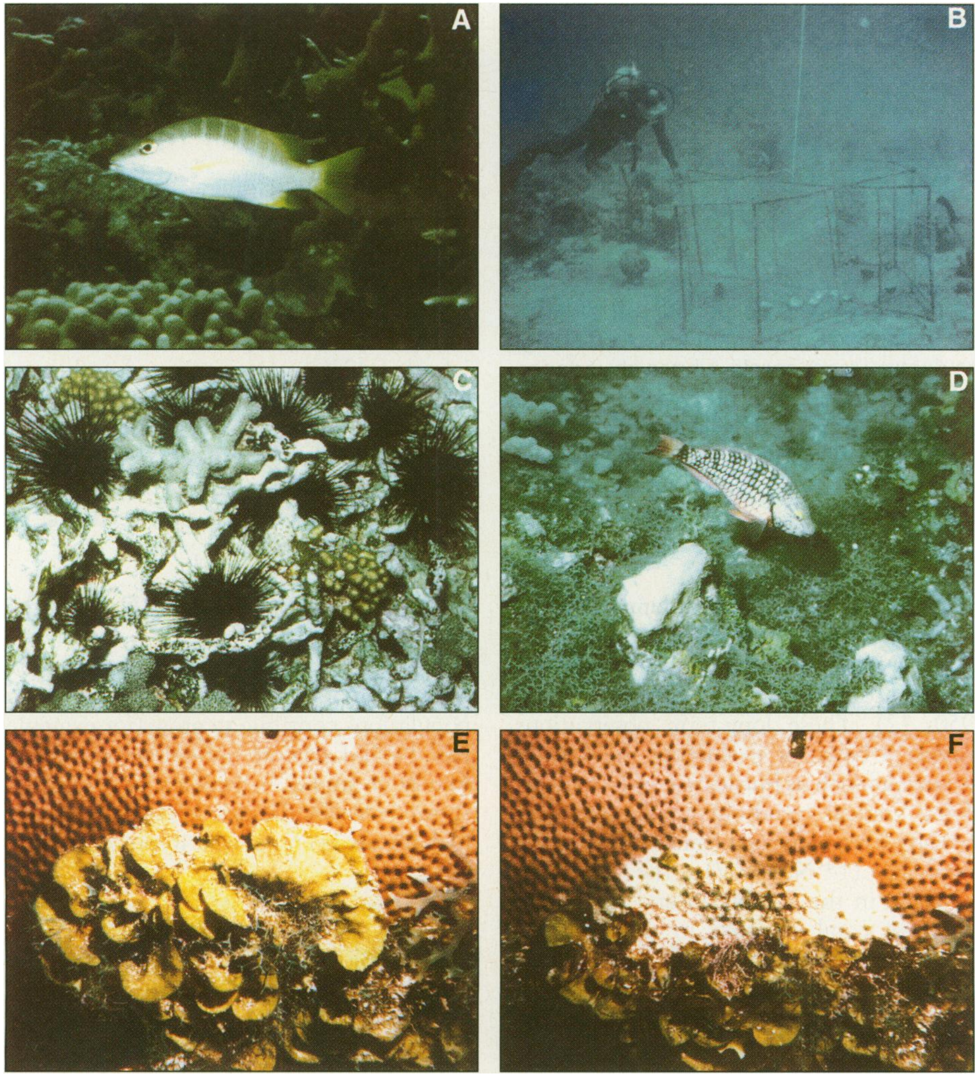
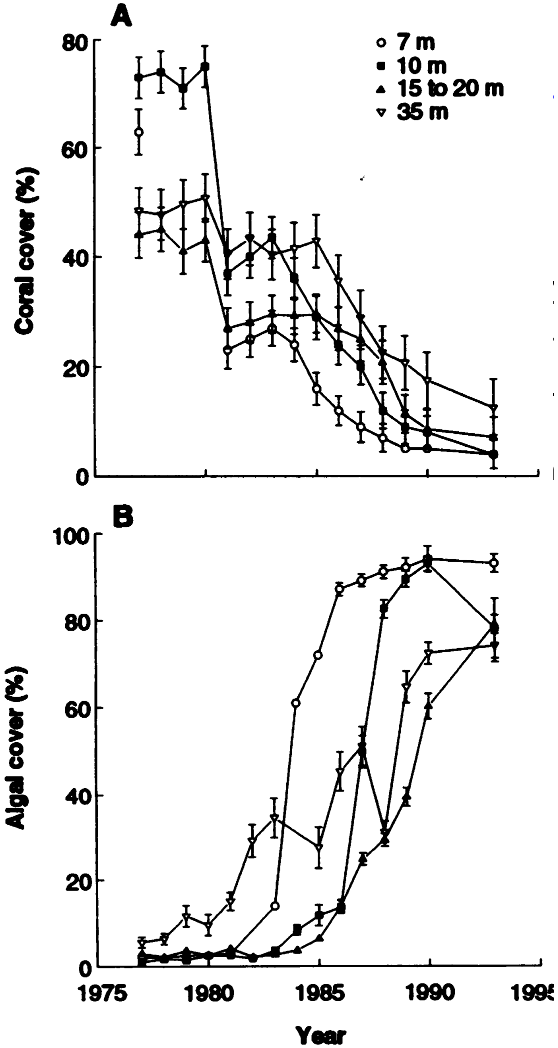
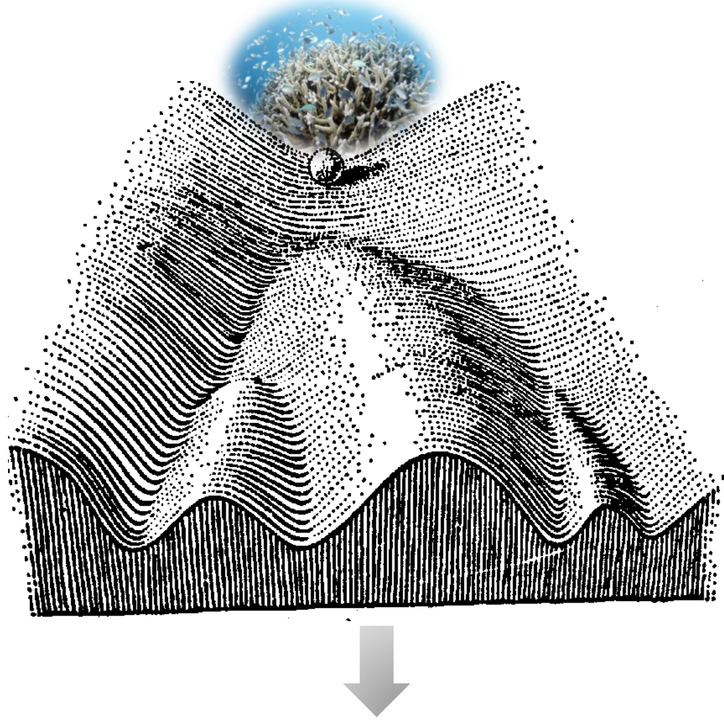


Fig. 2. (**A**) Healthy reefs are characterized by a high degree of habitat heterogeneity, which provides habitat for fish and invertebrates. (**B**) A Z-shaped fish trap commonly used throughout the Caribbean (*7*). (**C**) Removal of fish is likely to have promoted population growth of the echinoid *Diadema antillarum*, which became the dominant macroherbivore on overfished reefs throughout the Caribbean (*13*). (**D**) After the mass mortality of *Diadema* from disease in 1983, spectacular algal blooms ensued on overfished reefs. In Jamaica, abundance of macroalgae has increased steadily for the past decade (see Fig. 3B). (**E** and **F**) Macroalgal overgrowth and preemption of space for larval recruitment has caused a dramatic decline in abundance of corals. Here, a massive coral has been partially smothered by *Lobophora* (E), killing tissue overlying the white coral skeleton as revealed by peeling away the algae (F).



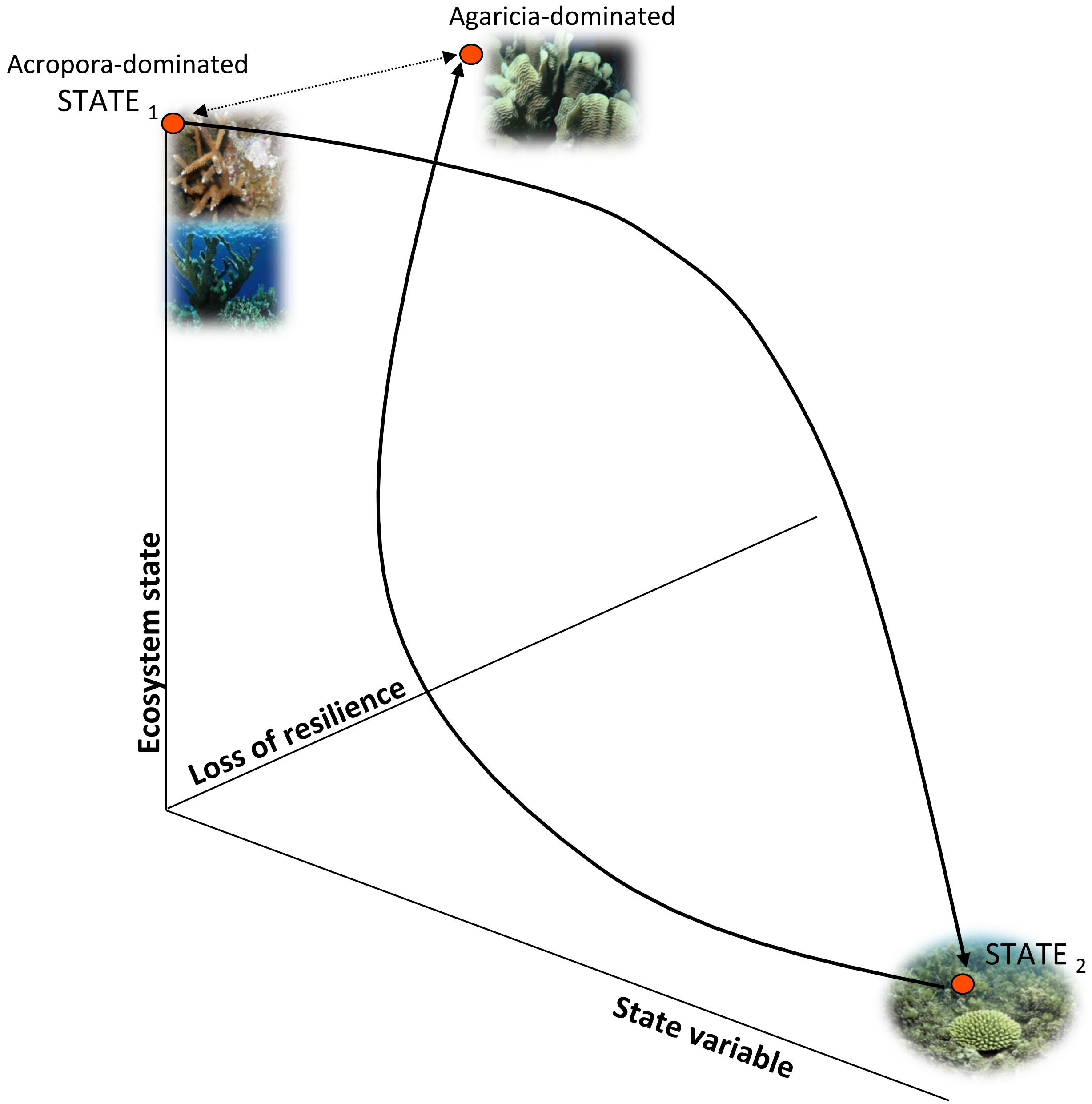
Hughes 1994 (Science)

Multiple-states in coral reefs



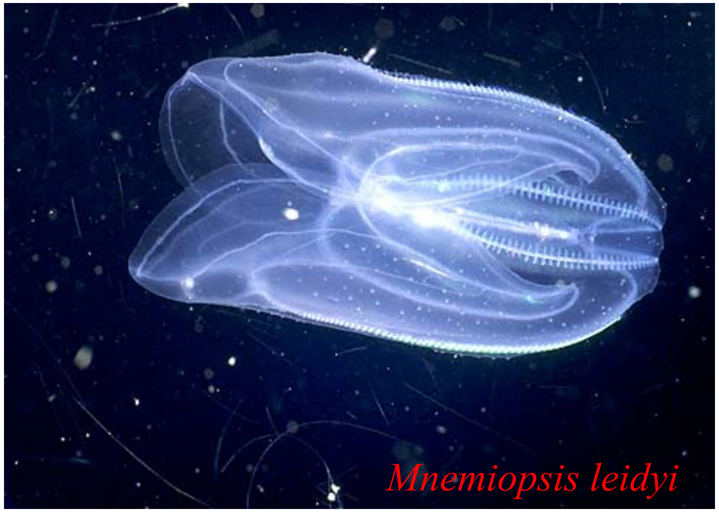
Norström *et al.*, 2009 (MEPS)

Recovery to what?

