Spreading Dead Zones: How Low Dissolved Oxygen Became a Global Problem

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Background:

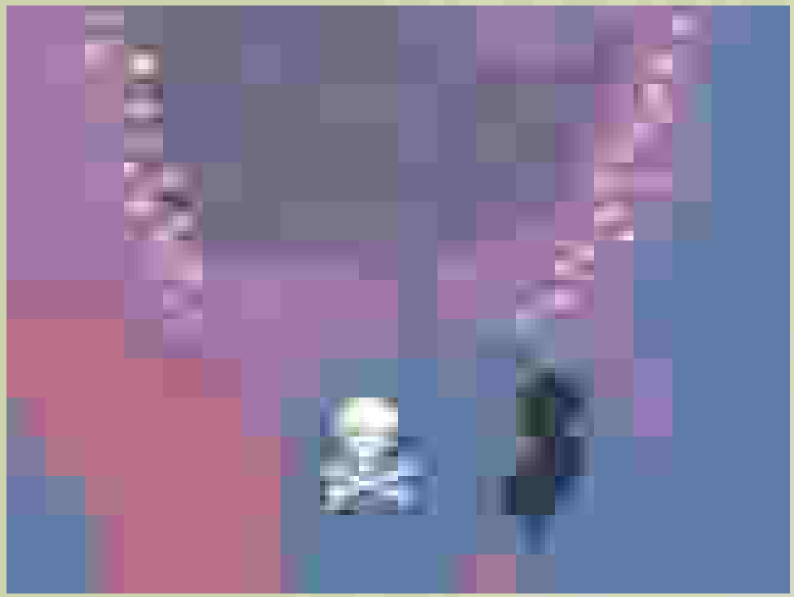
Seriousness of low Dissolved Oxygen is best expressed by motto of American Lung Association:

"When You Can't Breathe, Nothing Else Matters."

