# Integrative approaches to assess marine ecosystem health

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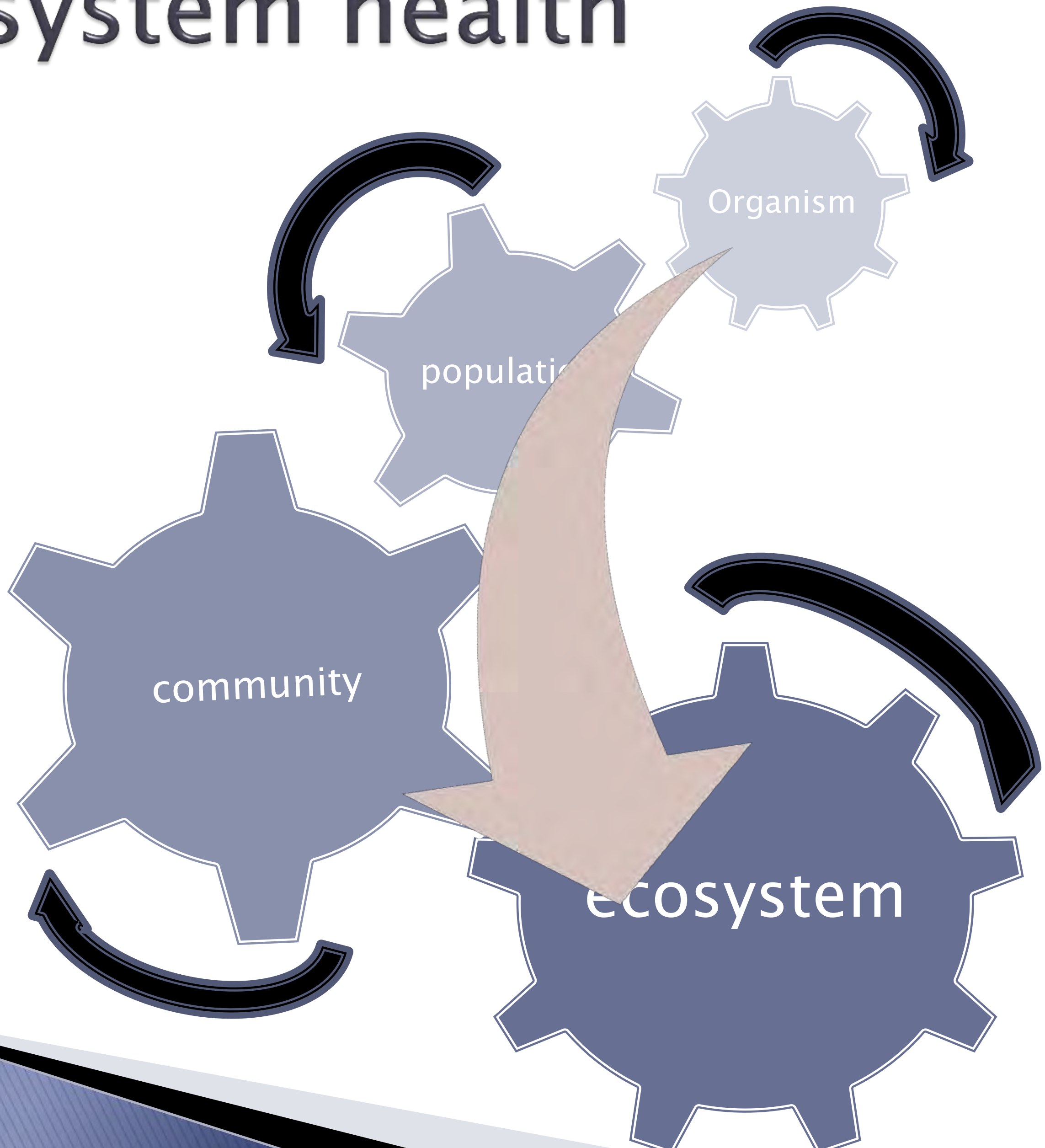
# Ecosystem health