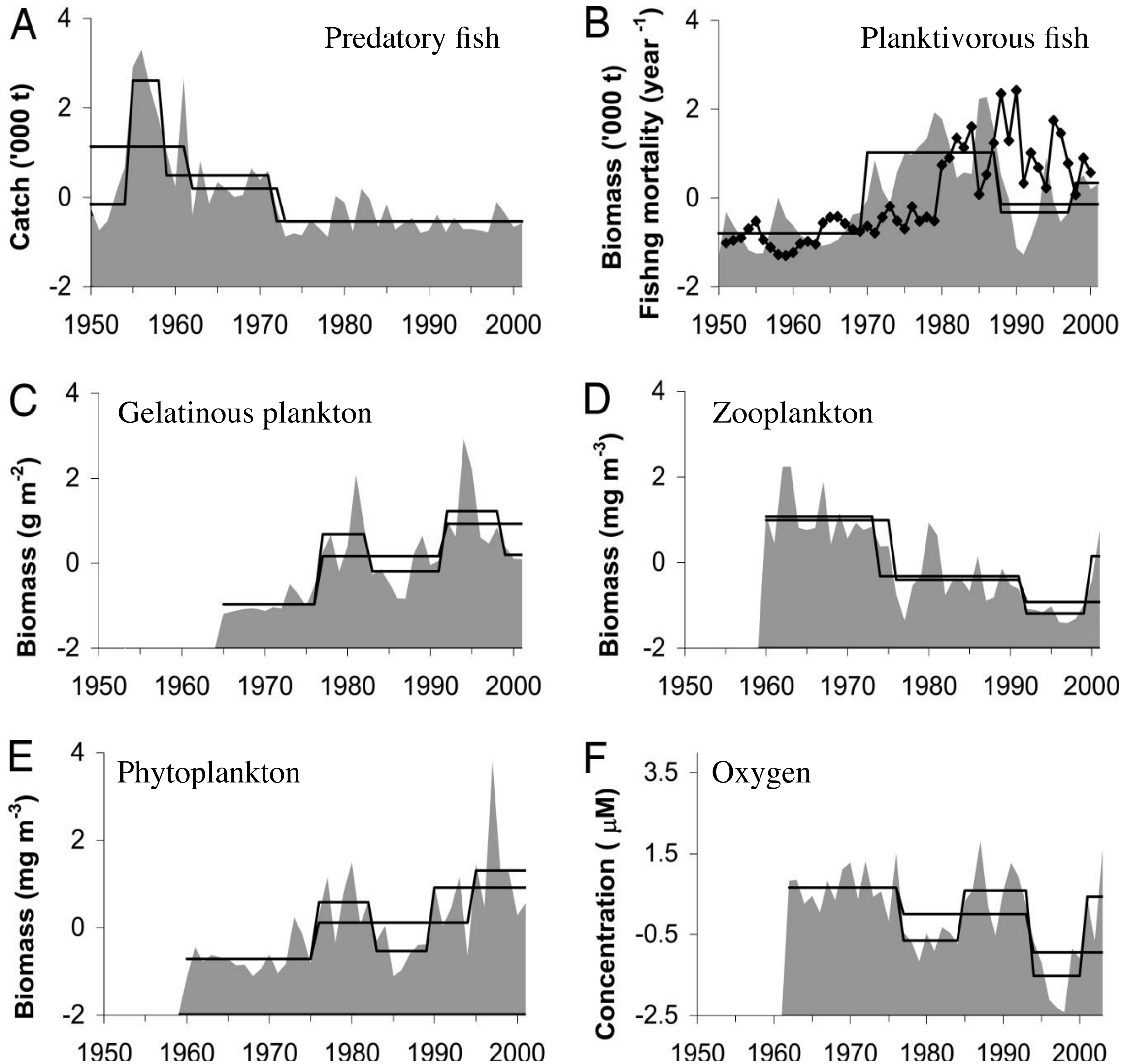


Nyström 2006

Black Sea



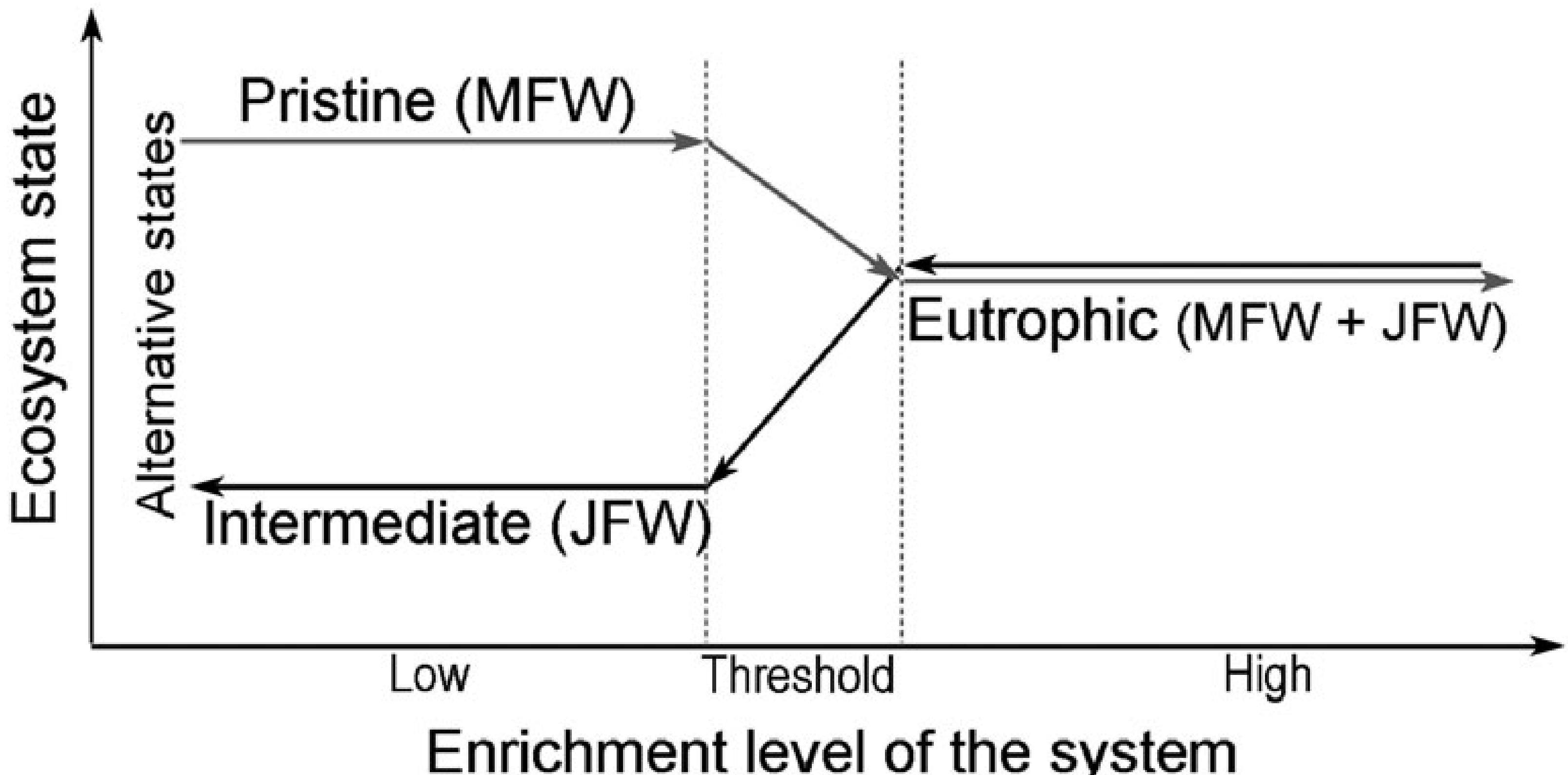
Changes in trophic levels



Daskalov *et al.* (2007)

Several shifts have been described for the various trophic levels

Today lower zooplankton biomass and fish catch



Oguz & Velikova 2010

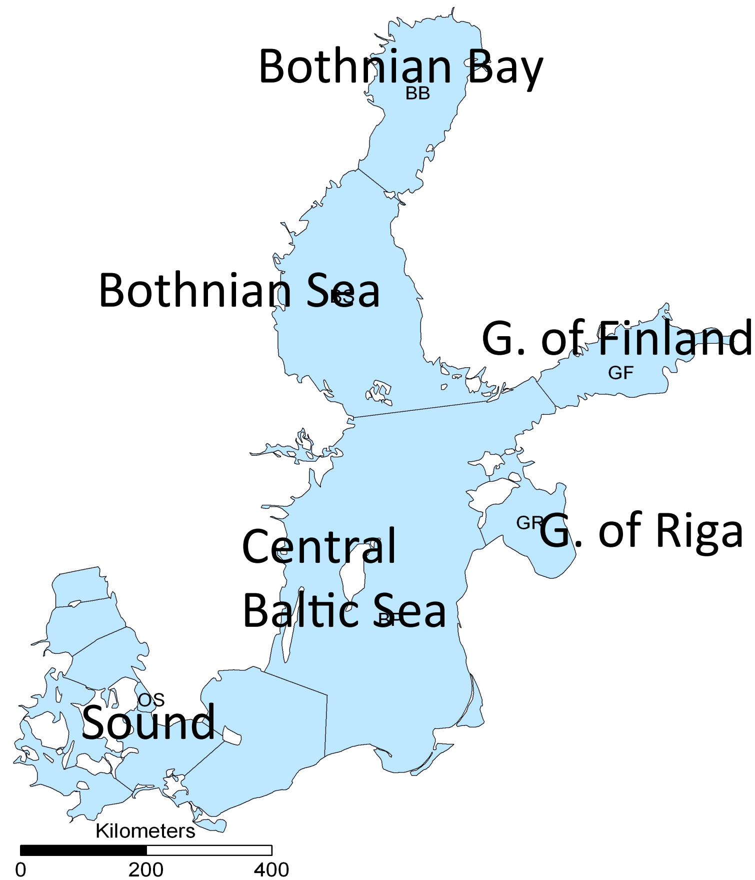
Do we see shifts in the Baltic Sea ?

The Baltic Sea

<u>Characteristics</u>

- large semi-enclosed brackish water body
- low diversity
- high productivity
- eutrophication
- high fishing pressure
- climate influences through temperature and salinity

Sub-system	Hydrography	Diversity	T	S
The Sound	Strong halocline			
Central Baltic Sea	Strong halocline			
Gulf of Riga	Mixed but partly stratified			
Gulf of Finland	Mixed but partly stratified			
Bothnian Sea	mixed			
Bothnian Bay	mixed			



Aim

- Comparative approach to study the importance of global to regional drivers on 6 connected sub-ecosystems
- Do the 6 sub-systems with different environmental and structural settings respond in common or idiosyncratic ways to external forcing

Methods: Ecosystem State & Abrupt Shift

- Principal Component Analysis (PCA) on all biotic variables – PC1 as index of ecosystem state
- Regime shift test:
  - Sequential regime shift detection method (STARS, Rodionov, 2004)
  - Chronological clustering (Legendre et al 1985)

Methods – Test for Drivers

- Regression analysis of abiotic time-series vs biotic PC1
  - Overall 6 sub-systems analysis: Generalized Additive Mixed Model (GAMM) accounting for spatial and temporal correlation
  - Single sub-system analysis: Generalized Additive Model (GAM)) accounting for non-linearity
  - the most parsimonious model was identified using the Akaike Information Criterion (AIC)

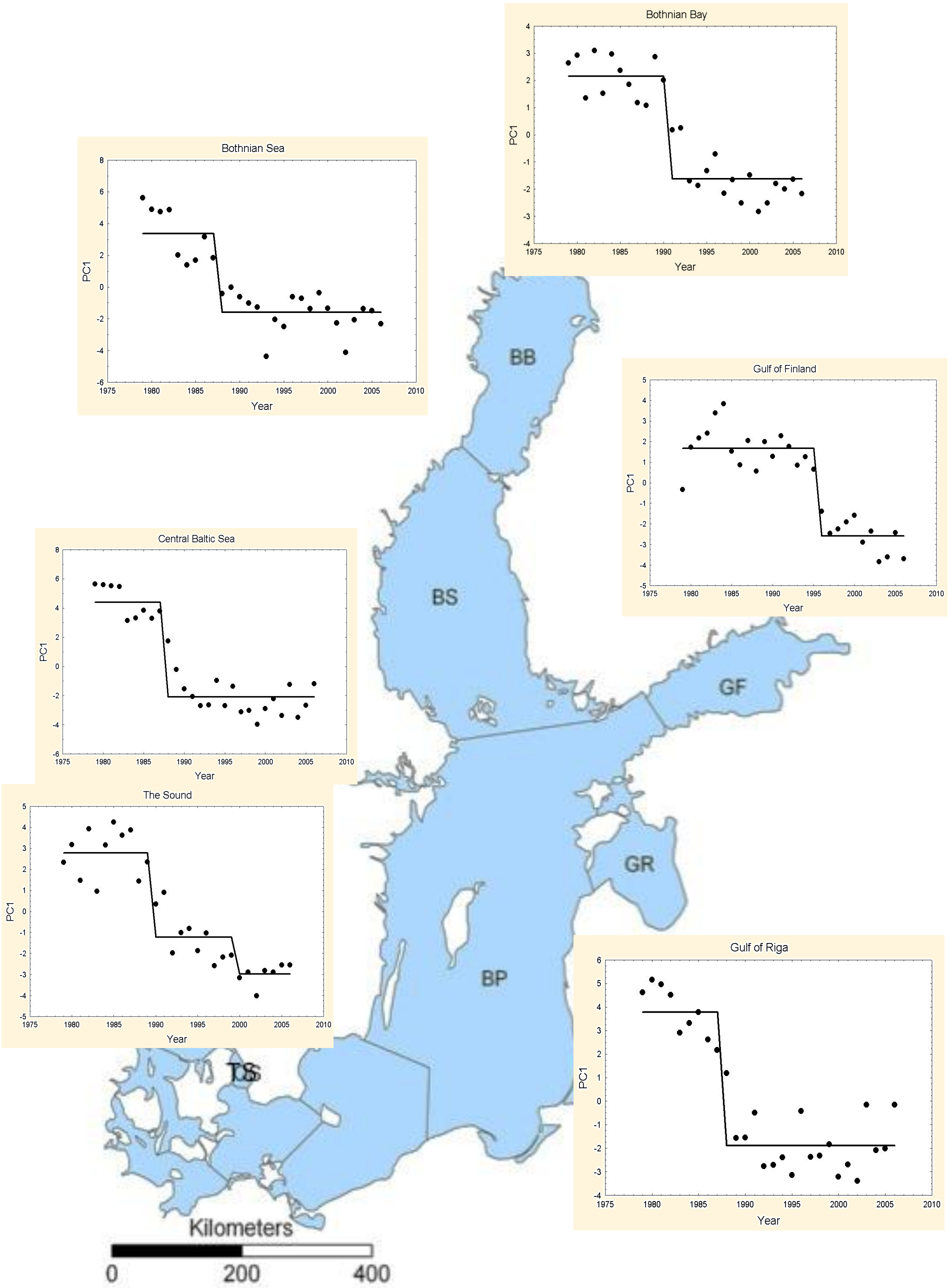
Data Monitoring (218 in total)

on multiple trophic levels 1979-2006

System	The Sound	Central Baltic	Gulf of Riga	Gulf of Finland	Bothnian Sea	Bothnian Bay
Biotic	28	31	13	16	22	13
Abiotic	14	29	12	14	13	13
Sum	42	60	25	30	35	26

Abrupt changes in all Sub-Systems

- All abiotic & biotic variables ($PC1_{A\&B}$ from PCA)
- Regimes identified using STARS on PC1s (red lines)
- Almost synchronous changes in all sub-systems

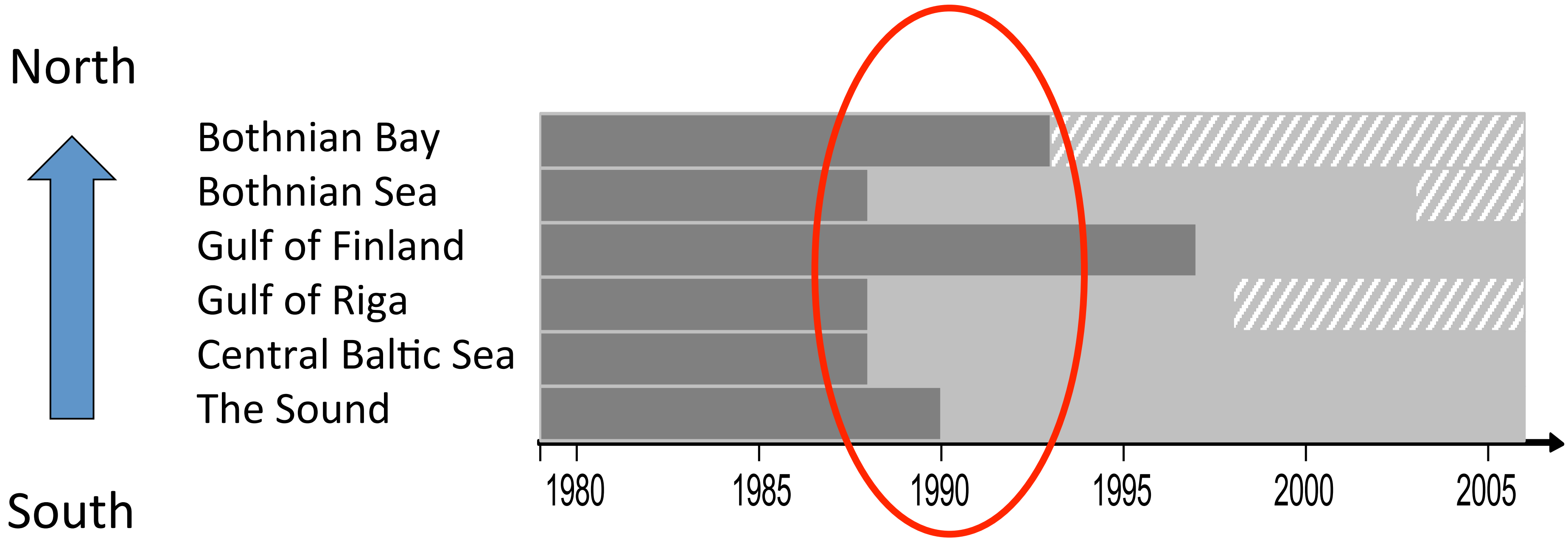


Blenckner in prep

Drivers
Overall 6 Sub-Systems Analysis

- using basins as factors and basin-specific year smoothers to account for spatial and temporal autocorrelation
- Abiotic variables used: winter nutrients, salinity, winter climate (Baltic Sea Index), fishing
- best model:
  - **only winter climate (Baltic Sea Index) as the overall significant driver (17%, $p<0.01$, $n=167$)**

Abrupt Shifts in Biotic Variables



Drivers in Single Sub-System Analysis

$PC1_{bio}$	Temp spr	Temp su	Salinity	Pwin	F	Explained variance %
Bothnian Bay			***		*	78
Bothnian Sea			***			86
Gulf of Finland	**			***	*	69
Gulf of Riga			*	***		65
Central Baltic Sea		*			***	75
The Sound		**		***		76

Significance levels: $p<0.05$*, $p<0.01$**, $p<0.001$***

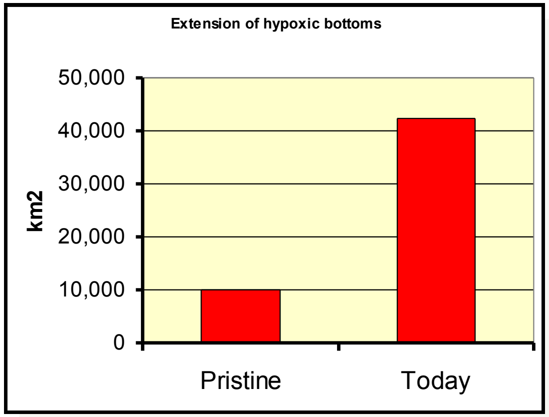
Conclusions

- Synchronous large-scale climate induced changes in the connected Baltic Sea systems
- Sub-system changes are induced by stochastic interplay of multiple drivers, i.e., nutrients, temp, salinity and fishing acting basin specific
- Ecosystem based management must be cross-sectoral, adaptive and based on data assessments and modelling

But what is really happening?