Dead zones - a global change water quality problem in the coastal ocean

Excess nutrients (fertilizers, cars) → Too many algae → Algae die

By Mark Patterson



www.shiftingbaselines.org

↓ Sink to bottom → Decompose → Oxygen gets used up

Global Disturbance Land

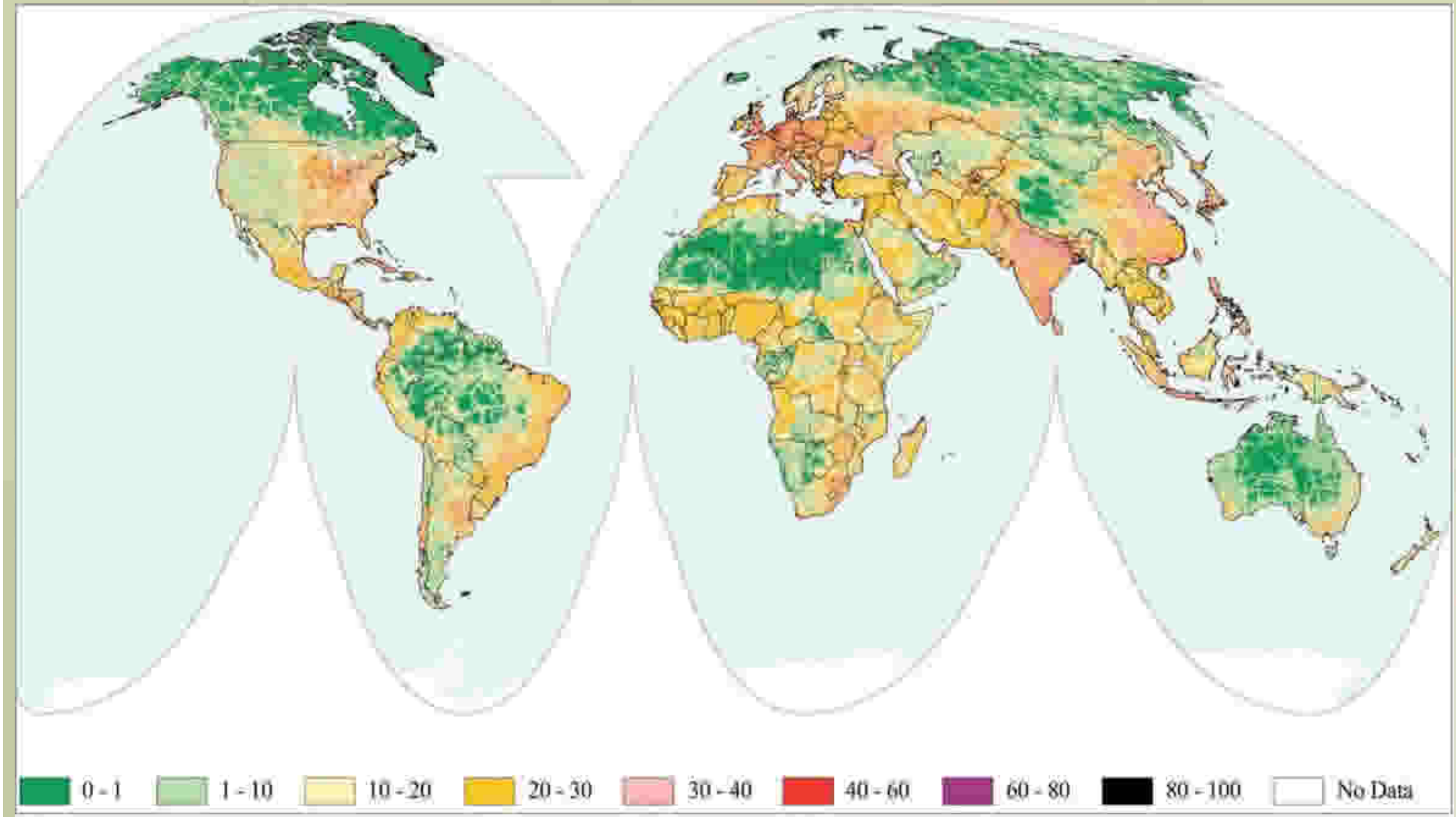


Figure 3. The human footprint, a quantitative evaluation of human influence on the land surface, based on geographic data describing human population density, land transformation, access, and electrical power infrastructure, and normalized to reflect the continuum of human influence across each terrestrial biome defined within biogeographic realms. Further views and additional information are available at "Atlas of the Human Footprint" Web site, www.wcs.org/humanfootprint. Data are available at www.ciesin.columbia.edu/wild_areas/. National boundaries are not authoritative.