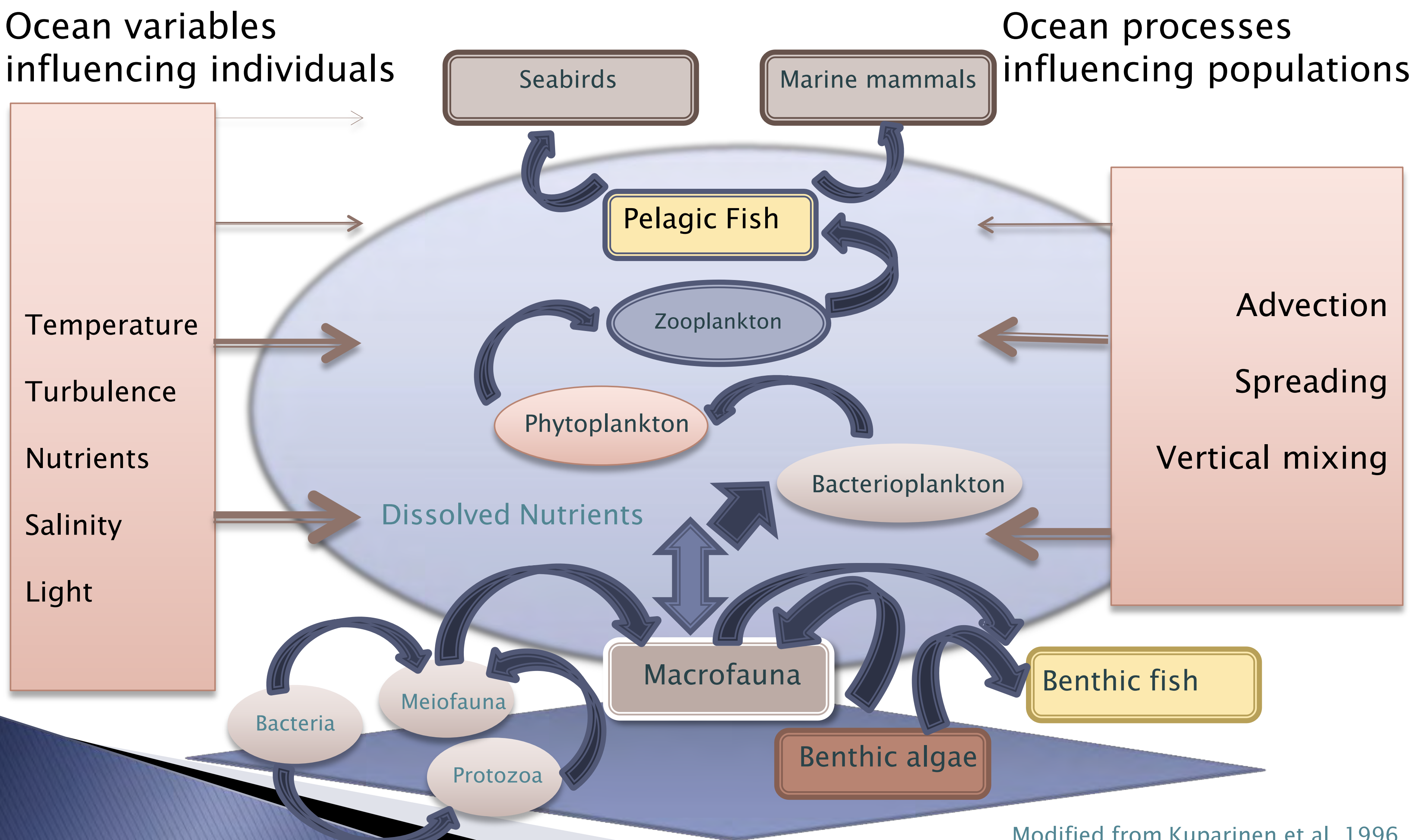


# Ecological health and disturbance

- Natural and anthropogenic stressors can affect ecosystem functioning

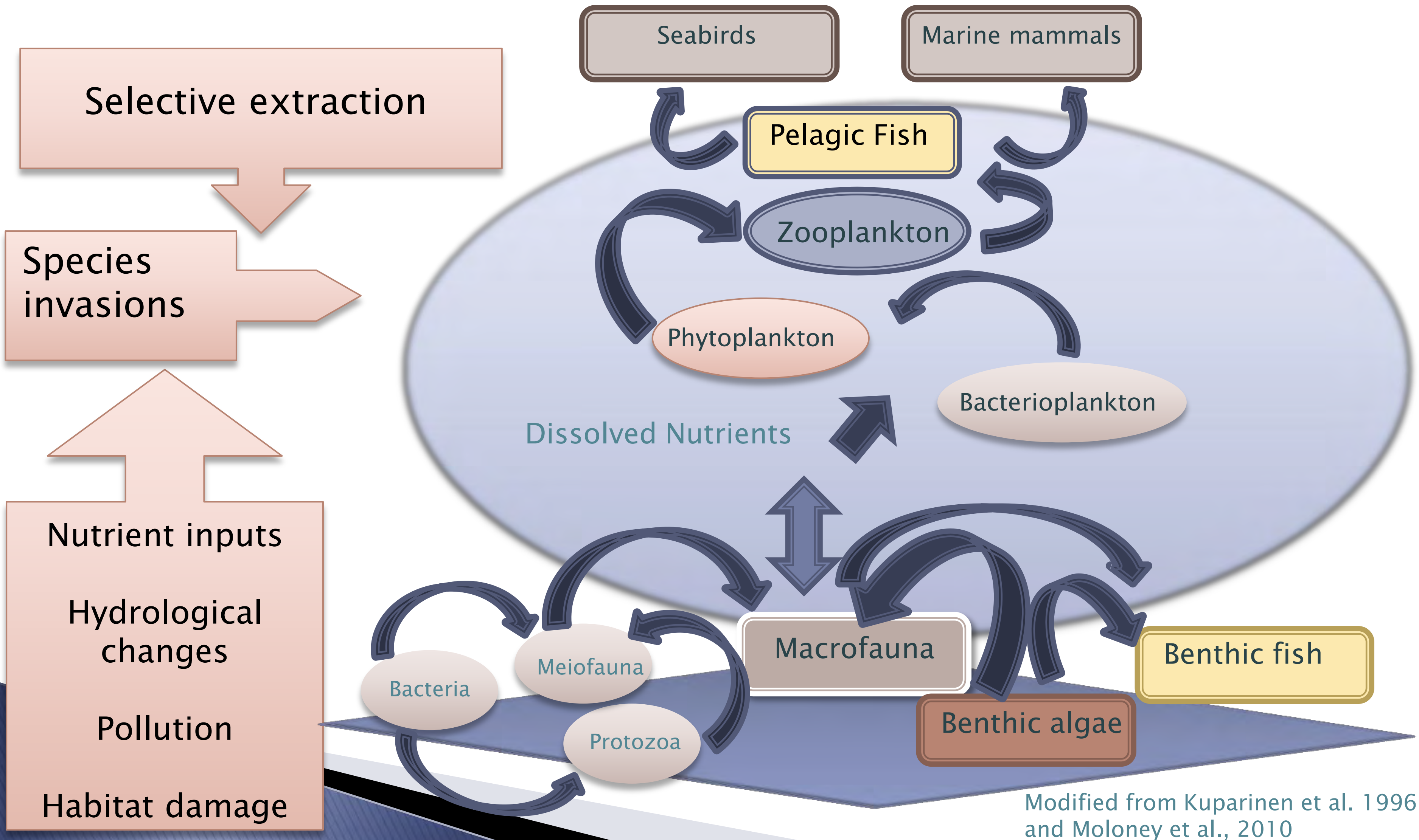
- Interaction types of stressors:
  - Response level: species, community, ecosystem (Crain et al. 2008)
  - Trophic level > pathways of pressures
    ( bottom-up/top-down) (Moloney et al., 2010)
  - Type of stressors pairs

# Environmental forcing hierarchy




Modified from Kuparinen et al. 1996 and Moloney et al., 2010

# Pathways of anthropogenic pressures



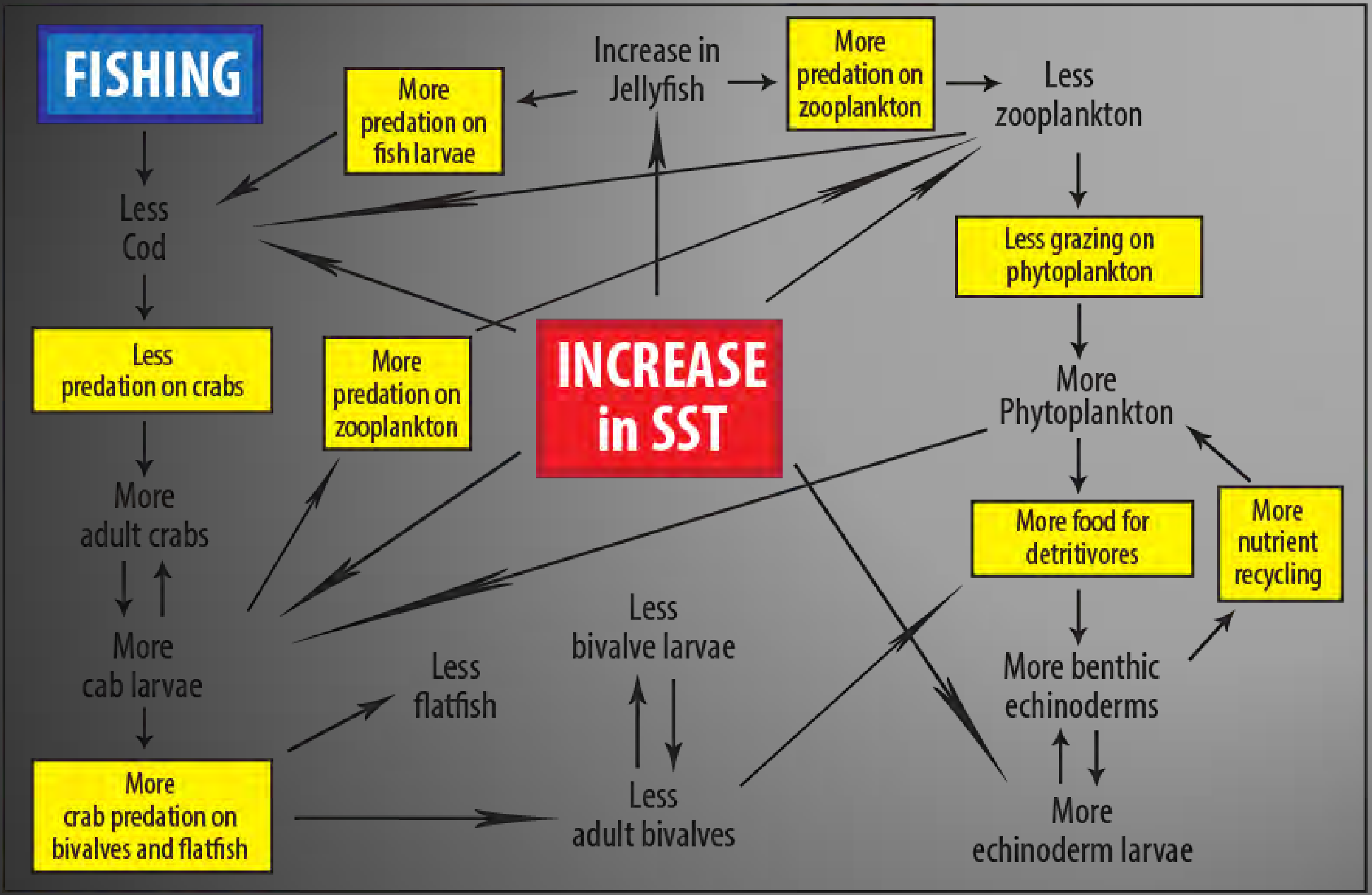

Modified from Kuparinen et al. 1996 and Moloney et al., 2010

| | Hl | Hc | Pd | Sr | Tc | Sa | Wf | Er | We | Li | Nc | Sc | Do | Ne | Oe | Pa | In | Rs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Habitat loss (to land) (Hl) | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Habitat change (to another marine habitat) (Hc) | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Physical disturbance (Pd) | X | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Siltation rate changes (Sr) | X | X | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Temperature change (Tc) | X | ↑ | ↑ | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Salinity change (Sa) | X | X | X | X | ↑ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Water flow (Wf) | X | X | X | X | X | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Emergence regime (Er) | X | X | X | X | X | ↕ | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Wave exposure changes-local (We) | X | X | X | X | X | X | X | X | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Litter (Li) | X | X | X | X | X | X | X | X | X | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| Non-synthetic compounds (Nc) | ↑ | ↑ | ↑ | X | ↕ | ↓ | X | X | X | X | _ | _ | _ | _ | _ | _ | _ | _ |
| Synthetic compounds (Sc) | X | X | X | X | ↕ | ↓ | X | X | X | X | X | _ | _ | _ | _ | _ | _ | _ |
| De-oxygenation (Do) | ↑ | ↑ | ↑ | X | X | X | X | X | X | X | X | X | _ | _ | _ | _ | _ | _ |
| Inorganic nutrient enrichment (Ne) | ↕ | X | X | ↑ | + | + | X | ↑ | X | X | ↓ | ↓ | X | _ | _ | _ | _ | _ |
| Organic enrichment (Oe) | X | X | X | X | X | X | X | X | X | X | X | X | ↑ | ↕ | _ | _ | _ | _ |
| Introduction of microbial pathogens (Pa) | X | + | + | X | X | ↑ | X | X | X | X | ↕ | X | X | X | X | _ | _ | _ |
| Introduction/spread of non-indigenous species (In) | X | X | X | ↕ | X | X | X | X | X | X | X | X | X | X | X | X | _ | _ |
| Removal of target and non-target species (Rs) | X | X | X | X | X | X | X | X | X | X | X | X | X | ↕ | X | X | X | _ |

(+) additive; (↑) synergistic; (↓) antagonistic; (↕) complex; (x) insufficient evidence (--) not applicable.