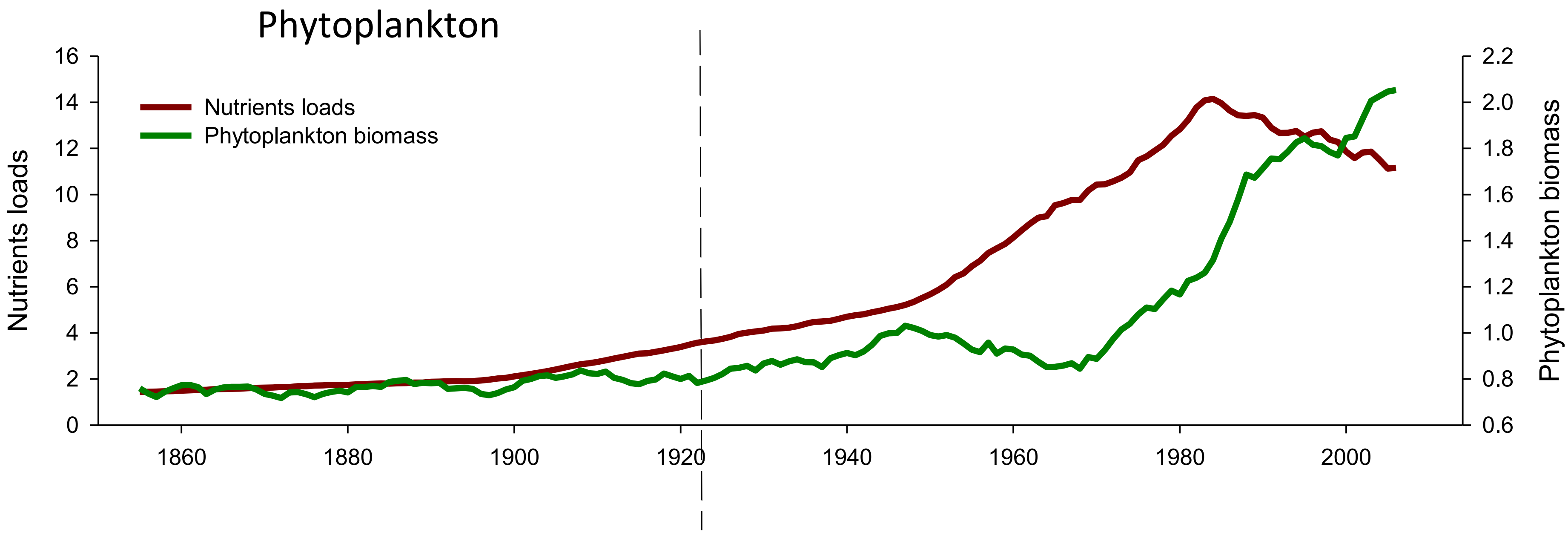
Eutrophication

- Causing increase in prim. prod,. and anoxic areas (feedback with P)
- Still positive trends/constant in P and/or N load in some areas (GoF, GoR, BoS)
- Decrease in both N and P in the Sound
- Effects phytoplankton but no clear overall species change
- Effects anoxic area



Savchuk et al. 2008

Long-term dynamic of the Baltic Sea ecosystem



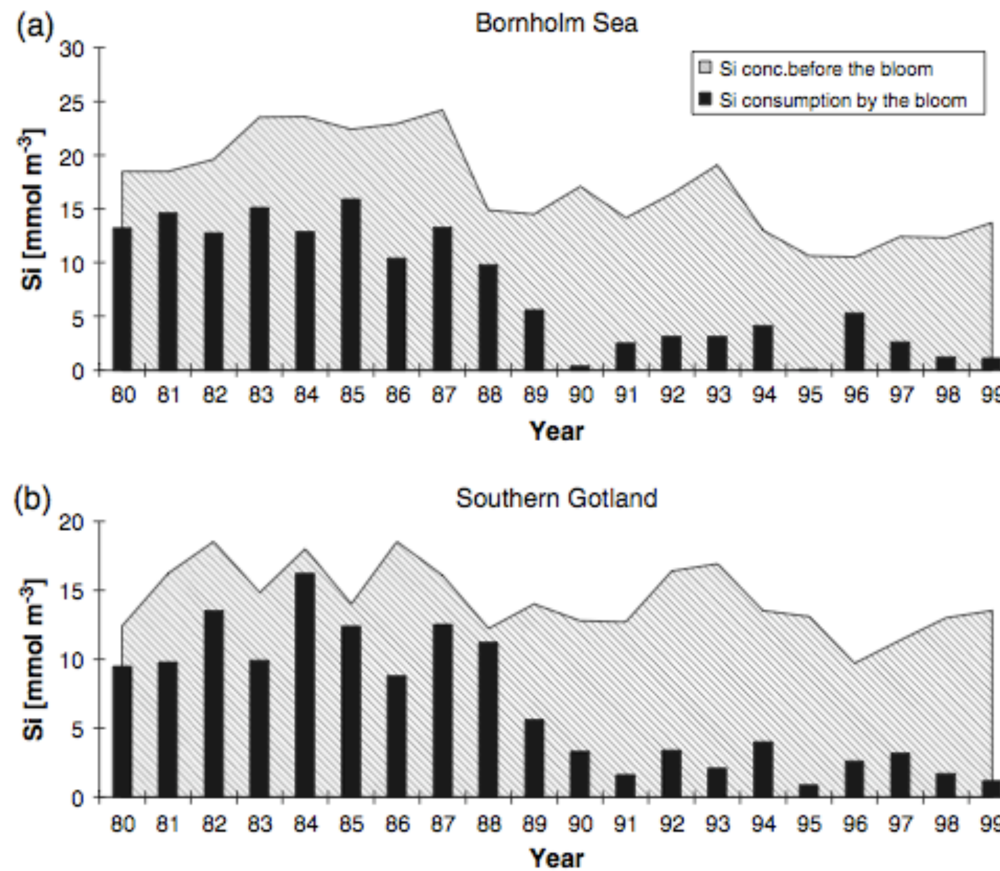
Results from ECOSUPPORT Bo Gustafsson & Bärbel Muller-Karulis

Phytoplankton

Cold winters => Diatoms
Mild Winters => Dinoflagellates

Increased grazing after mild winters control diatom spring bloom (Wasmund et al 2013)

Changes in the phytoplankton community have taken place both at species (Hajdu et al. 2000) and functional group level (Wasmund et al. 1998) and composition is not associated with eutrophication (Olli 2011).



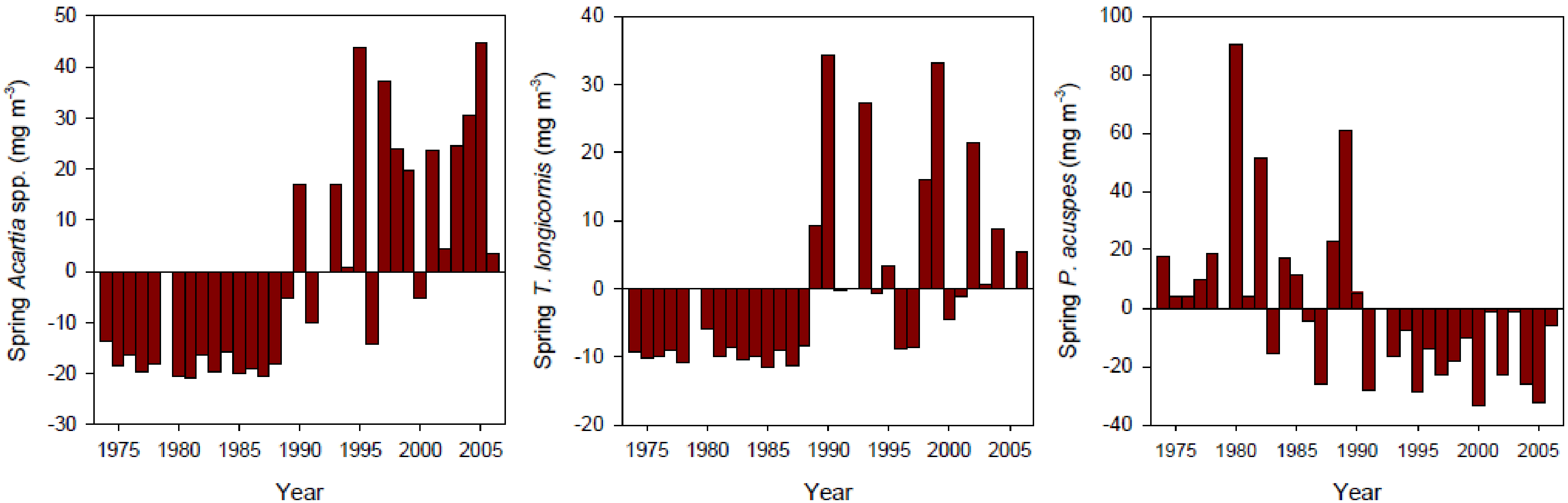
Alheit et al. 2005

Zooplankton & climate

- Changes in plankton abundances, community structure, phenology and geographic ranges are evident over large scales (Hays et al 2005, Richardson 2008)
- Responses are species-specific
- In the Baltic Sea two drivers, temp & salinity
  - Spring biomass of *Acartia* sp and *Temora longicornis / Eurytemora* increased due to spring SST in late 1980s
  - *Pseudocalanus sp* decrease due to salinity decrease
  - *Bosmina sp* increase due to salinity decrease

Zooplankton, Central Baltic Sea

- Climate: salinity and temperature



Source: ICES (2010)

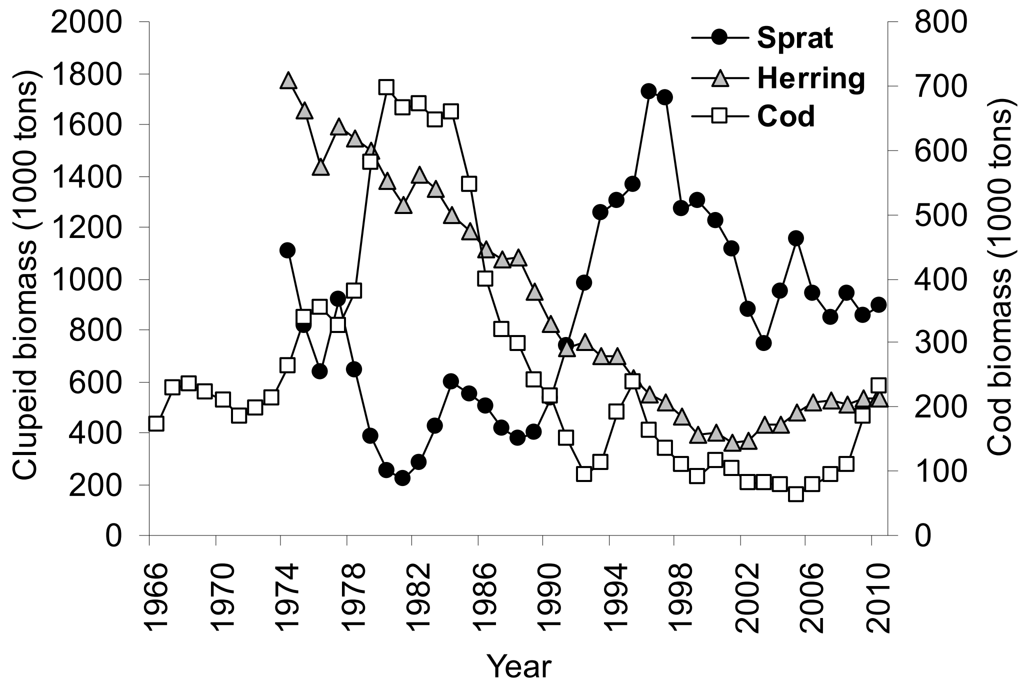
Fish & climate

- Direct and indirect climate effects on fish species well documented (Stenseth et al 2003, Ottersen et al 2004, MacKenzie 2001 etc…)
- In the Baltic again both temp and salinity
  - Sprat August sea surface temp
  - Cod, reproductive volume
  - Indirect zooplankton biomass/quality, macrozoobenthos

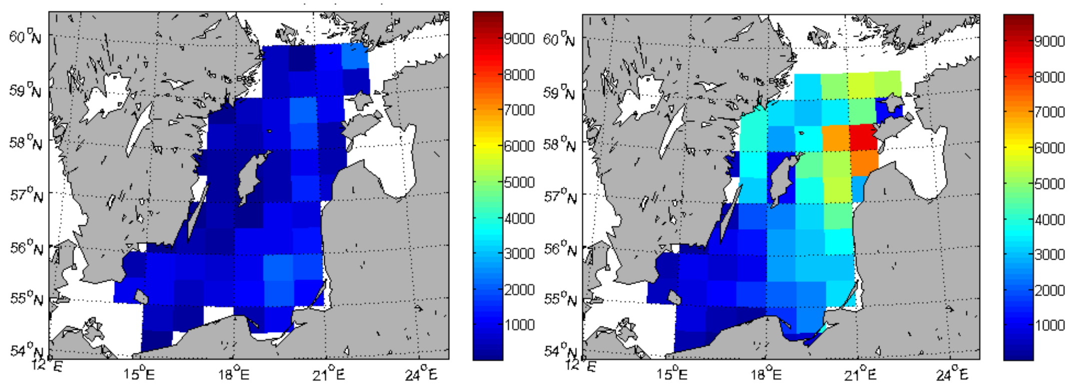
Fisheries

- Largely effect fish populations
- Effects sensitivity to climate through smaller size and age (Otterssen 2006)
- => trophic cascade

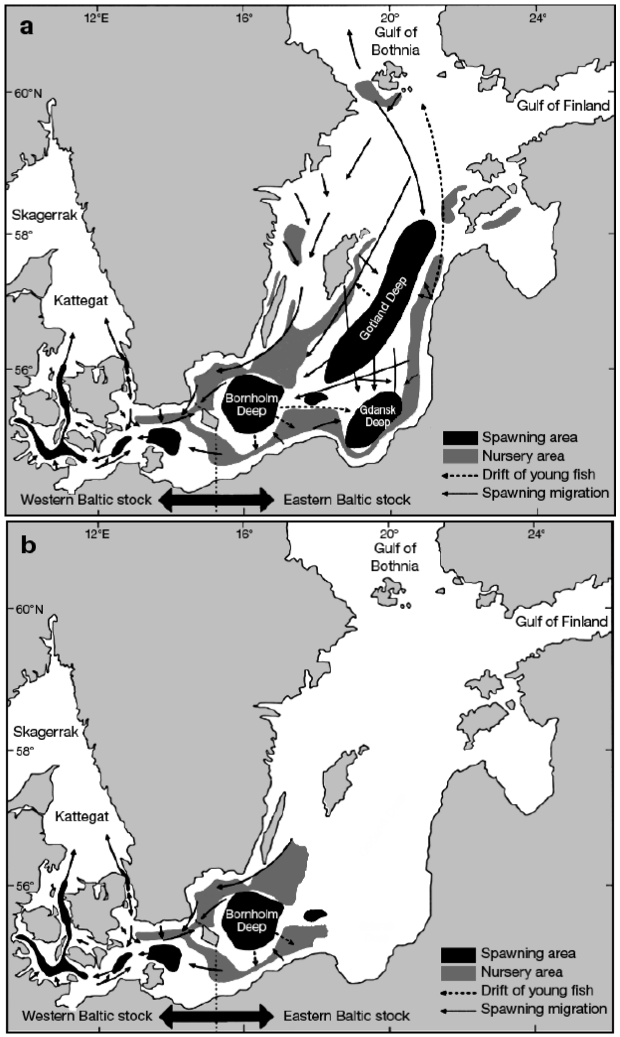
Commercial fish stocks



Source: Data from ICES (2011)