Sanderson et al. 2002

Reactive Nitrogen

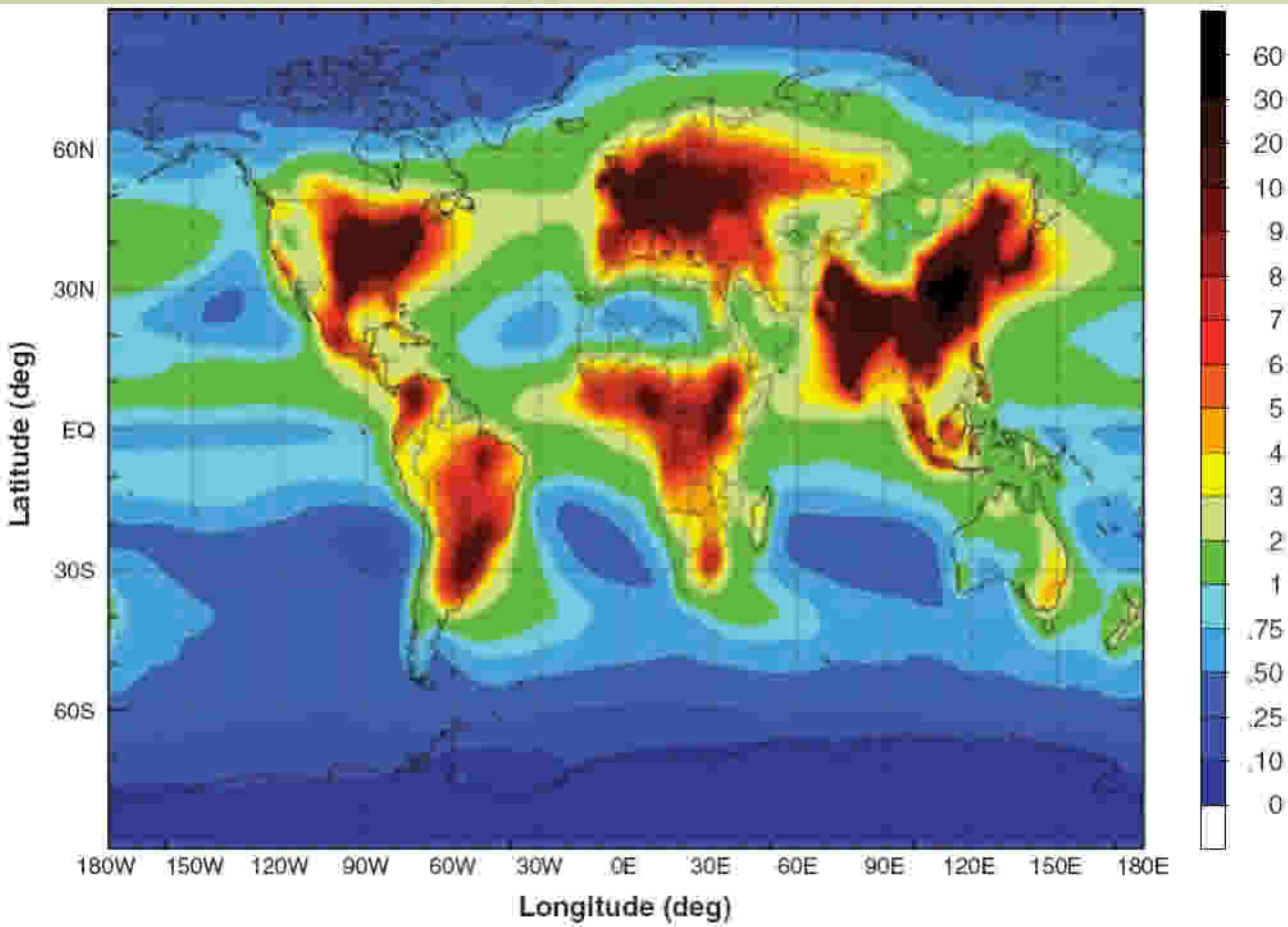