# Interactions pairs of pressures

From Crowe et al. (2013) SYMBIOSIS




# Synergistic effects of climate and fishing

Kirby et al., 2009

# Ecological health and management

- Cause-effect relationships (e.g. DPSIR)

  (Atkins et al. 2011)

- Linear approach > development of a theory of ecosystems as complex adaptive systems (CAS):
  - emergent properties;
  - adaptation;
  - self-organisation;
  - non-equilibrium behavior;
  - path dependency

- Systems with low resilience: particularly vulnerable to impacts of multiple stressor events

- Interest and development systemic approaches in management relatively new (Paucer-Caceres and Espinosa 2011)

# Assessment of health

- aggregate of contributions: components and processes
- **structural and functional** properties
- **combine indicators:** attributes, biological and habitat components, in relation to pressure-impacts

Composite view

e.g. Rombouts et al. (2013) Ecol. Indic

- integration of components; patterns of system behaviour;
- **emergent properties**: resilience, stability
- **state-space approach**: characterise ecosystem state and pressures

Systemic view

e.g. Tett et al. (2013) MEPS

# Holistic assessment


Adapted from
Tett et al., 2013

# Integrative approaches

Development of health indicators: key ecosystem factors

Integrative methods/tools

Descriptive and functional attributes

Physico-chemical habitat and biological attributes

Ecological interactions and variability

# Aggregation of attributes

- descriptive and functional

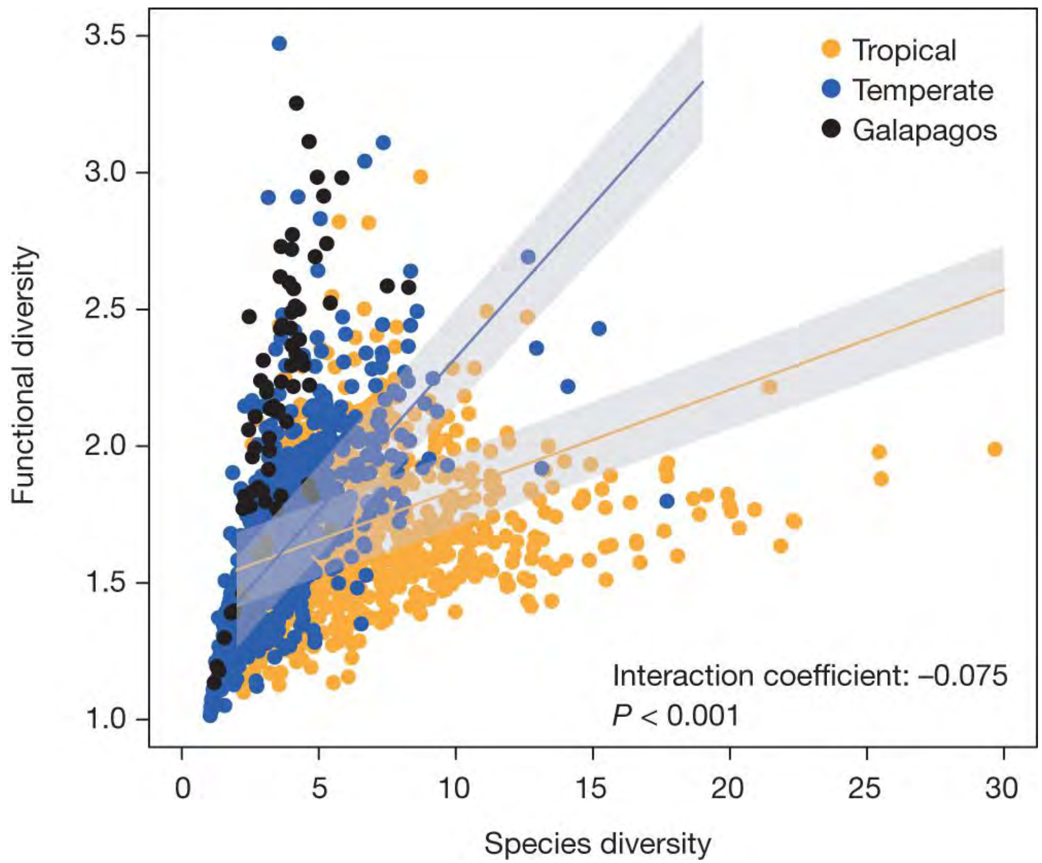
# Biodiversity

"Presence of one or a handful of
species, rather than the overall diversity of an ecosystem, is often the determinant of stability against different perturbations"

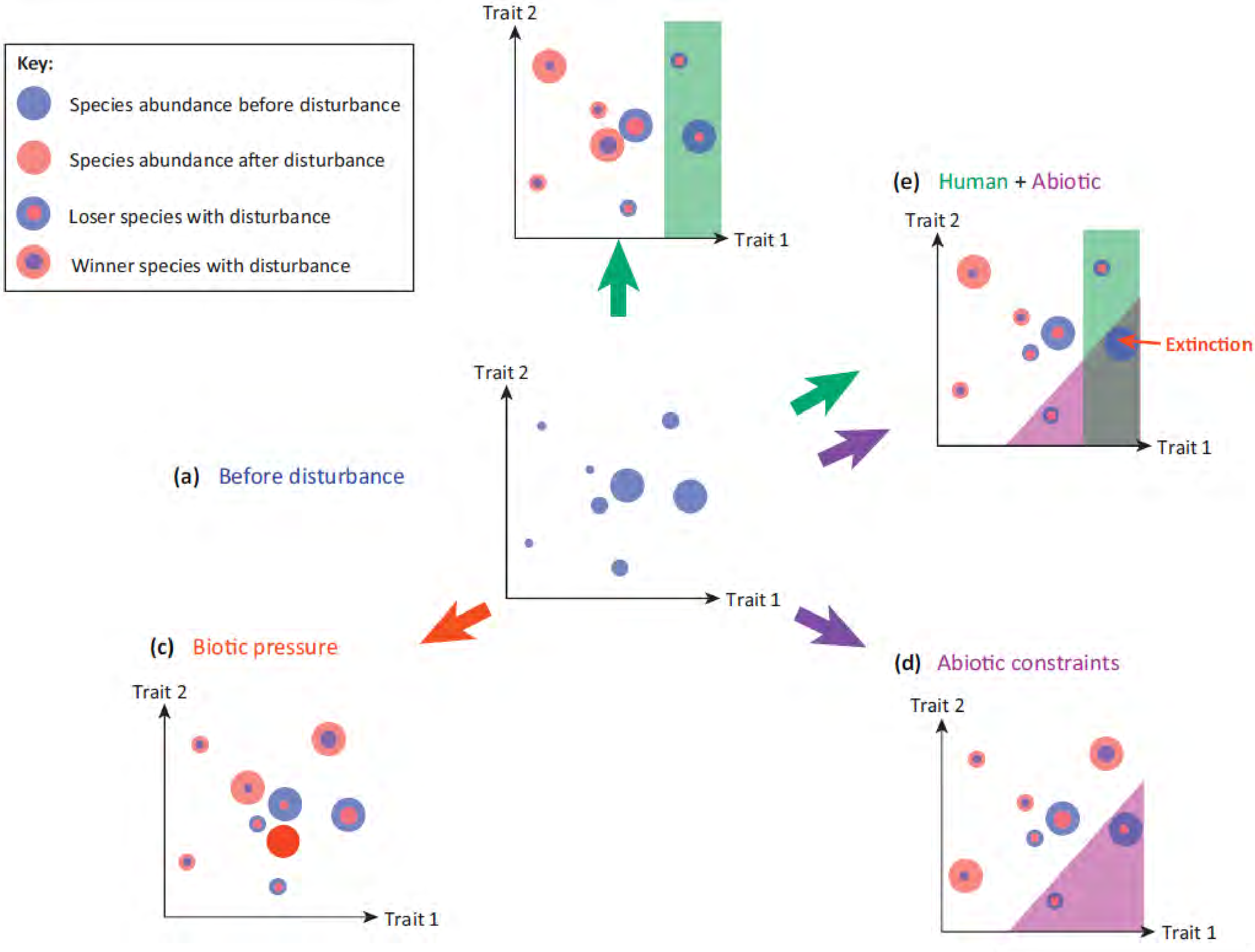
Ives and Carpenter (2007) Science

Genetic diversity?

Response diversity?

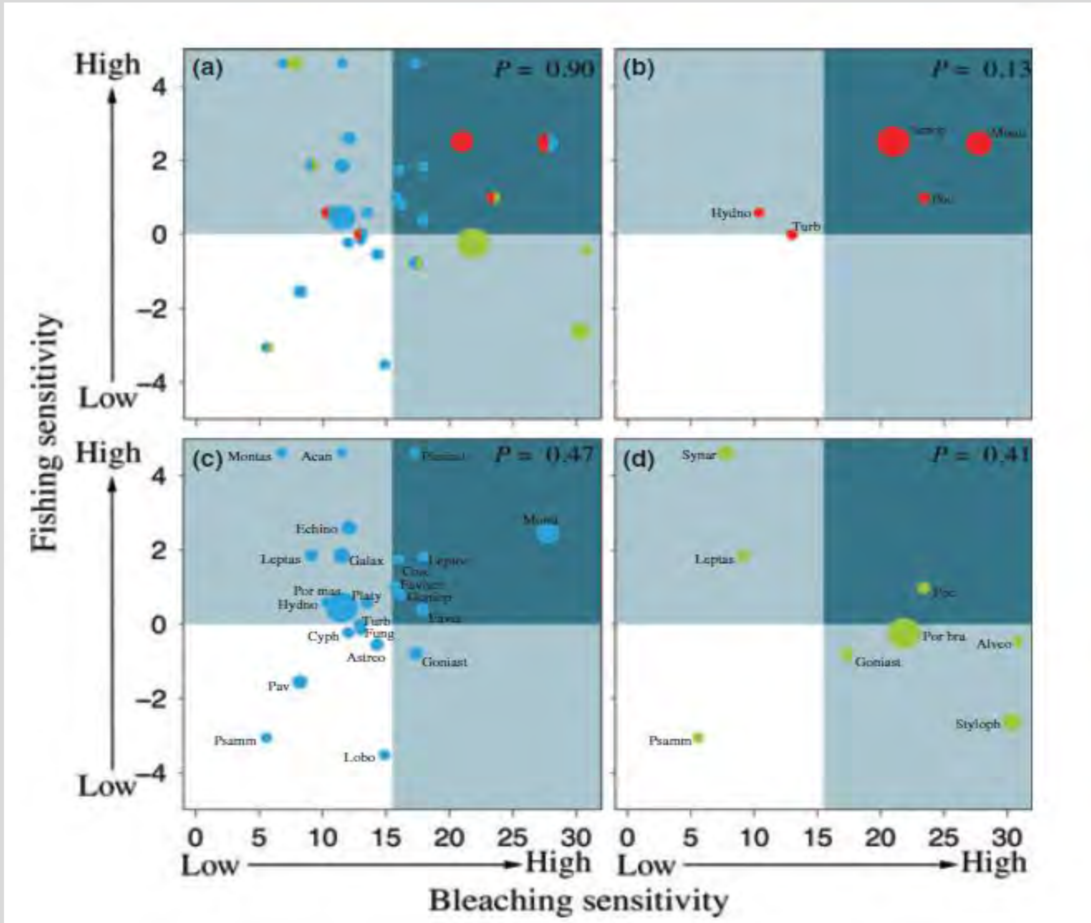



Stuart-Smith et al. Nature (2013)