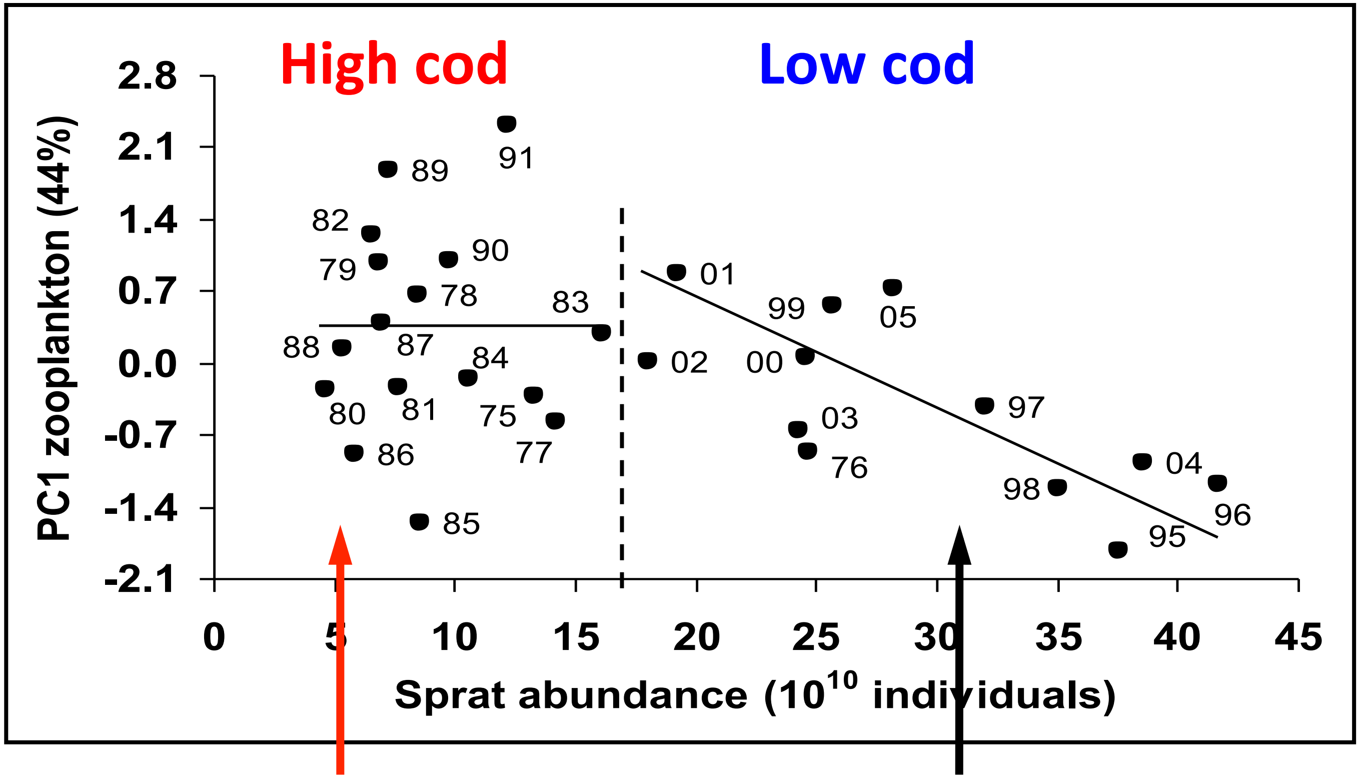


Source: Casini *et al.* (2011)



Source: Cardinale and Svedäng (2011)

Thresholds between climate and top-down controls



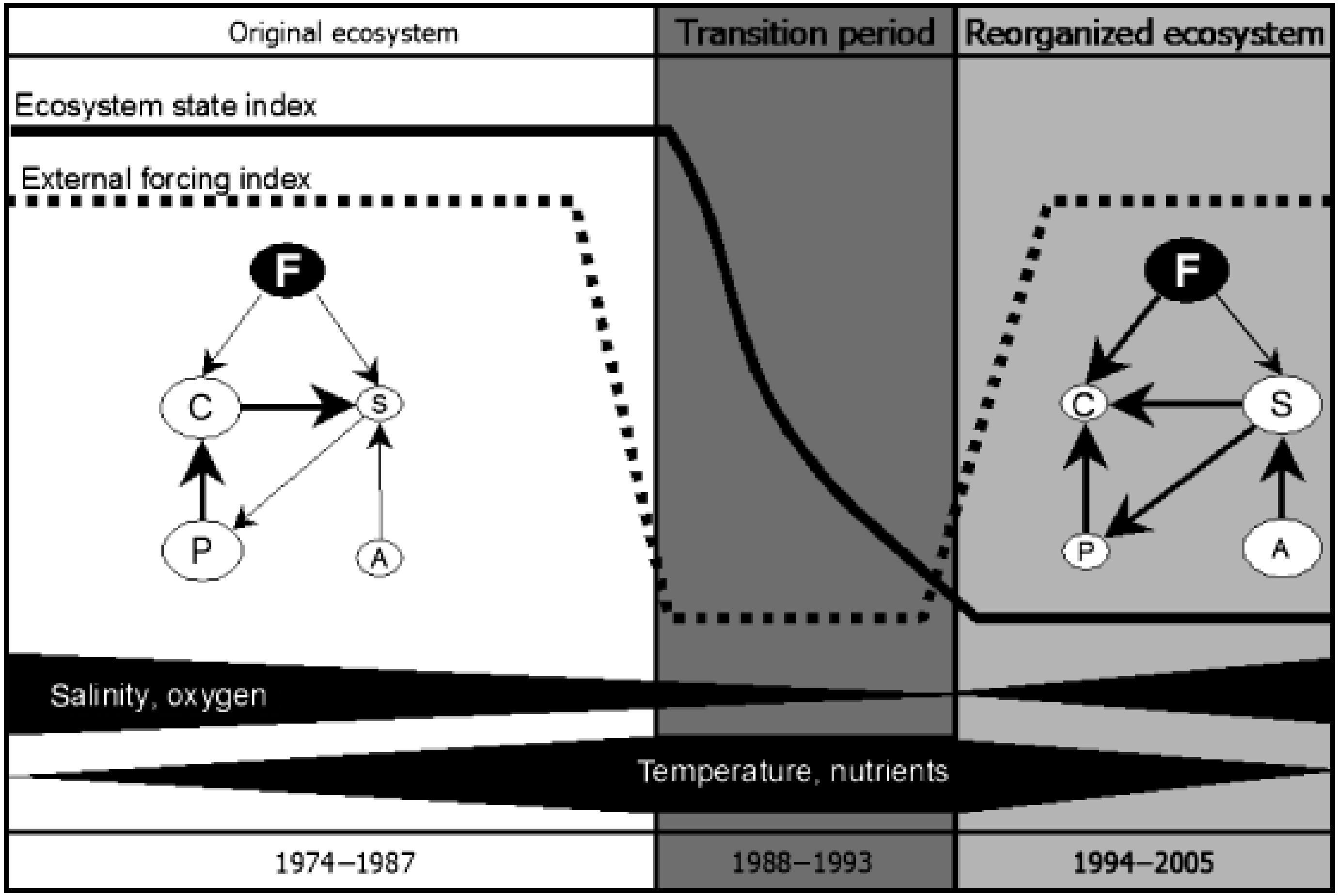
r = 0.004
p = 0.98

zooplankton is driven by hydrography

zooplankton is driven by sprat predation

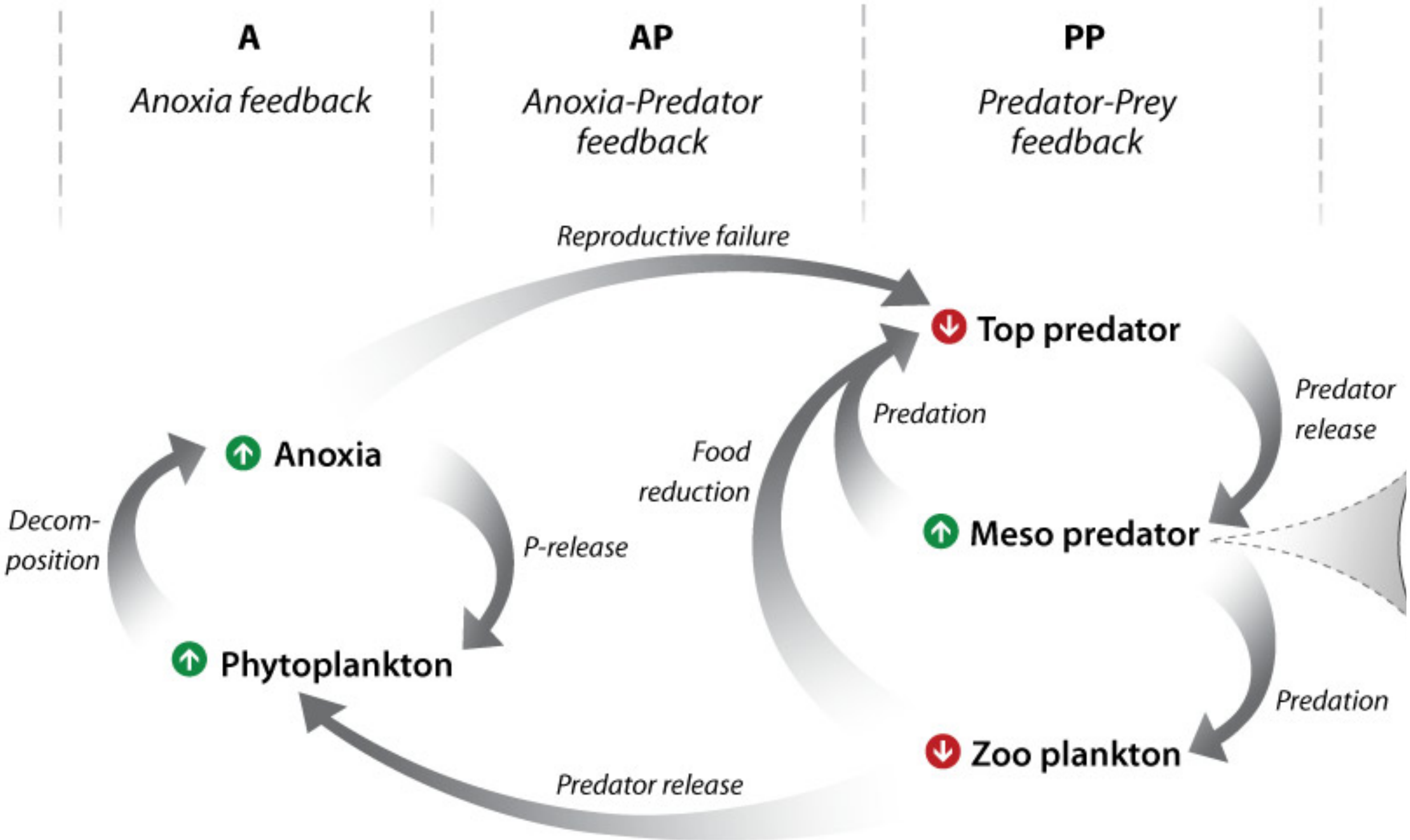
Casini et al. 2009

Potential regimes in the Central Baltic Sea



Möllmann et al 2009

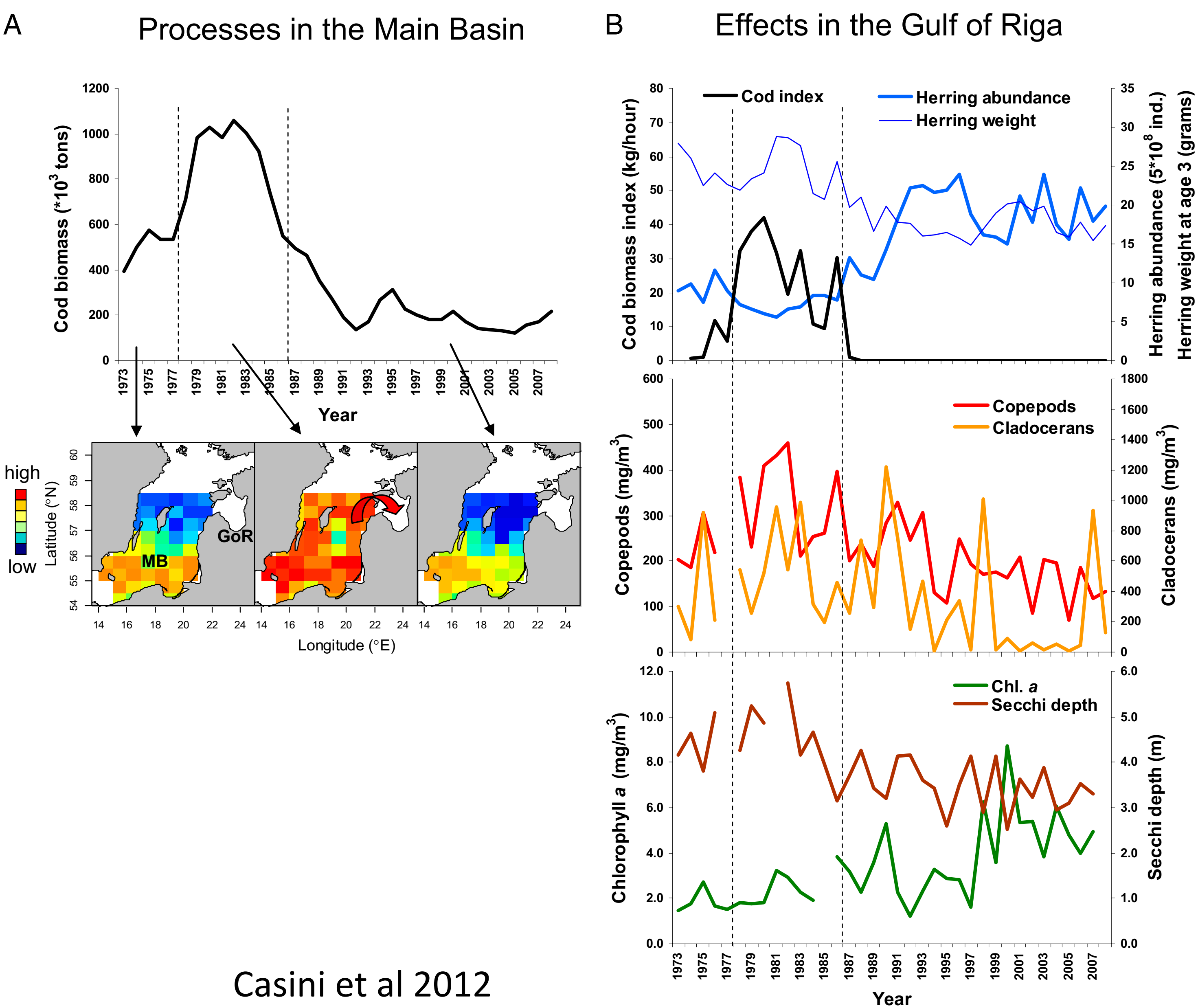
Potential ecological feedbacks



Nyström et al in 2012

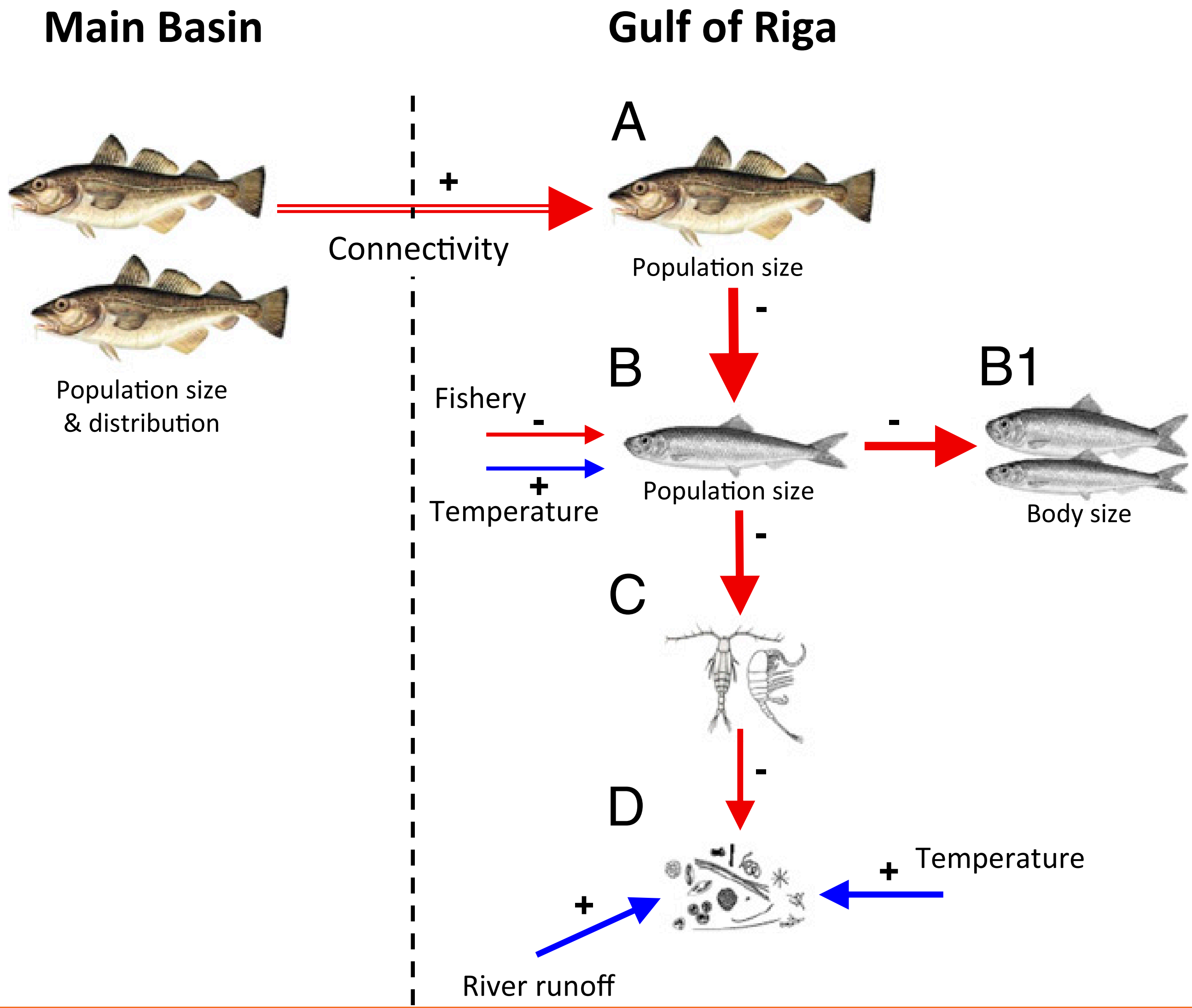
Does the shift in the Central Baltic Sea matter for other basins in the Baltic ?