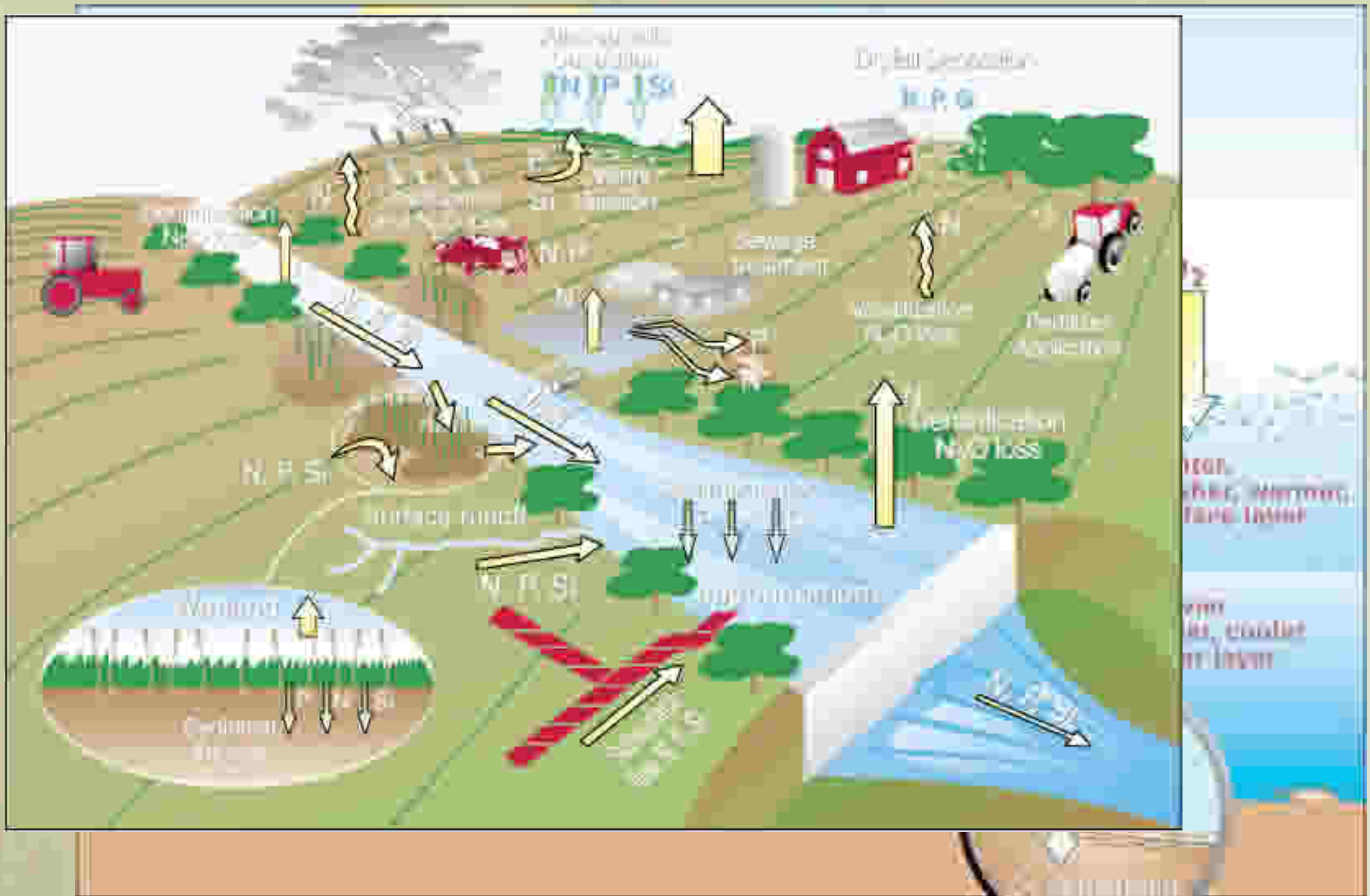