# Theoretical changes in the functional structure of a species community

Mouillot et al. 2013 TREE




# Life histories and cotolerance of reef-building corals under multiple stressors

Darling et al. 2013 GCB

# Plankton indicators and climate

Trait-based descriptions of plankton communities

Litchman et al., 2013

Indicators > Aggregation of attibutes

(1) the abundance of individual taxa;
(2) functional attributes;
(3) species assemblages;
(4) links with higher trophic levels

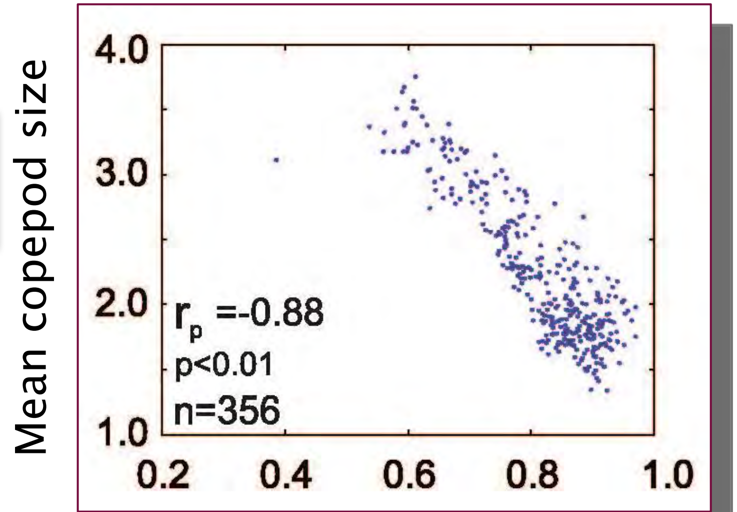
community structure– biogeochemical cycling – trophic interactions – transfer of energy – resilience

Beaugrand et al., 2005; Rombouts et al., 2013

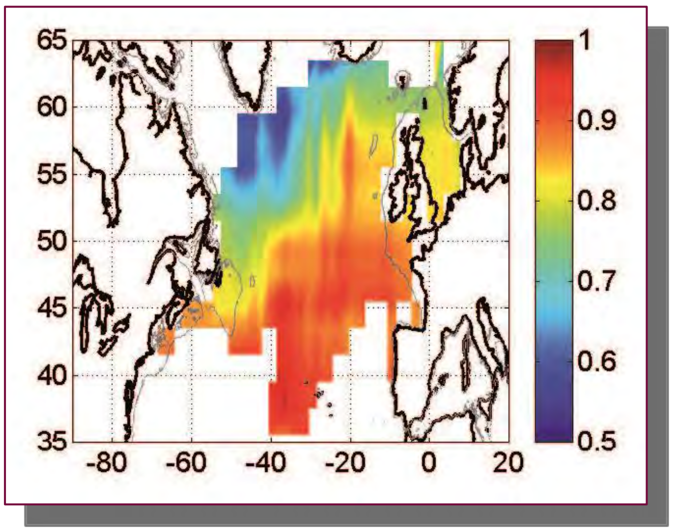
# Plankton indicators and climate

Marine biodiversity, ecosystem functioning, and carbon cycles

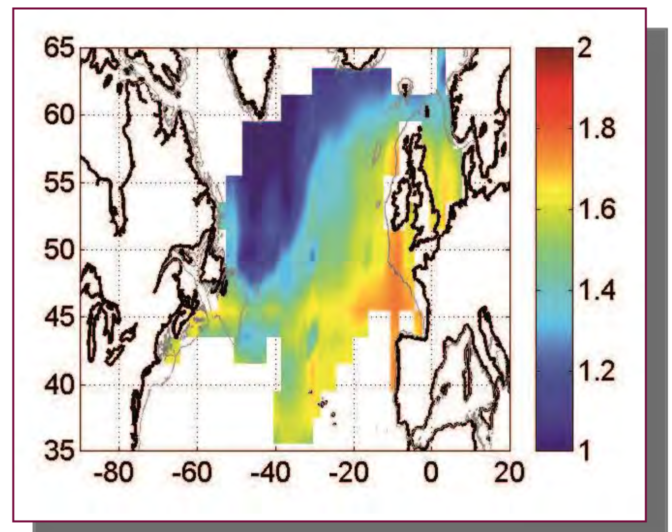
Beaugrand et al. 2010, PNAS




Mean copepod biodiversity



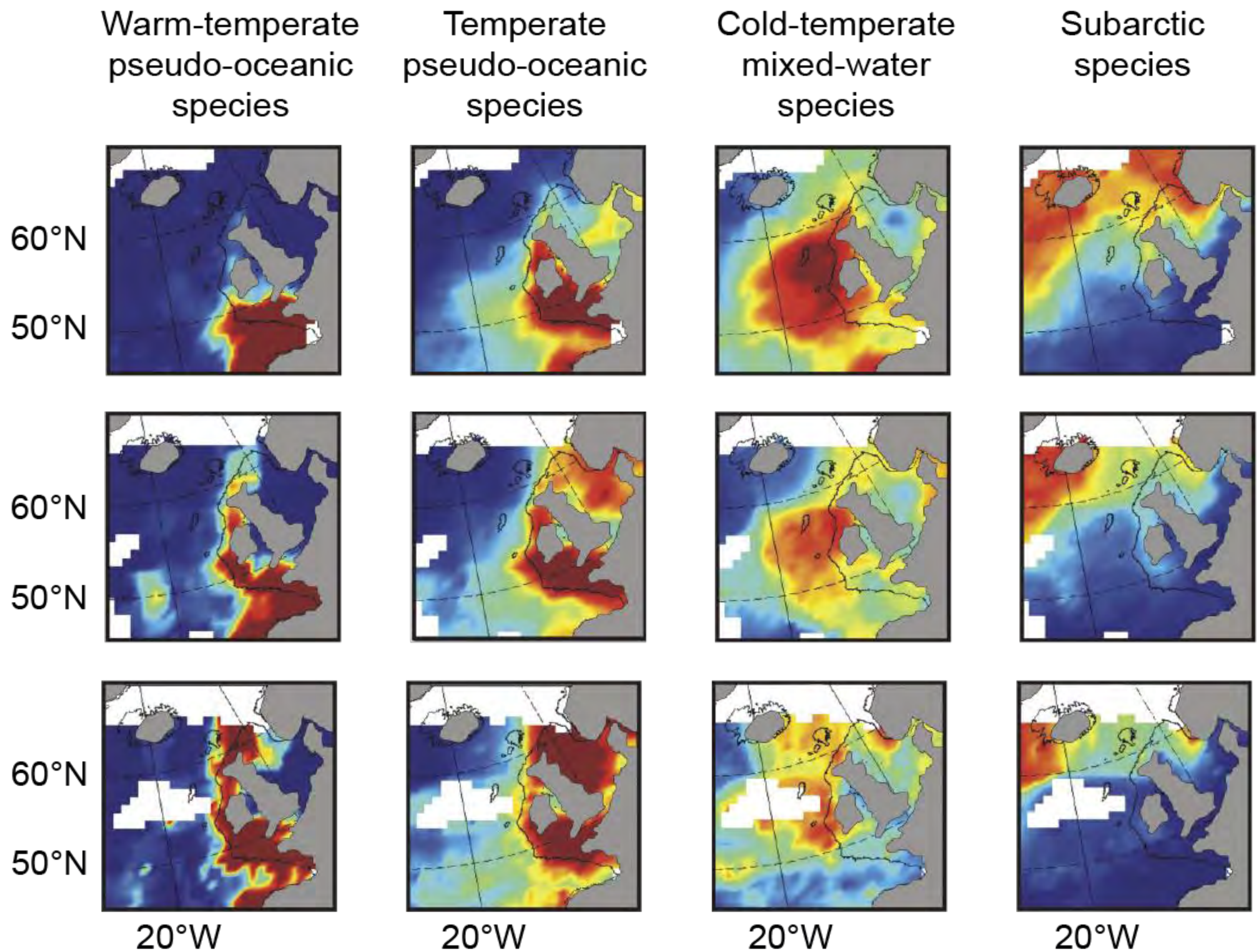

Mean copepod diversity in the North Atlantic




Mean residence time of particulate carbon (days)

# Plankton indicators and climate

- Increase in warm–water assemblages northwards
- Assemblage indicator facilitates the interpretation of changes in copepod community in the North Atlantic




Mean number of calanoid copepod species / CPR sample

Beaugrand et al. 2002 Science
Rombouts et al. 2013 Ecol. Ind.

# Aggregation of components

- Trophic groups and their interactions

# Trophic indicators

- Trophic interactions – whole system energy flow:
  ecosystem-level assessment

- Integrative and functional indicators that consider
  under MSFD (Rombouts et al. 2013)
  (1) multiple trophic levels or whole-system approach,
  (2) processes and linkages, e.g. trophic transfer efficiencies, connectance and material cycling,
  (3) the dynamics of food webs in relation to specific anthropogenic pressures.