Spatial effects



Casini et al 2012

Sink and source effects

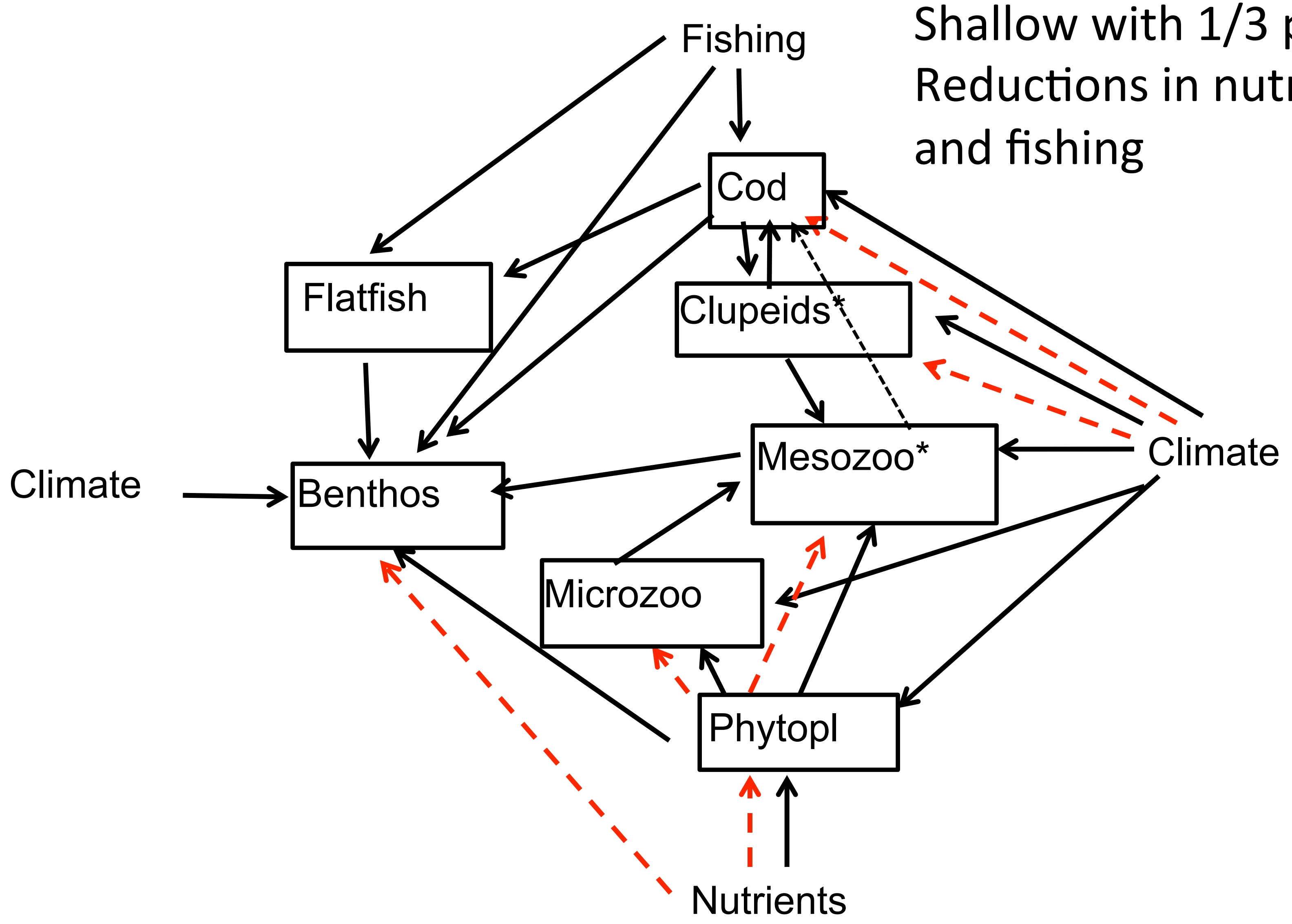


Casini et al 2012

Is this common for all basins ?

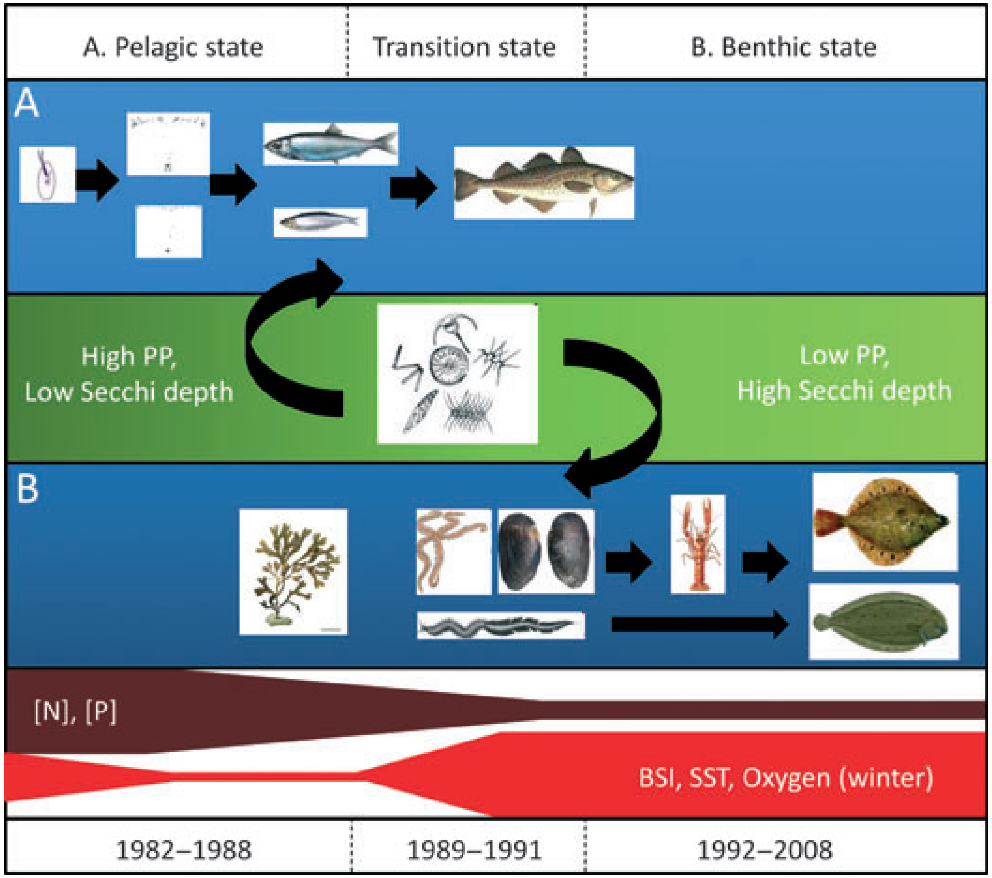
Kattegat

Shallow with 1/3 photic depth
Reductions in nutrients
and fishing



Regime shift in the Kattegat

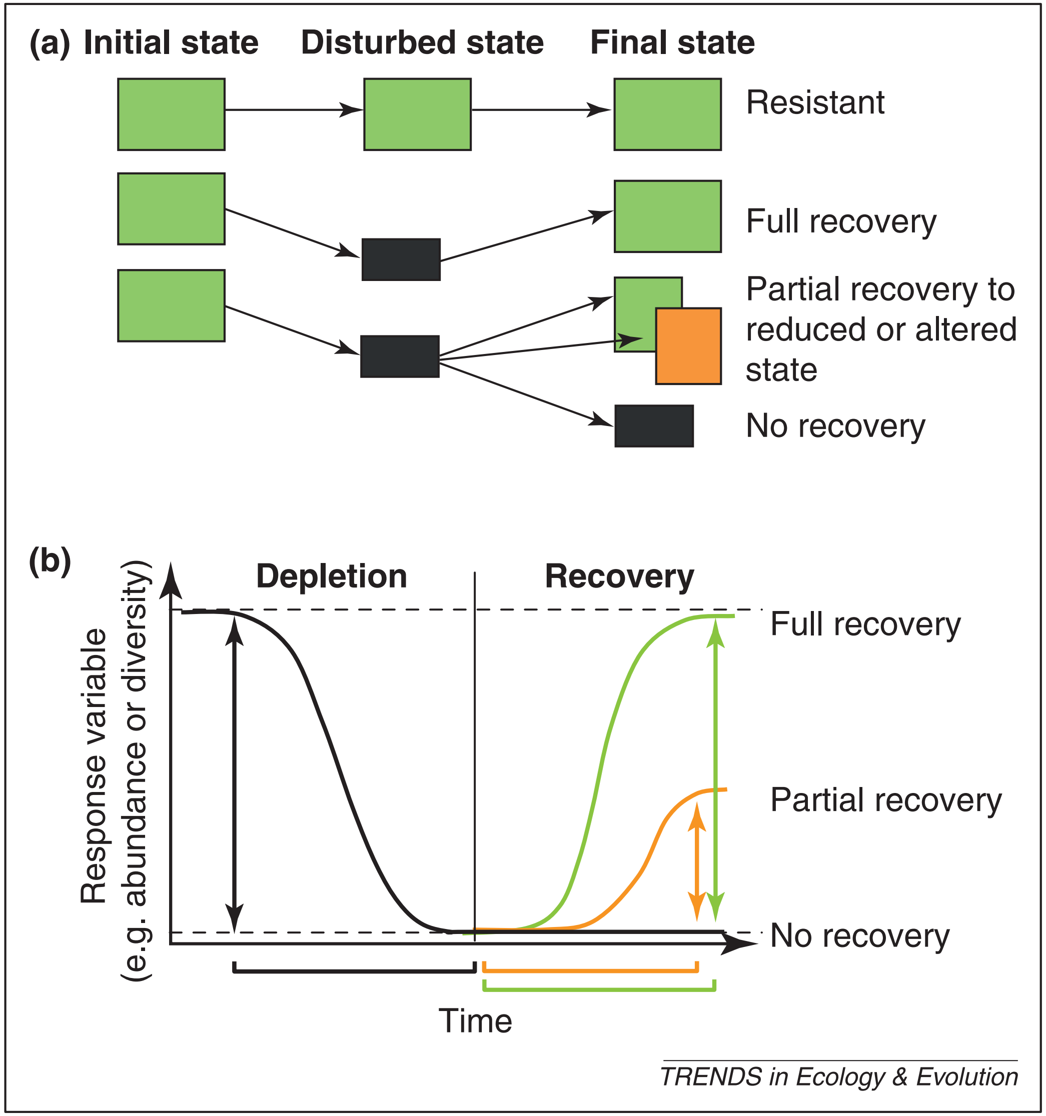
- Integrated assessment of long-term monitoring data
- Statistical analysis of multiple environmental & ecological factors
- Identified pelagic to benthic regime shift
- Shift driven by nutrient reductions, climate warming, & fishing



Lindegren, Blenckner, Stenseth, GCB, 2012

Is the shift in the Central Baltic reversible ?

Recovery research



Some hope but there is still much to learn about recovery, here more a regeneration

Lotze et al 2011

Aim

- Quantify thresholds in past food-web dynamics of the Central Baltic Sea
- Identify drivers leading to crossing of the threshold
- Test for the recovery potential of cod

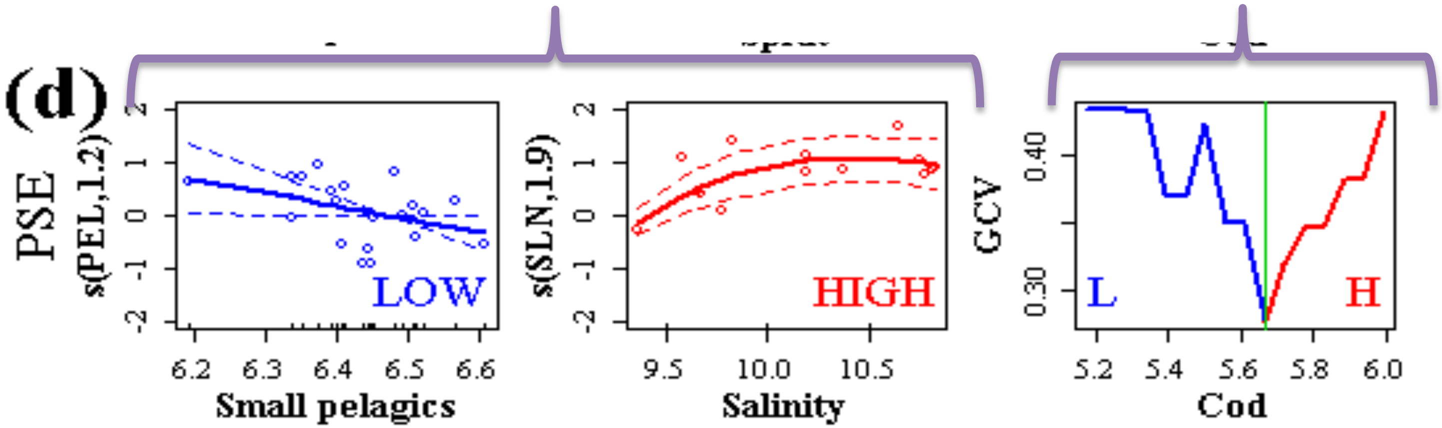
Analysis

- 3 trophic levels, zooplankton, planktivorous & predatory fish
- Generalized Additive Models and threshold formulation (TGAMs)
- Each trophic level regressed the others and environmental variables (lag 1)

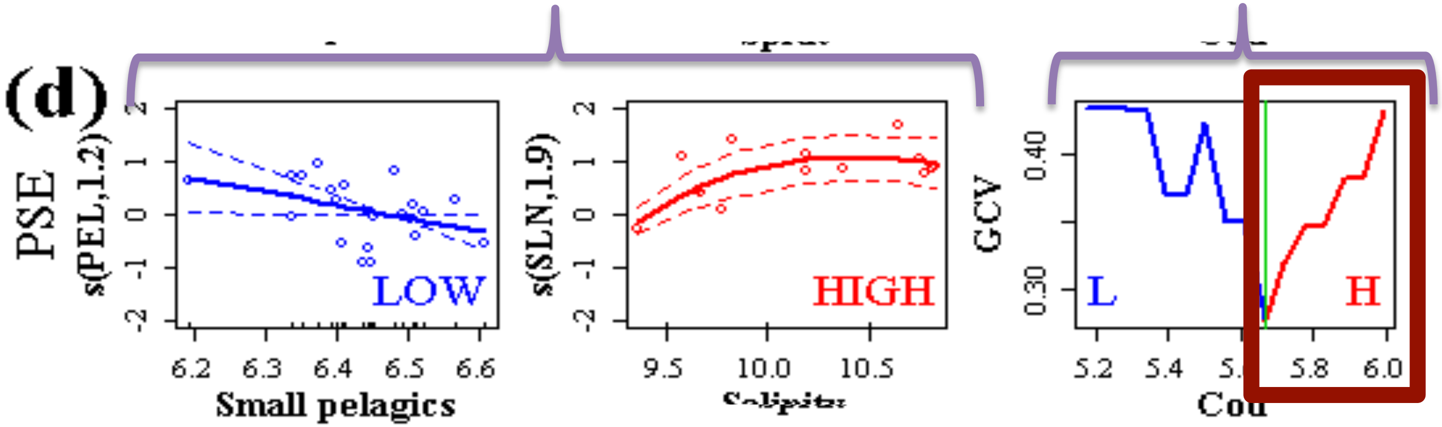
Example:

Pseudocalanus model

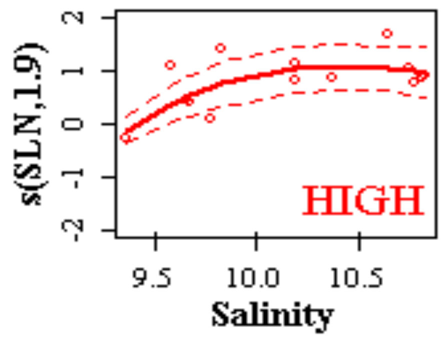
effects of covariates **Cod threshold**



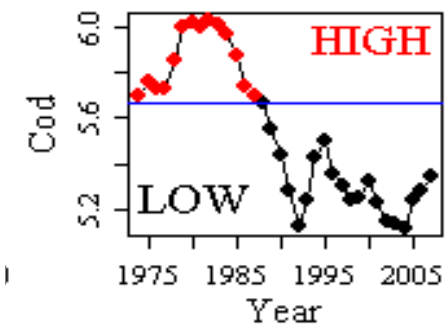
effects of covariates **Cod threshold**



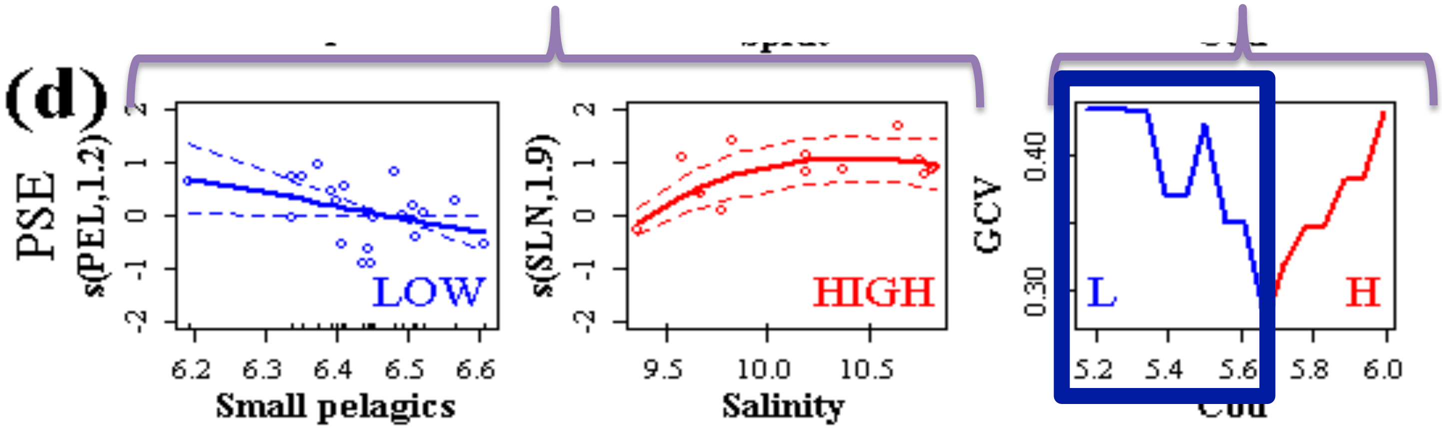
Salinity effect



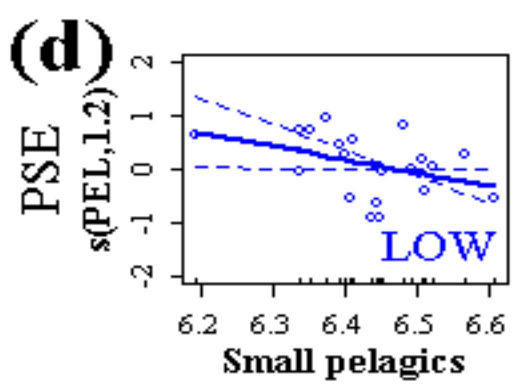
If cod is high



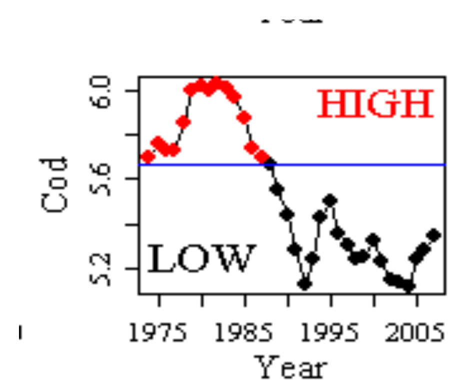
effects of covariates **Cod threshold**

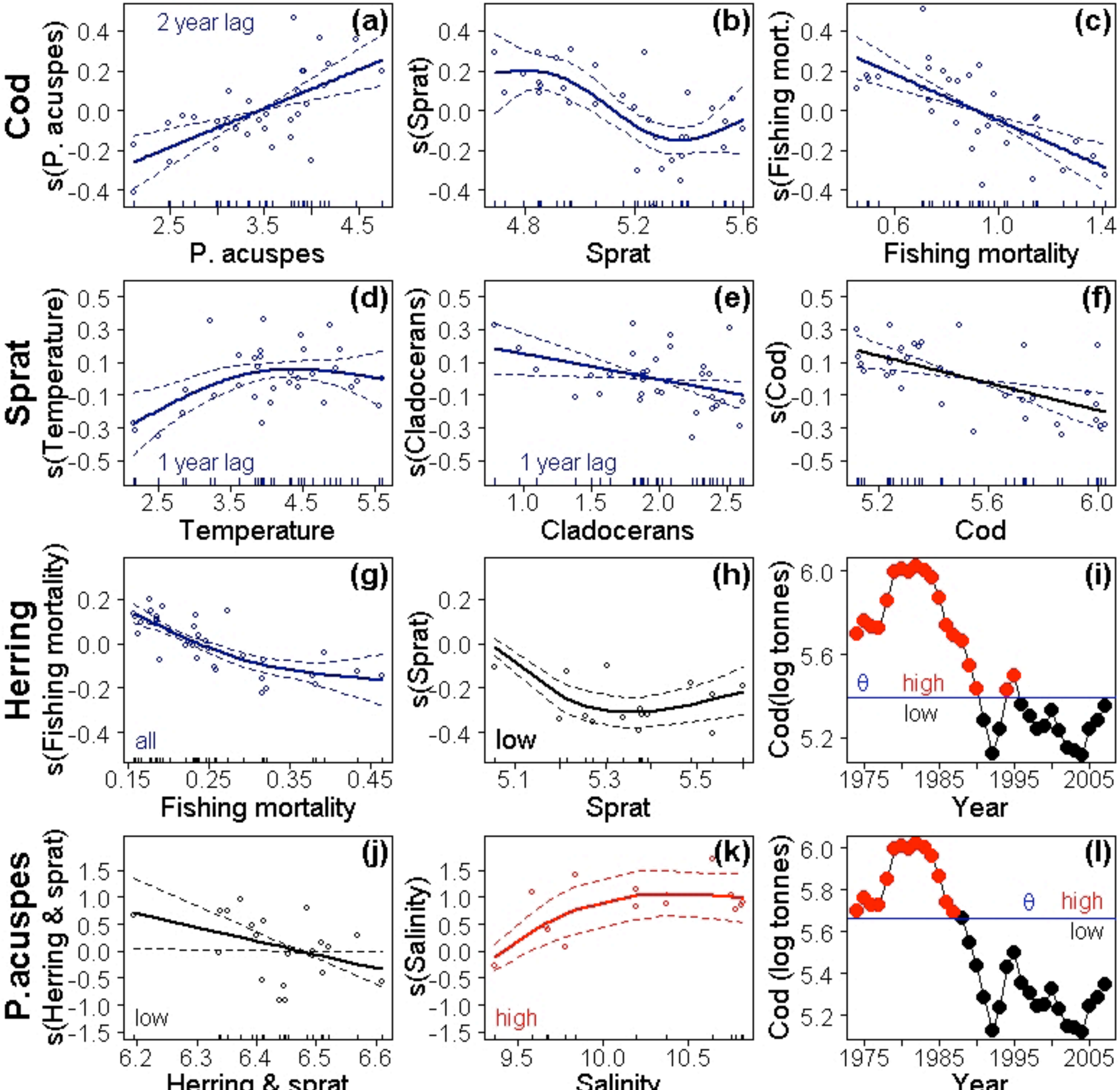


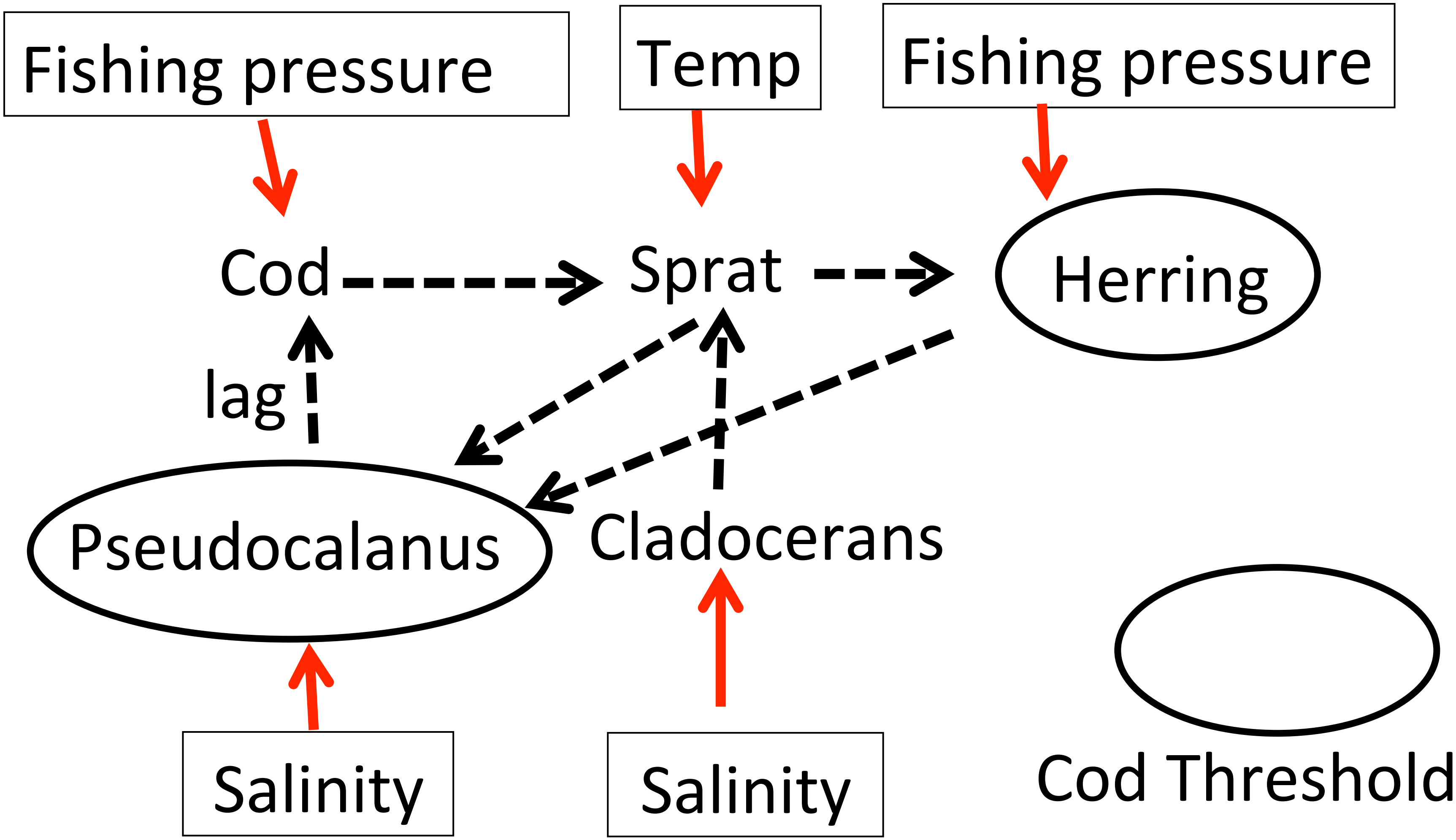
Consumption planktivorous fish



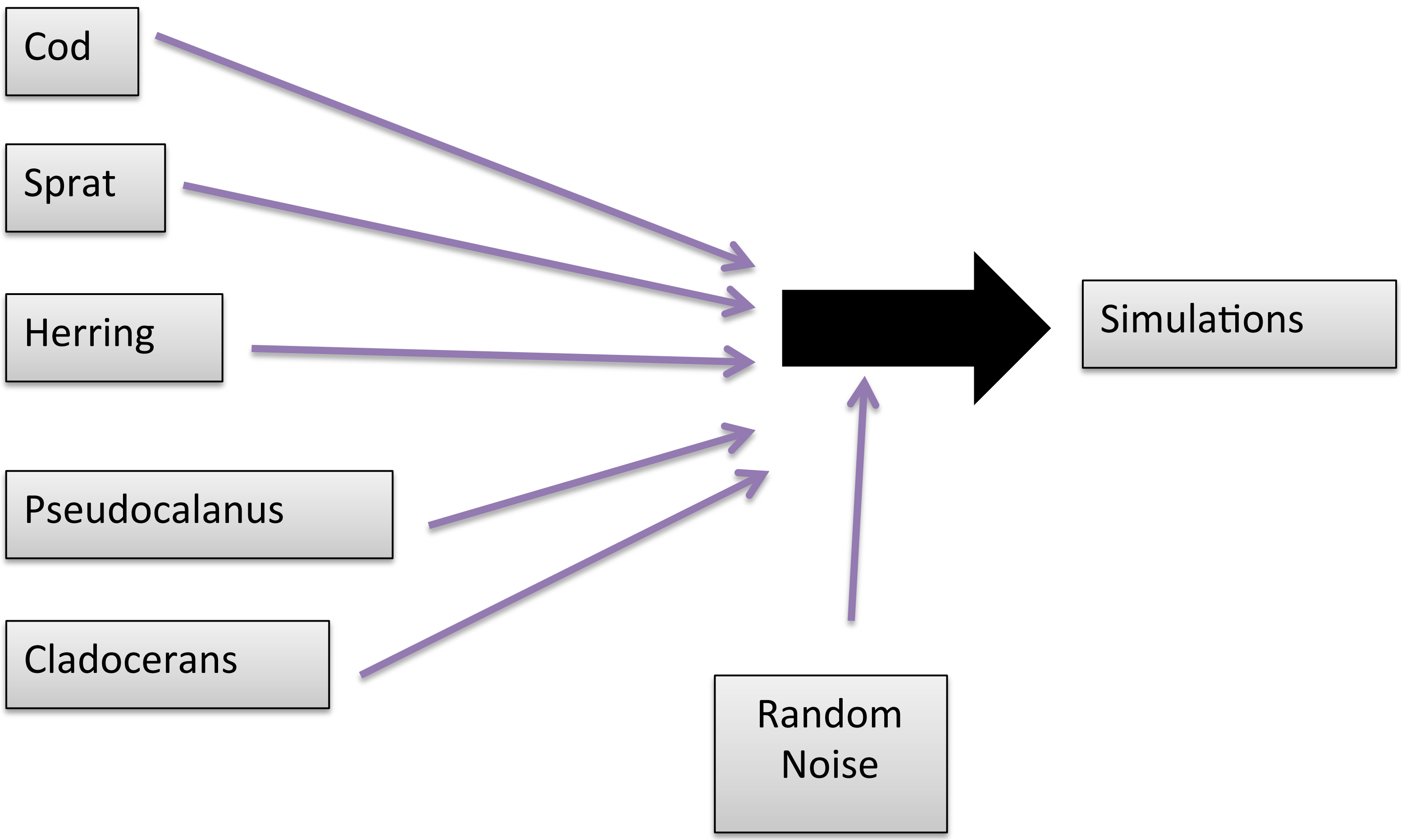
If cod is low




Cod
Sprat
Herring
P.acuspes
(a)
2 year lag
s(P. acuspes)
P. acuspes
(b)
s(Sprat)
Sprat
(c)
s(Fishing mort.)
Fishing mortality
(d)
s(Temperature)
1 year lag
Temperature
(e)
s(Cladocerans)
1 year lag
Cladocerans
(f)
s(Cod)
Cod
(g)
s(Fishing mortality)
all
Fishing mortality
(h)
s(Sprat)
low
Sprat
(i)
Cod(log tonnes)
θ
high
low
Year
(j)
s(Herring & sprat)
low
Herring & sprat
(k)
s(Salinity)
high
Salinity
(l)
Cod (log tonnes)
θ
high
low
Year