- Complementary use of empirical and modelling approaches to derive population, community and ecosystem indicators

# Trophic indicators: tools

- *In situ* **techniques**: stable isotopes' analysis; stomach contents' analysis; Fatty Acid Trophic Markers (FATMs)

- **Theoretical/empirical models**:

  - ecosystem responses to **different stressors**
    (e.g. Christensen et al. 2007, Fulton 2010)
  - patterns of interactions and processes of **regime shifts**
    (e.g. Tomczak et al 2013)
  - measure the **resistance and resilience** of food webs to multiple pressures (e.g. Vallina and Lequéré 2011)

Combination of tools > integrative view of ecosystem health

# Trophic indicators: case studies

| | |
|---|---|
| Stable isotope analysis | *+ fatty acid trophic marker*<br>**organic matter sources** (Spilmont et al. 2009) |
| | *+stomach analysis*<br>**impacts of invasive species** (Syväranta et al. 2009) |
| | *+ chemistry assessment*<br>**origin of anthropogenic waste** (e.g. Fertig et al. 2009) |
| | *+ mass-balance model*<br>**fishing pressure – trophic pathways** (Fry et al. 2006) |
| | *+ multivariate analysis*:<br>**climatic factors – nutrient enrichment** (Grangéré et al. 2009) |

Rombouts et al. 2013

# Integration of components

- trajectory and resilience

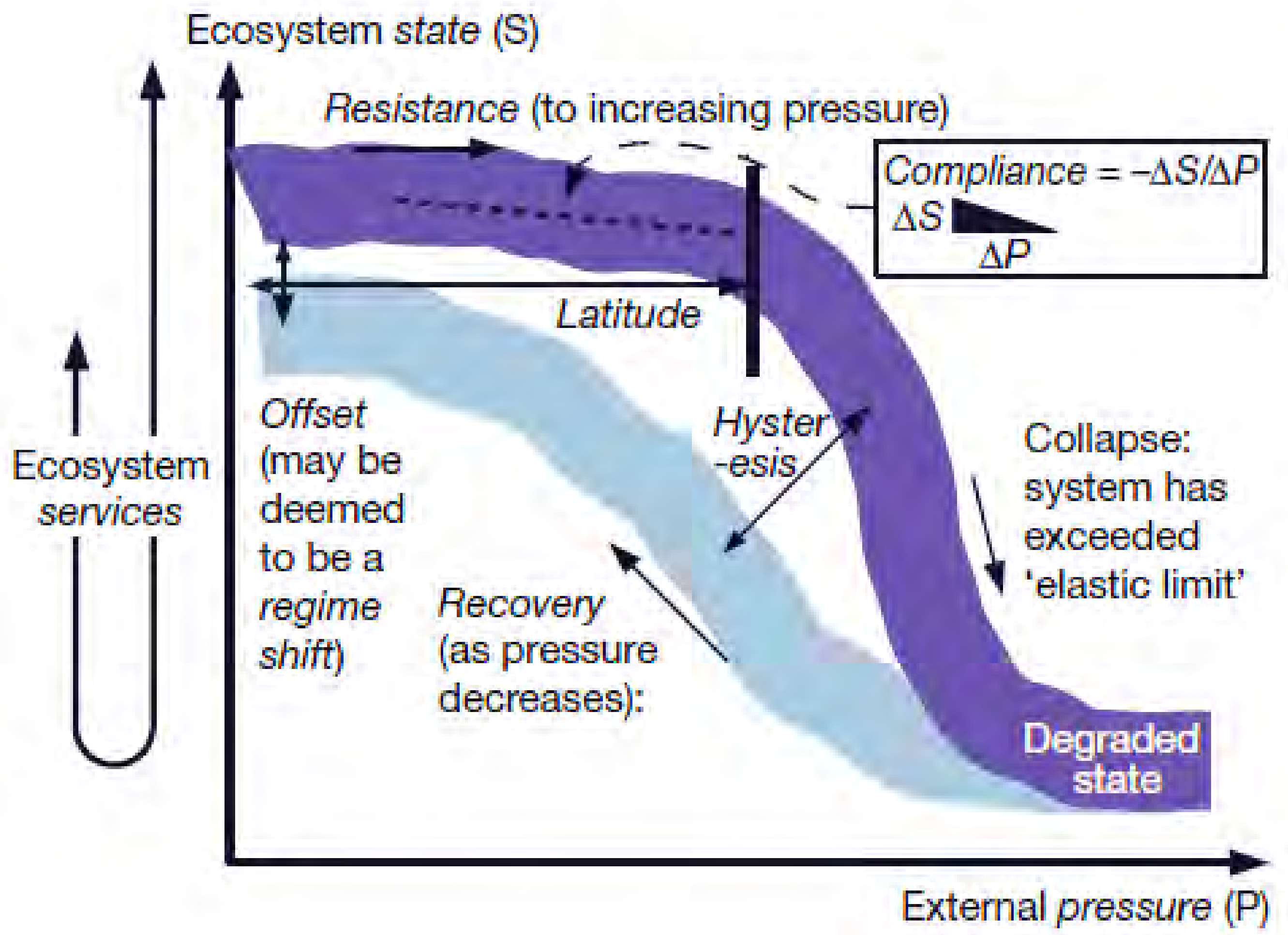
# Ecological resilience

- key to management of complex systems
  (e.g. Gunderson, 2000)

- non-linear dynamics – uncertainty and surprise – multiple stability domains – tolerance to perturbations

- emerges from « organisation and vigor »

# Ecological resilience and pressures




From Tett et al., 2013 MEPS

# State-space approaches

**concept**

- Essential variables (n-dimensions)
- No time axis
- Complexity, stability and change
- Non-linearity

**objectifs**

- Quantify « trajectory » « resilience »
- Identification of reference domain
- Detect major shifts in ecosystem states

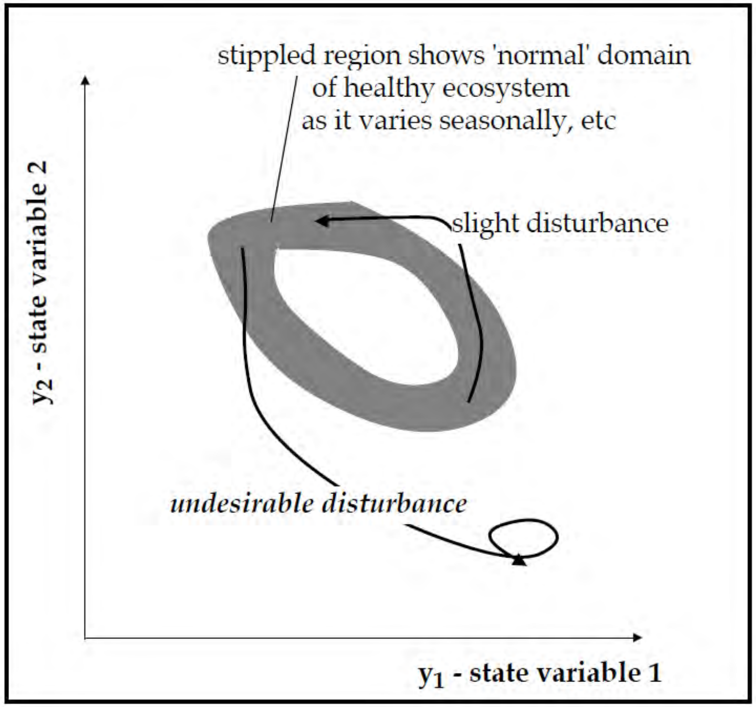
**applications**

- Phytoplankton Community Index (Tett et al., 2008)
- PERSE (Goberville et al., 2011)
- Trajectories in ecosystem state space (Tett et al., 2013)

# Phytoplankton community index (PCI)

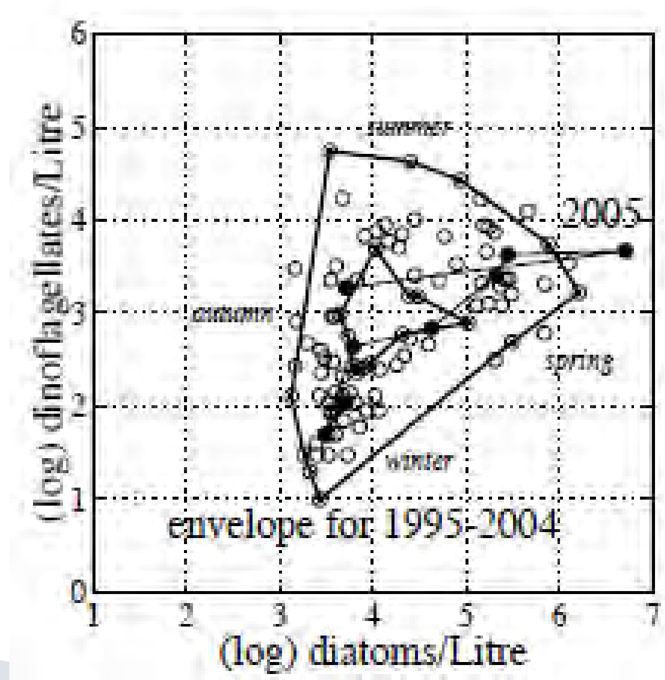
- Indicator of biological quality and ecosystem health in the context of eutrophication
- Change in phytoplankton community composition relative to a reference condition
- Alternative states:
  - Diatoms – large copepods – herring – cod
  - Flagellates – protozoans/small copepods – jellyfish
- Life-forms instead of indicator species

# Phytoplankton community index (PCI)




From Tett et al. 2007, 2008

- Succession of state-variables
- Measure change relative to a reference condition
- Includes natural seasonal and interannual variability

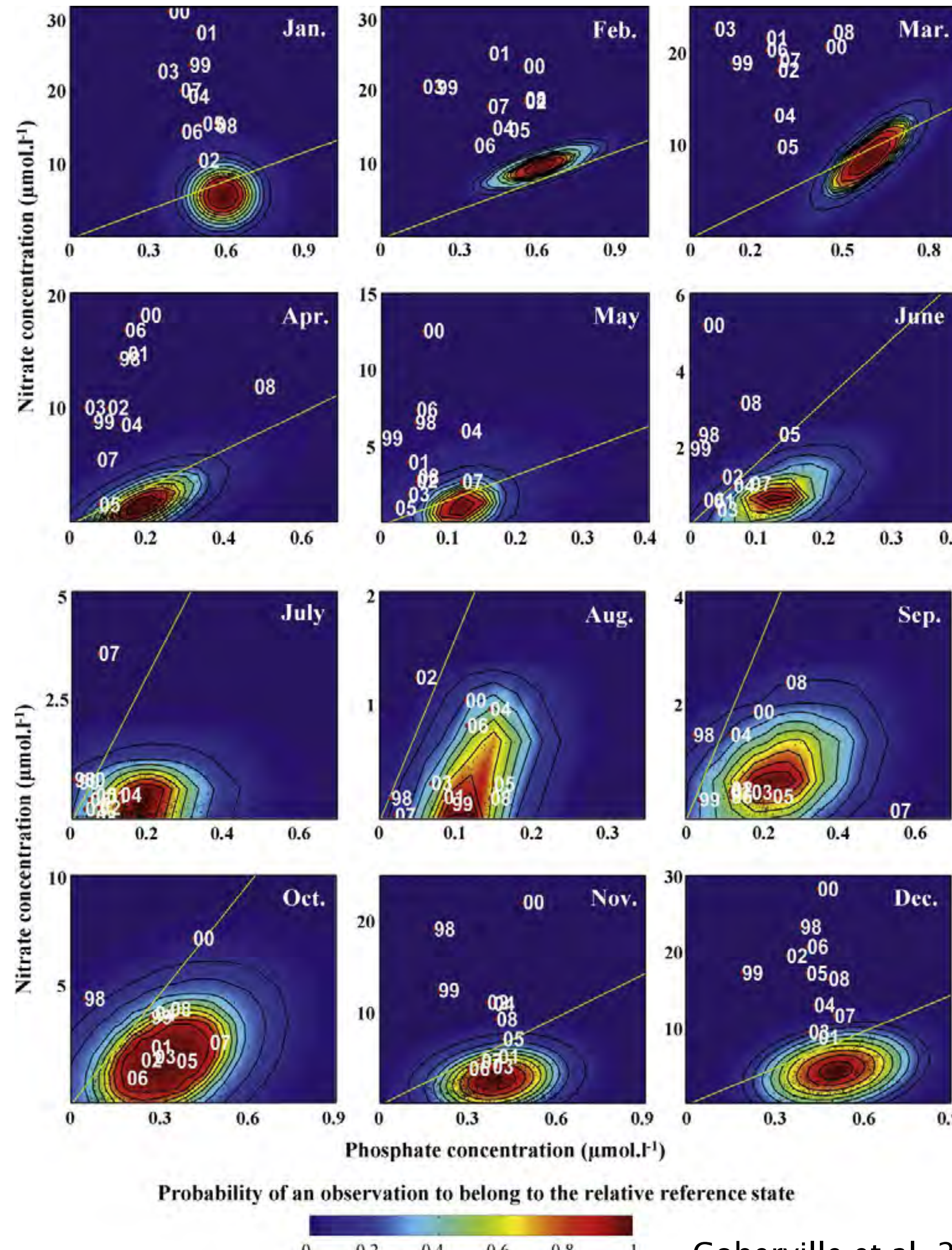


# PERSE

- Excess nutrients: indicative of anthropogenic activities
- Reference value: variability in space
- Procedure to Establish a Reference State for Ecosystems (PERSE; Goberville et al 2011 Ecol. Ind.)
    - Identify relative reference condition so as to detect change
    - Quantify nutrient enrichment in French estuaries in relation to hydrographical factors

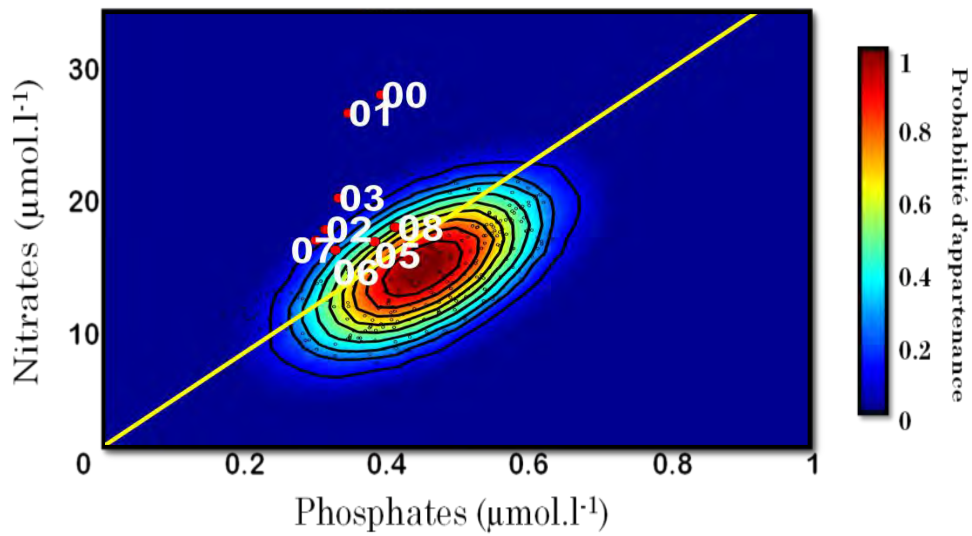
# PERSE

- Seasonal and annual variability in phosphates and nitrates (Brest, France)
- Redfield ratio (N:P =16)
- Probability that an observation belongs to reference state