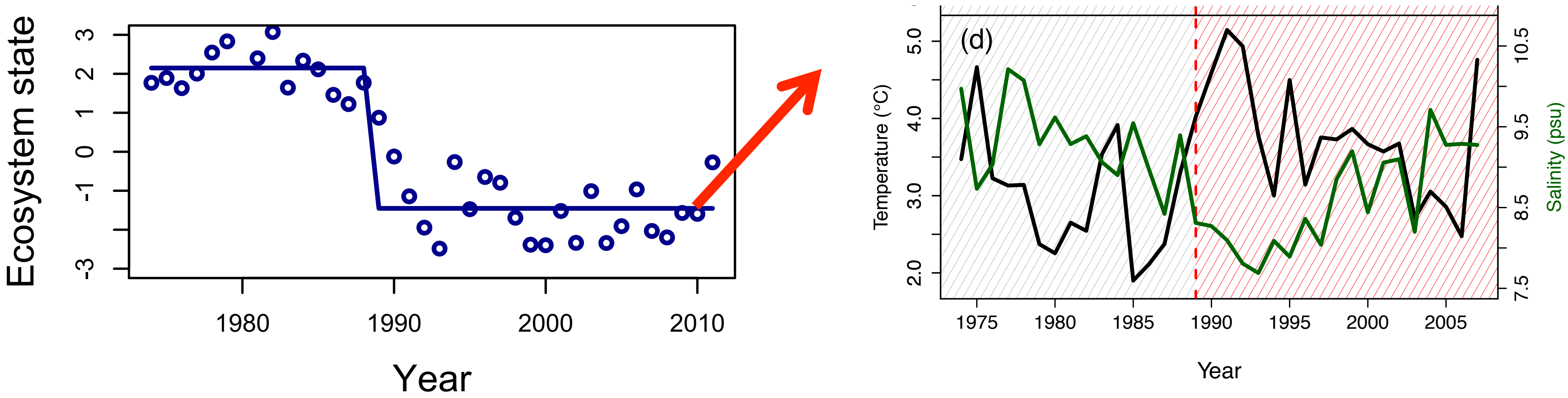

Fishing pressure
Temp
Fishing pressure
Cod
Sprat
Herring
lag
Pseudocalanus
Cladocerans
Salinity
Salinity
Cod Threshold

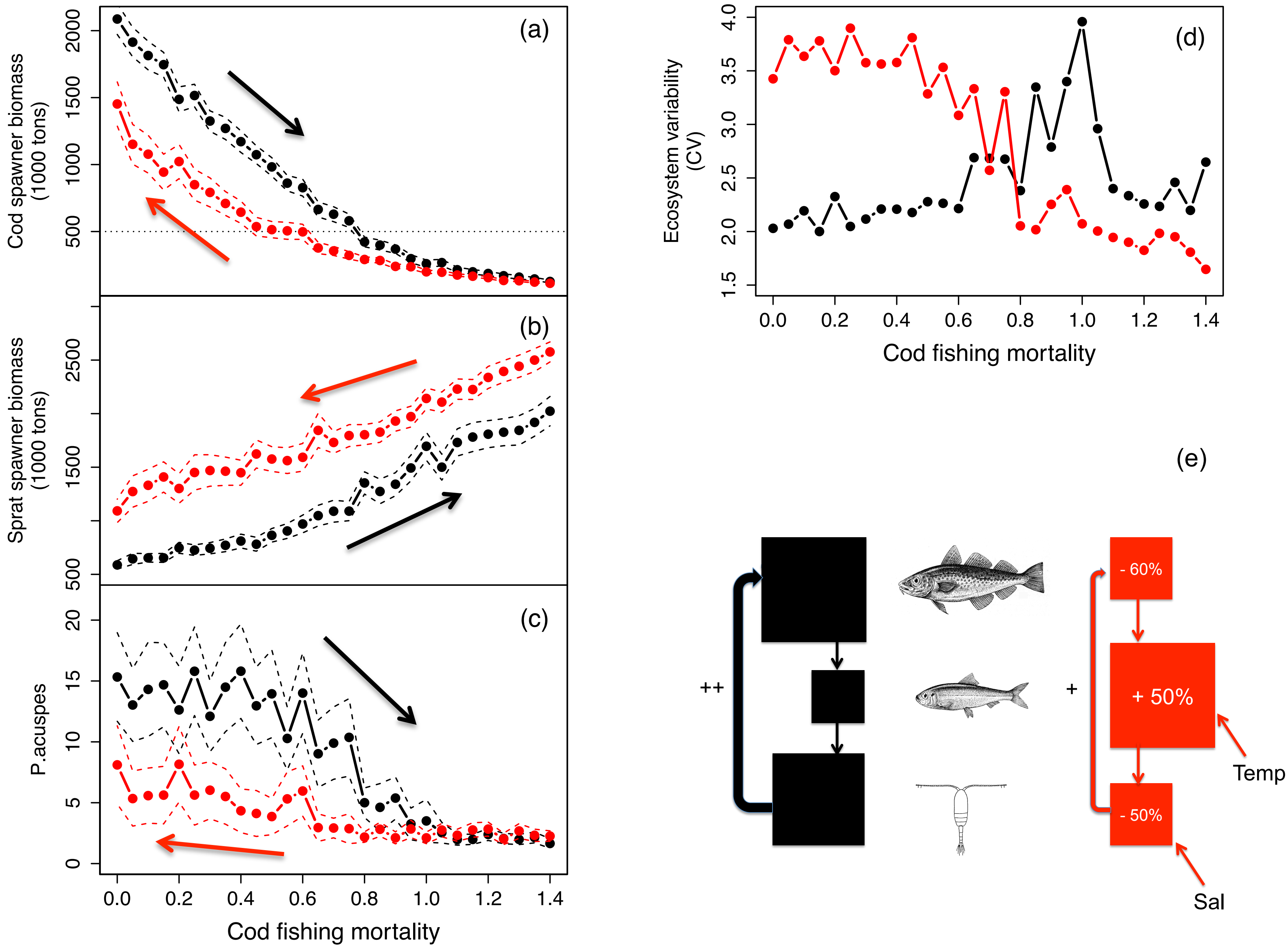
Building a joint model



Regeneration potential

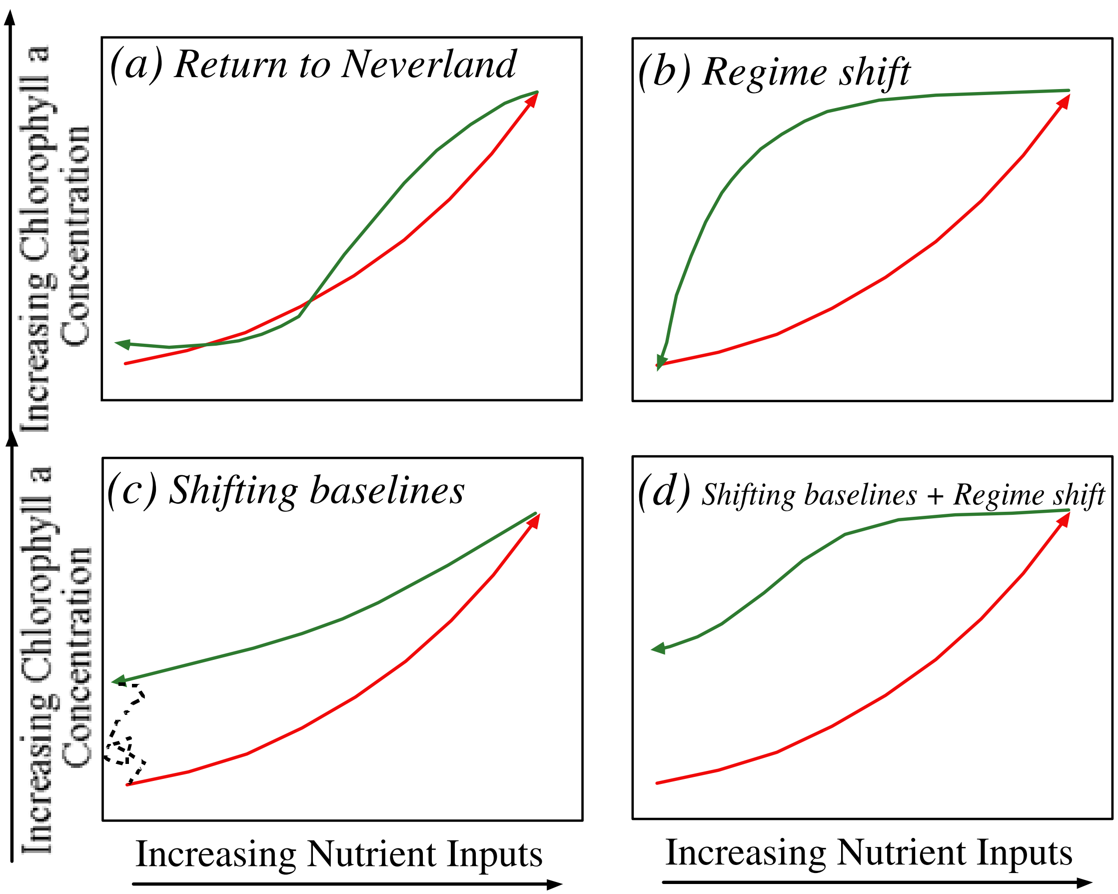
- To test the ability of the ecosystem to *regenerate* to a new cod-dominated state under todays environmental conditions





Blenckner et al 2015

Shifting baseline



Duarte et al 2009

Summary

- Both additive **and** threshold effects seem to exist in the Central Baltic Sea food-web
- Main drivers are fishing, temp. and salinity

- Hysteresis effects in three trophic levels
- Shifting baseline and higher variability
- Partly recovery to altered ecosystem state

=> Important for ecosystem-based management

Overall summary for the Baltic Sea

- Regime shifts in the Central Baltic and Kattegat but different processes and drivers
- Spatial effects i.e. Gulf of Riga
- Species dynamics and interactions vary spatially, no general ecosystem dynamics
- The effects of drivers is basin dependent, local and basin-specific management needed

Unknowns:

- Stengths of feedbacks
- Coastal-offshore
- Compounding effects of drivers and thresholds

Why are regime shifts important?

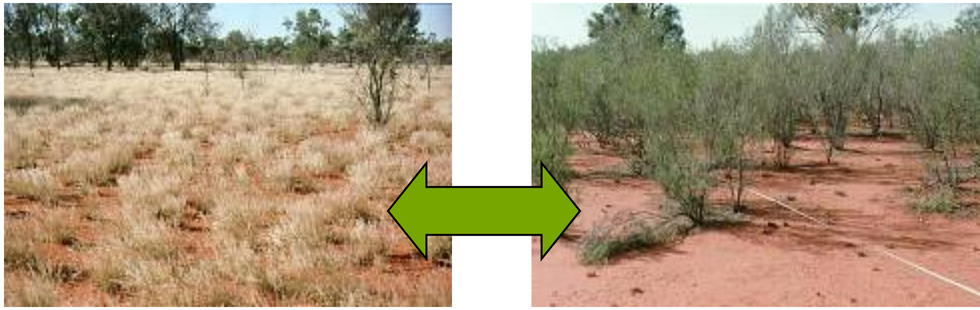
They often have large impacts on human wellbeing,

Are often difficult and costly to reverse,

Are difficult to predict, often occur unexpectedly.

Regime shifts require management approaches which:

- Assess the ecosystem dynamics and regimes
- Cope with shifts
- Cope with trigger factors

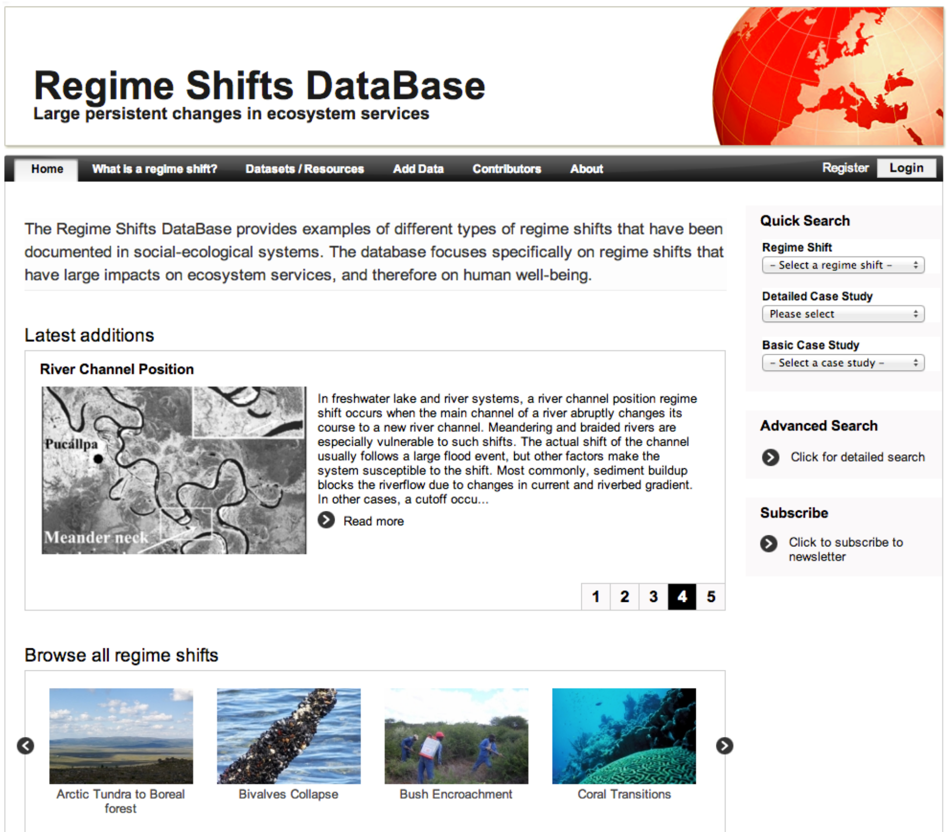


Research Frontiers

- Comparison of regime shifts
- Early warning signals
- Cross-scale dynamics that shape regimes
- Regimes & ecosystem service dynamics
- Methods, e.g. to account for ecosystem state