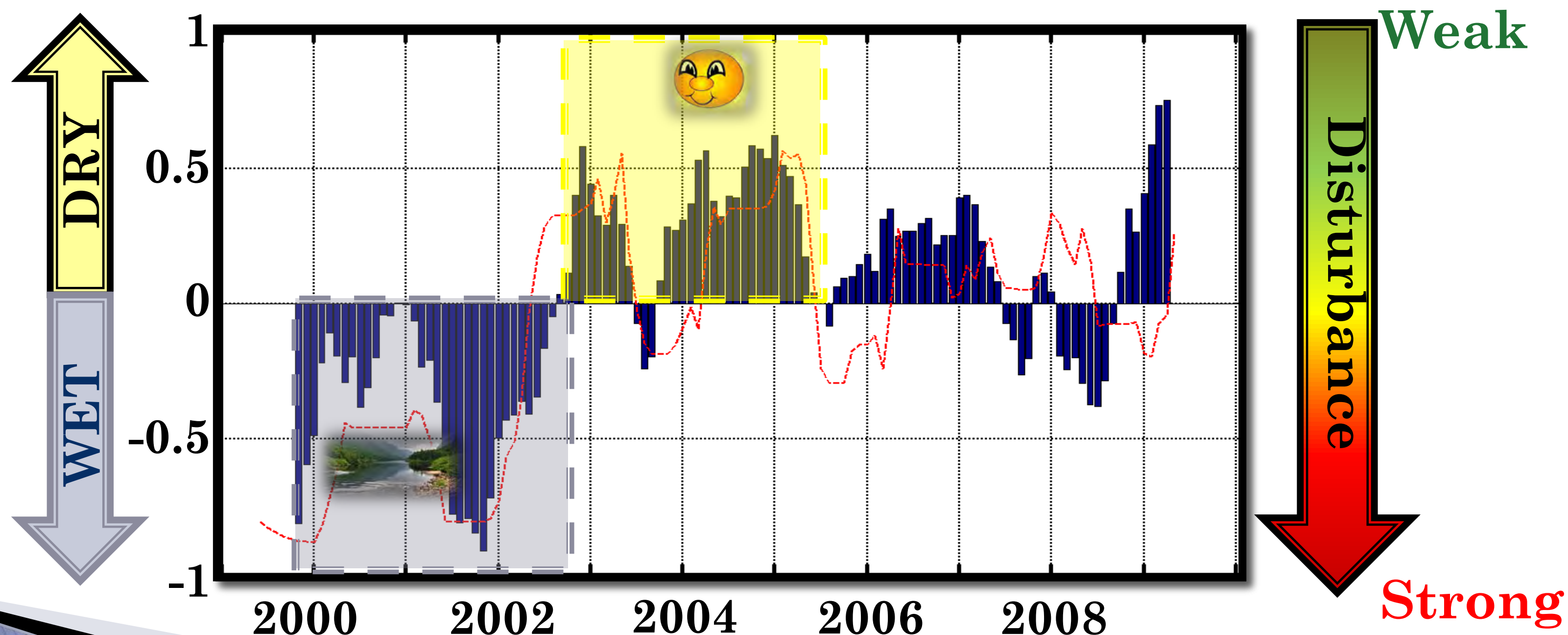



Goberville et al. 2011

# PERSE

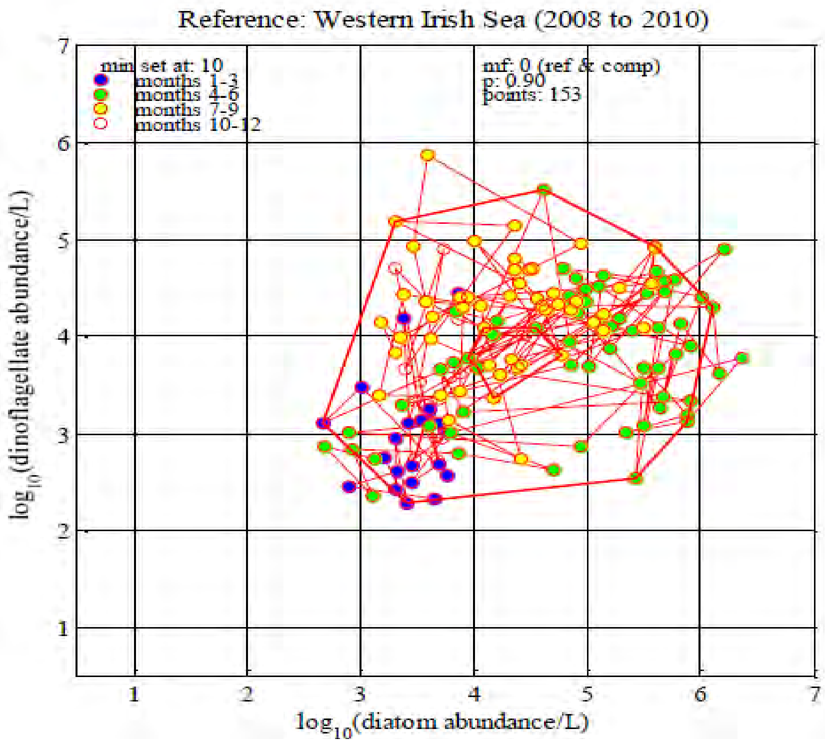


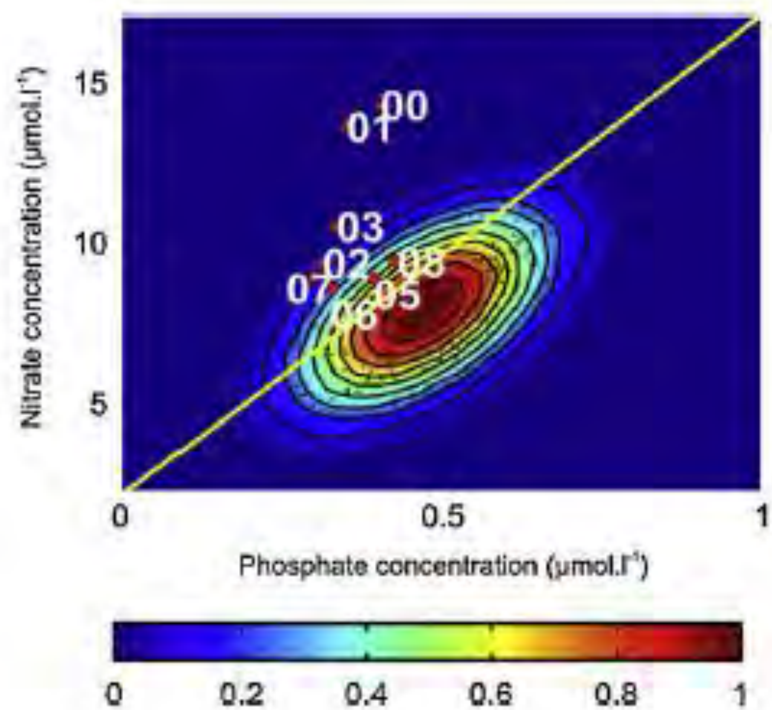
Nitrates (µmol.l-1)
30
20
10
0
0.2
0.4
0.6
0.8
1
Phosphates (µmol.l-1)
00
01
03
02
08
07
05
06
1
0.8
0.6
0.4
0.2
0
Probabilité d'appartenance

DRY
WET
1
0.5
0
-0.5
-1
2000
2002
2004
2006
2008
Weak
Disturbance
Strong

# Phytoplankton and nutrients



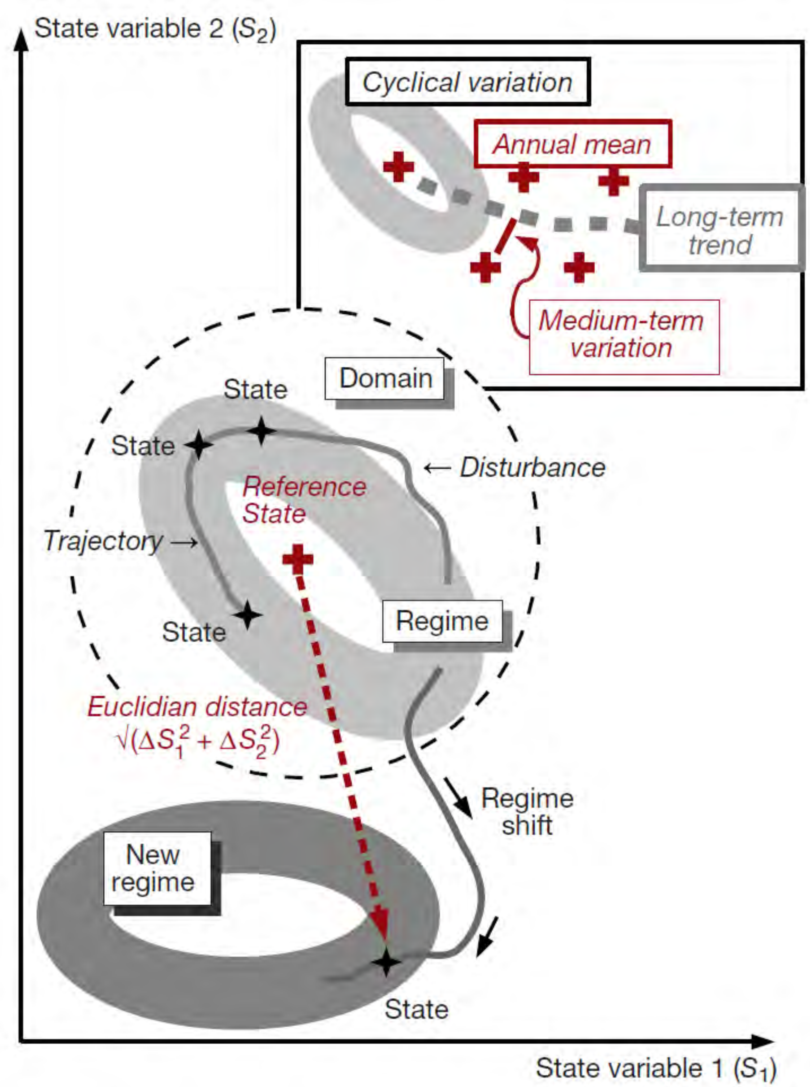

Goberville et al. 2011

Correlation between state and pressure indicators

Rombouts et al. 2013

# Trajectories in ecosystem space

- **State:** point in state space
- **Trajectory**: sequence of system states plotted in state-space
- **Regime**: bundle of trajectories
- **Regime shift**: breakdown of resilience




From Tett et al., 2013 MEPS

# Trajectories in ecosystem space

**Identify spatial extent**

- Natural conditions? Legislation?
- Transboundary fluxes?

**Identify spatial granularity–temporal variability**

- Contribution to resilience?
- Biomes?
- Seasonal variability?

**Select state variables**

- Represent condition
- Time-series spanning natural variability

**Plot trajectory and calculate distance**

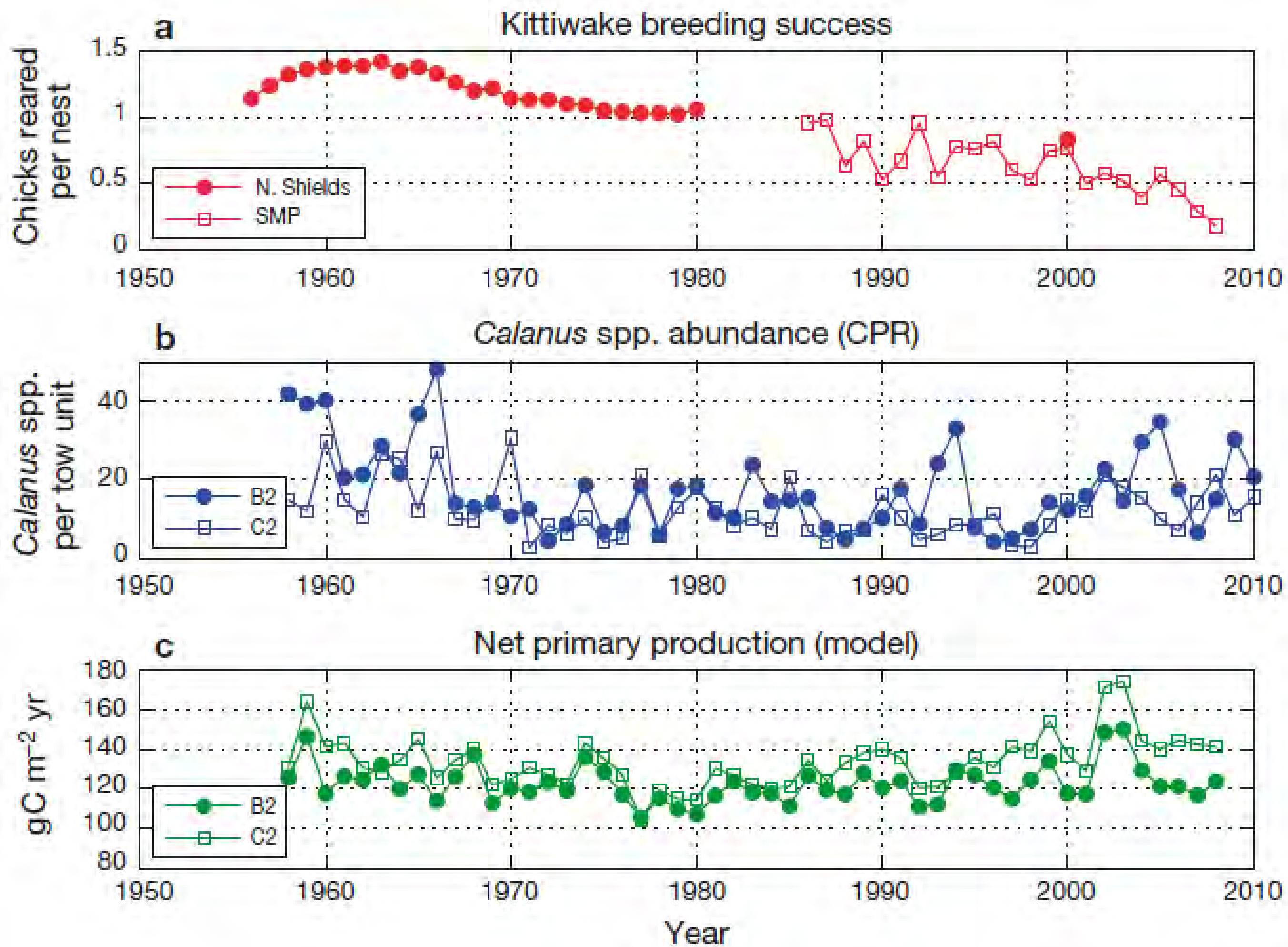
- Euclidean distance
- Extraction of PC's

**Calculate variability**

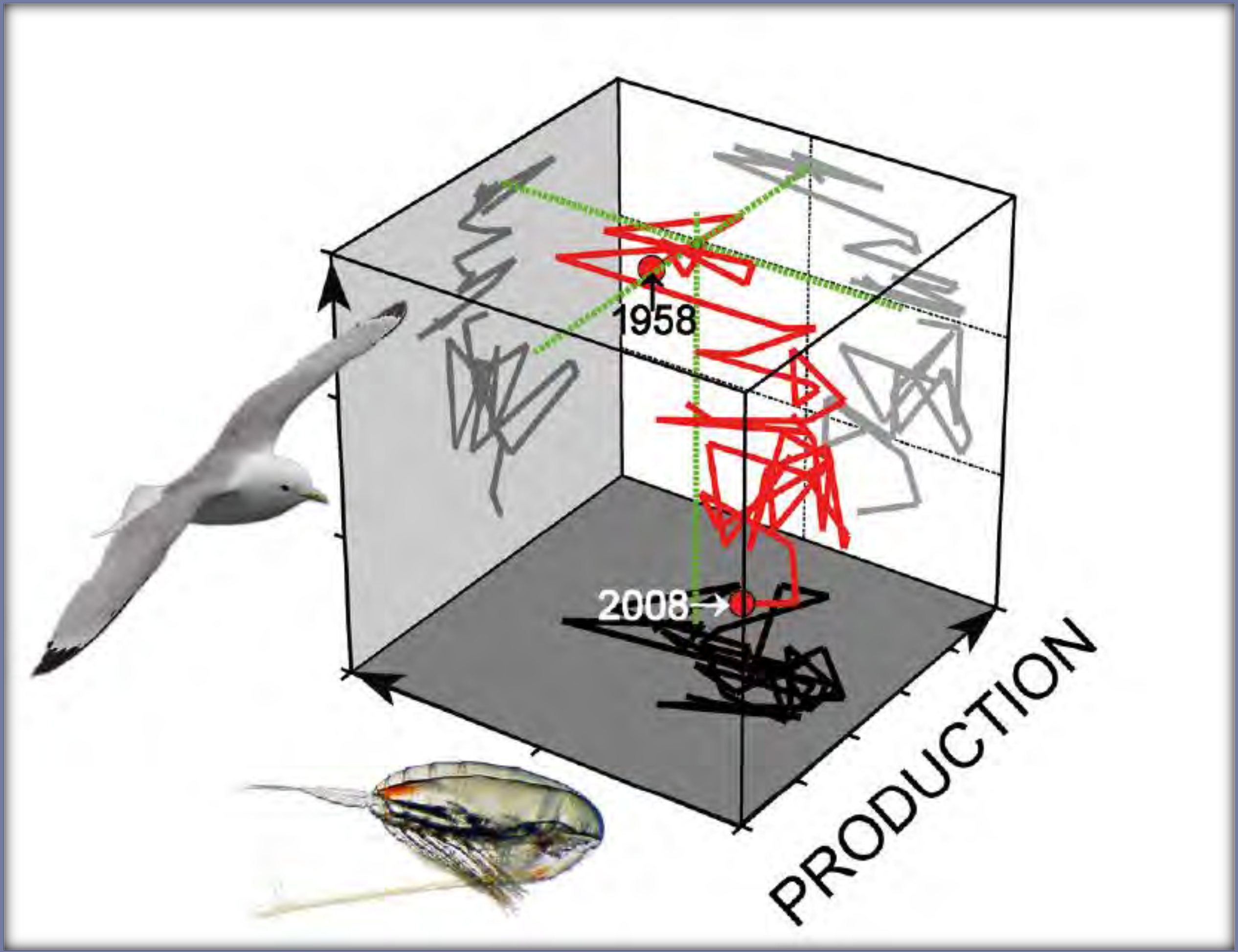
- Distinction between variabilities

From Tett et al., 2013 MEPS

# Trophic network in the North Sea




From Tett et al., 2013, MEPS



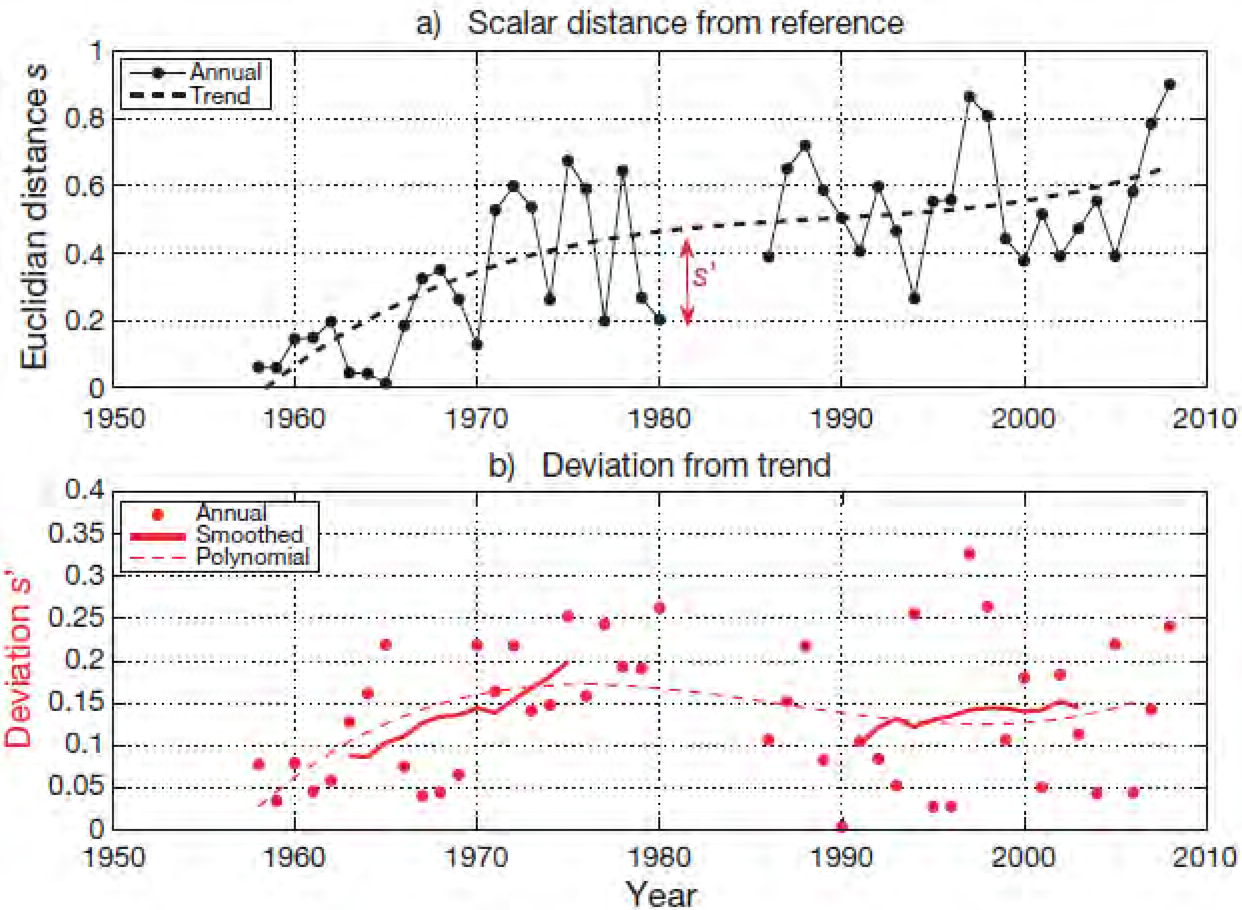

# Trajectories in state-space

Changes in the Northern Sea (1958-2008) defined by the breeding success of kittiwakes, abundance of copepods and simulated annual production (From Tett et al., 2013)

# Change in ecosystem space

- No clear regime shift
- Deviation from trend

> compliance




From Tett et al., 2013, MEPS

# Summary

- Integrative approaches at different levels: components – attributes – analytical methods

- **Pragmatic**: assessment of components and aggregation of attributes
- **Holistic**: systemic approach; quantifying emergent properties

- Management for resilience (Hughes 2005):
  - Select species/groups key to ecosystem function
  - Consider cross-scale interactions

# Summary

- complementarity of data analysis and modelling techniques

- state-space approaches

  - promising to estimate ecosystem resilience

BUT

methodology requires a sufficient amount of data

long time-frame

AND

other applications: pressure-impact studies?

# Thank you

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