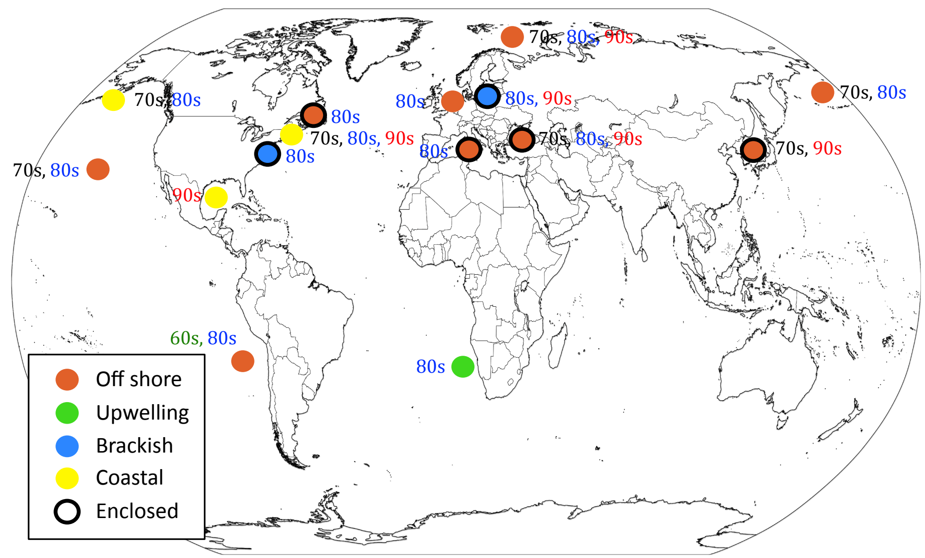
Comparing Regime Shifts

Literature Synthesis



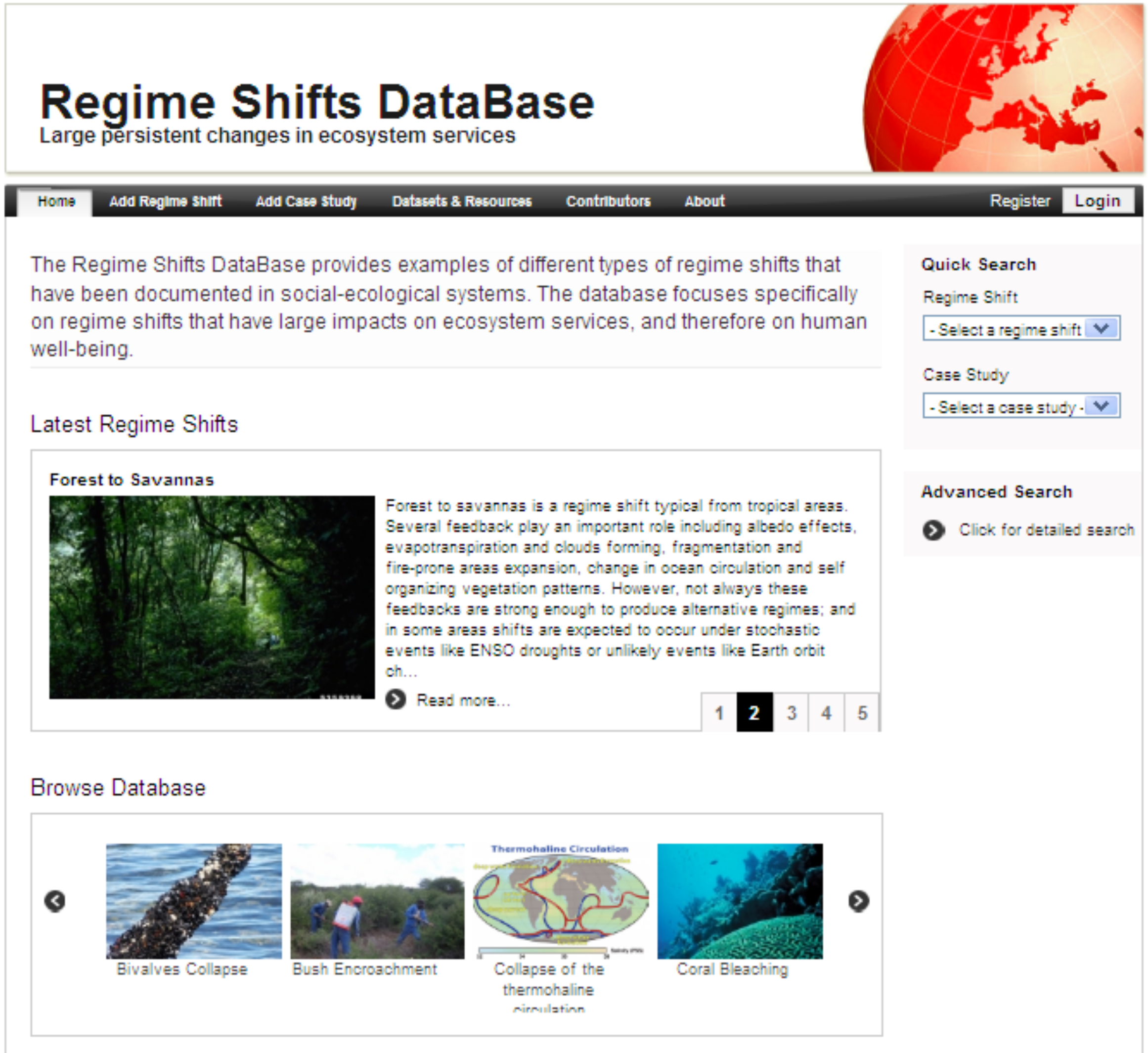
www.regimeshifts.org

Emprical Regime Shifts



Regime Shift Database

www.regimeshifts.org



AQUATIC SYSTEMS

1. Coral transitions
2. Kelp transitions
3. Bivalve collapse
4. Fisheries collapse
5. Marine food webs
6. Eutrophication
7. Hypoxia
8. Floating plants

CLIMATE SYSTEM

9. Ice sheet collapse
10. Summer Arctic sea ice
11. Thermohaline circulation
12. Monsoon collapse

TERRESTRIAL SYSTEMS

13. Bush encroachment
14. Forest – Savanna
15. Savanna – Desert
16. Tundra – Steppe
17. Tundra - Boreal
18. Soil Salinization
19. Salinization - snow geese

STRONG SOCIAL FEEDBACKS

20. Forest - Cropland
21. Dammed Rivers
22. Locust plagues – outbreaks
23. Development Poverty trap
24. Ecosystem management
25. Urban Sprawl

‘Not only is the science incomplete, but the [eco]system itself is a moving target, evolving because of the impact of management and the progressive expansion of the scale of human influences on the planet’

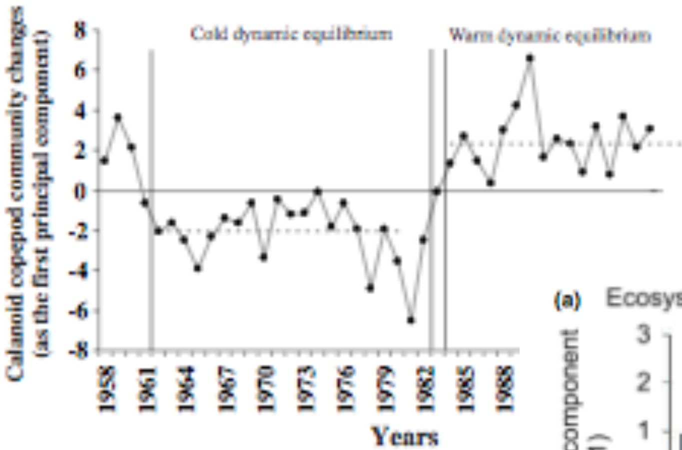
Holling C.S. (1995)

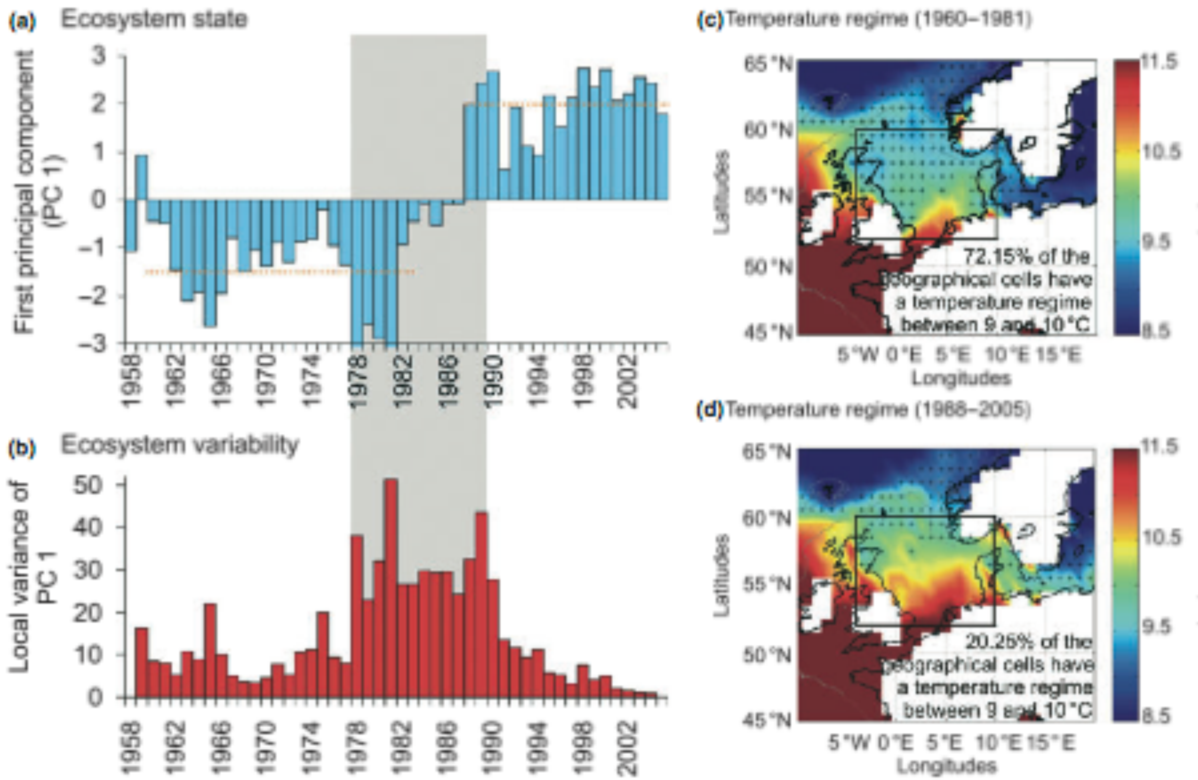
Thank you!

thorsten.blenckner@stockholmresilience.su.se

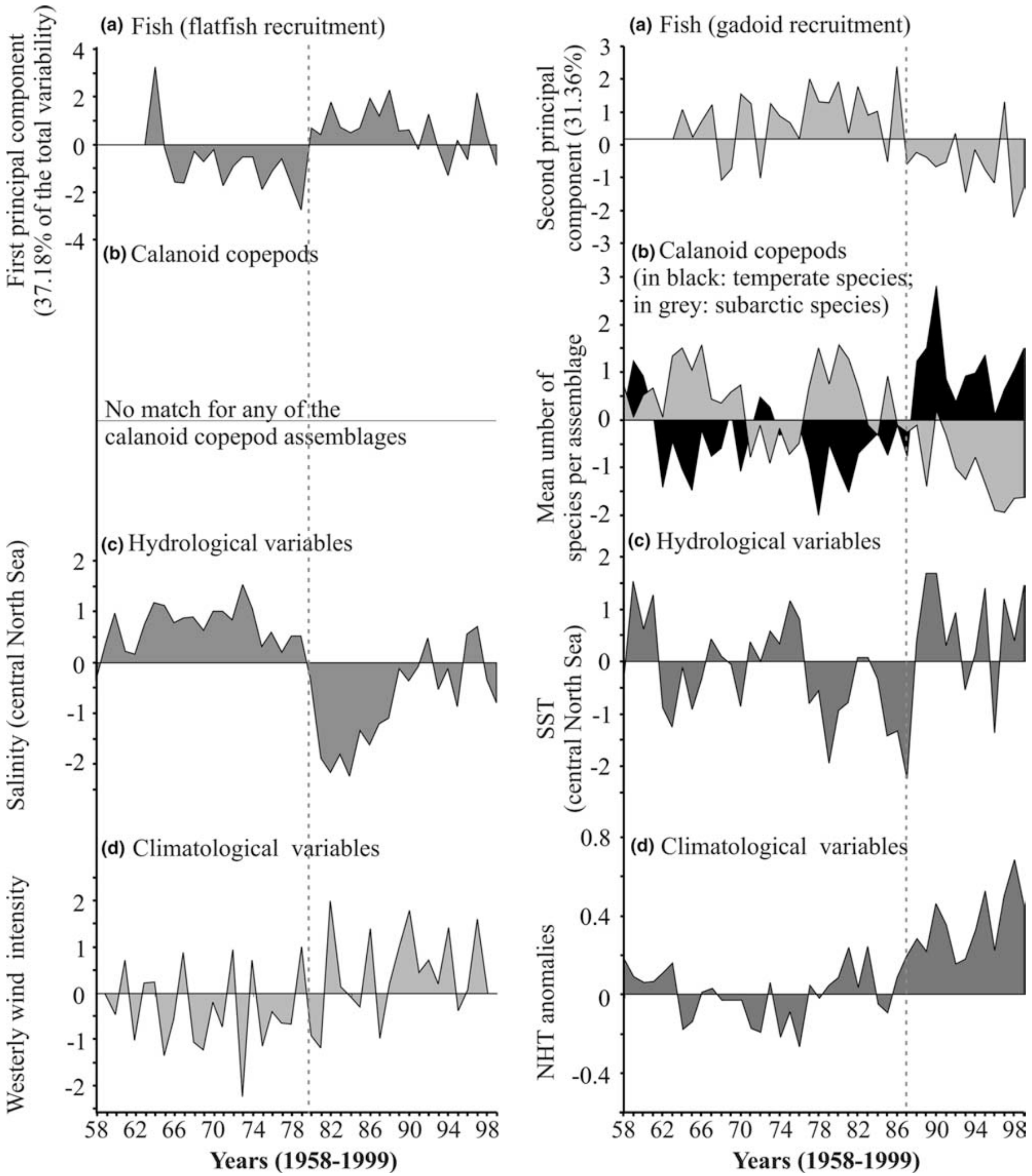
Special thanks to the BEAM project www.smf.su.se/beam
the Stockholm Resilience Theme on Regime Shifts
the Nordic Centre of Excellence- NorMer, www.normer.uio.no
the Formas "Regime Shift project", www.balticnest.org
the researchers performing monitoring and data analysis

Changes in zooplankton





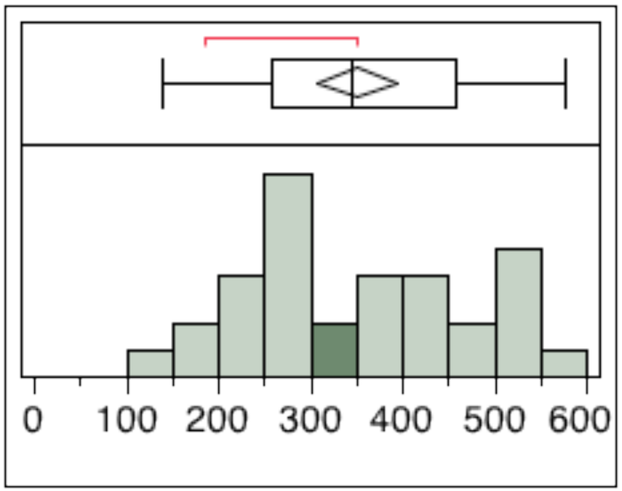
North Sea



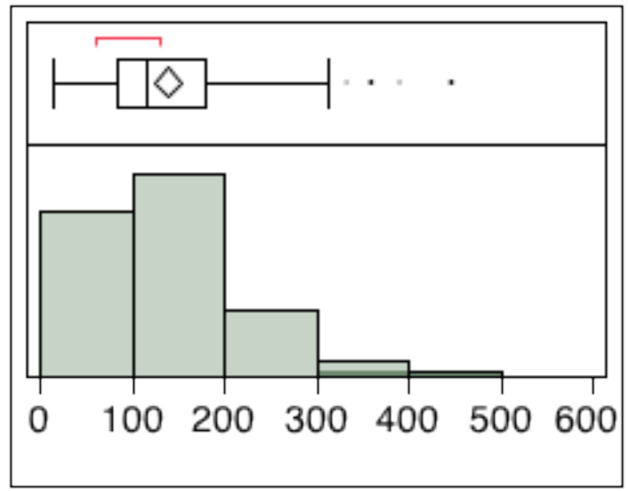
Beaugrand 2004

Cod reproductive volume
Changes in the future

1974-2006



2010-2040



Needs to be accounted by management