Fig. 2. Estimated N deposition from global total N (NOy and NHx) emissions, totaling 105 Tg N y^{-1}. The unit scale is kg N ha^{-1} y^{-1}, modified from the original units (mg m^{-2} y^{-1}) (*16*).

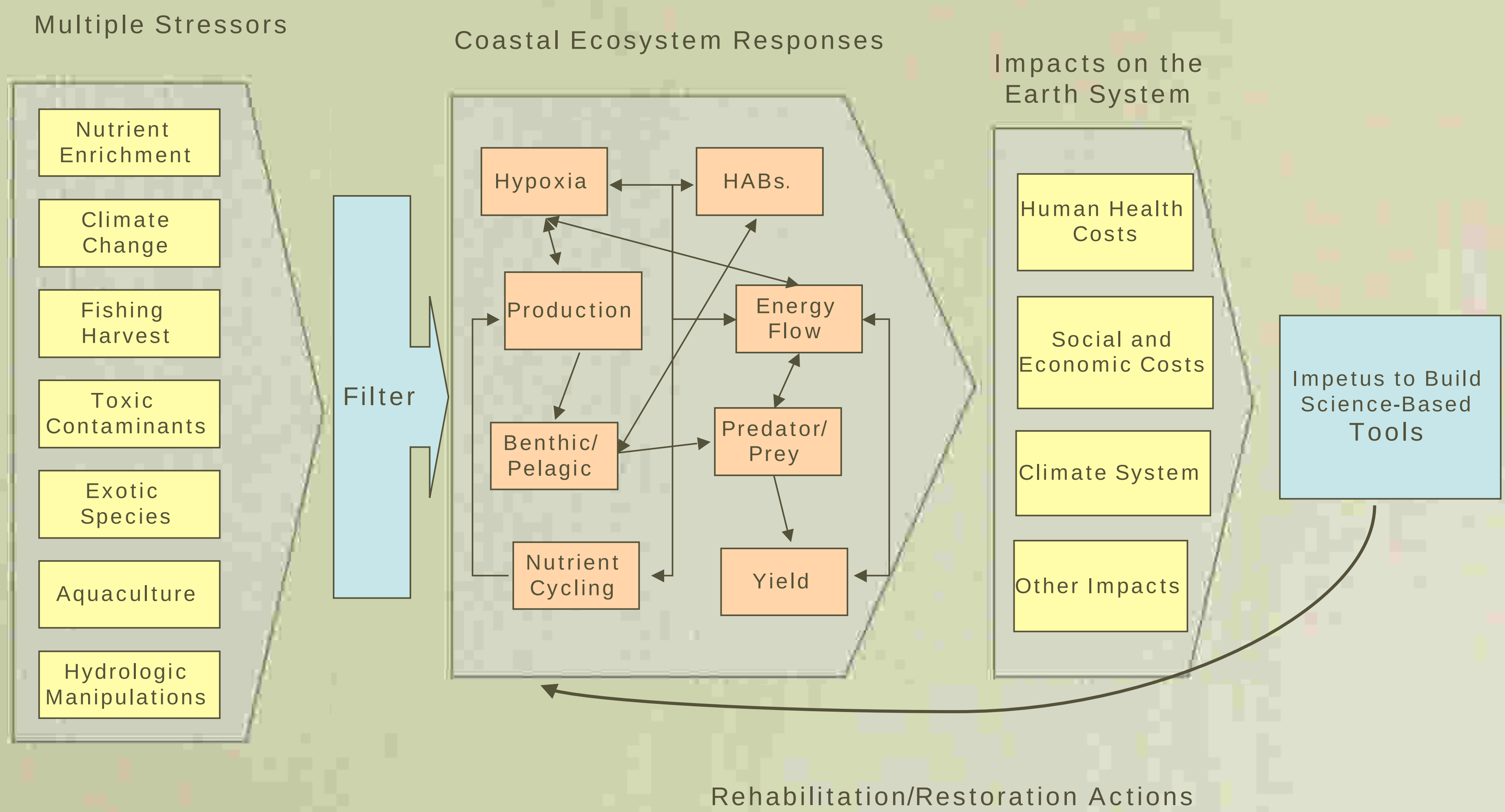
Galloway et al. 2008, Science

Formation of Hypoxia:



Downing et al. 1999

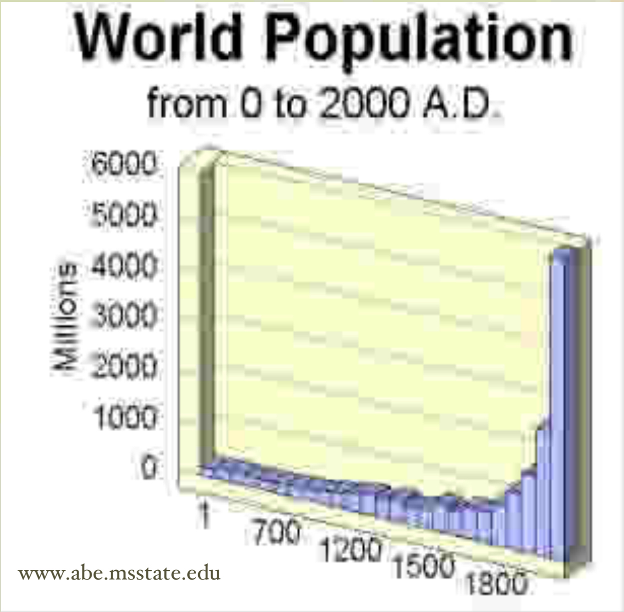
Nutrient Enrichment and Other Stressors are Connected:



Cloern 2001, Marine Ecology Progress Series

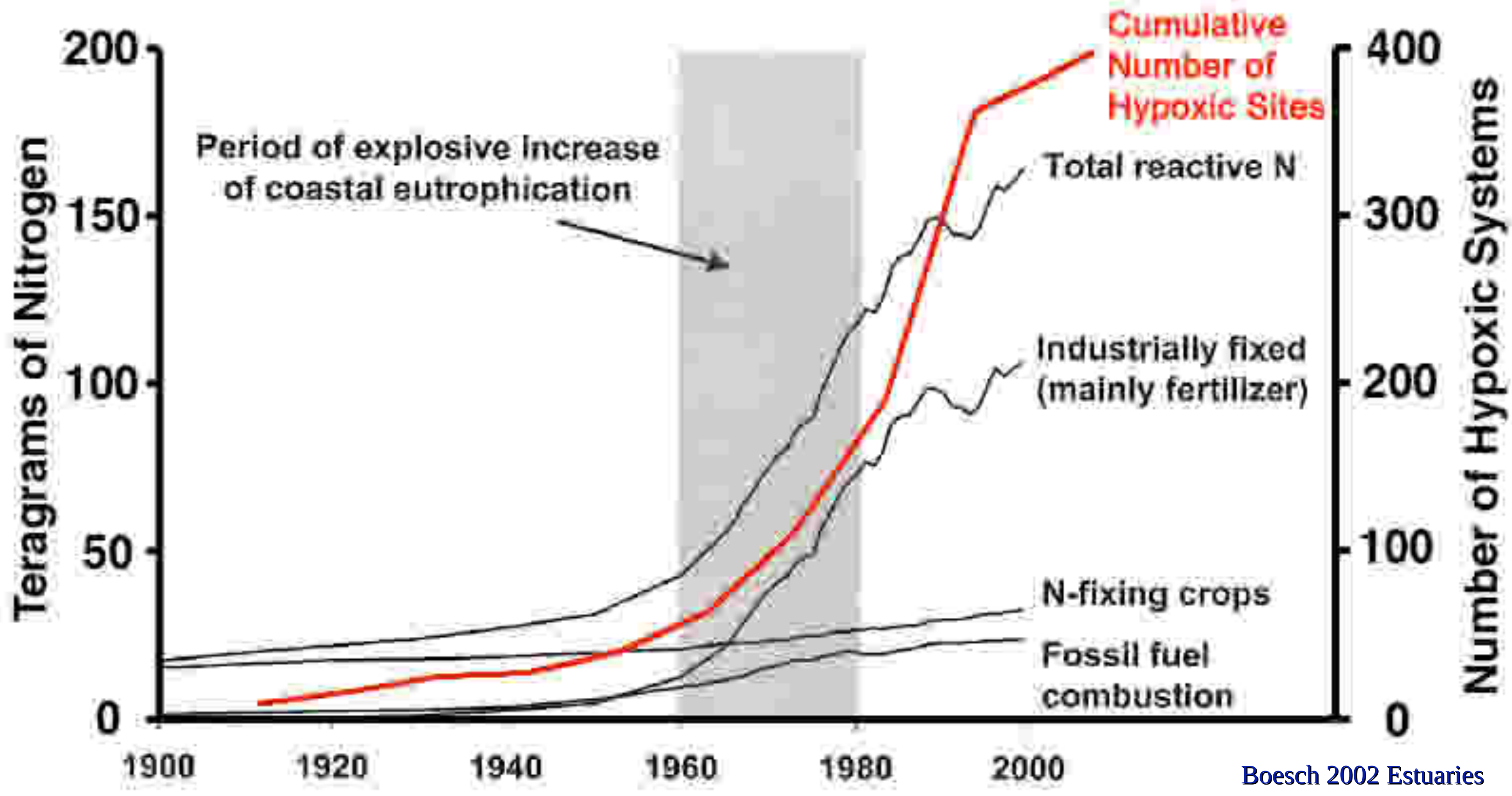
How Eutrophication/Hypoxia Became a Global Problem

- The increasing input of nutrients to coastal areas over the last 60 years resulted in system overload.
- Strong correlation through time between:
  - population growth
  - increased nutrient discharges
  - increased primary production
  - increased occurrence of hypoxia and anoxia.



Nutrients & Hypoxia a Global Problem:

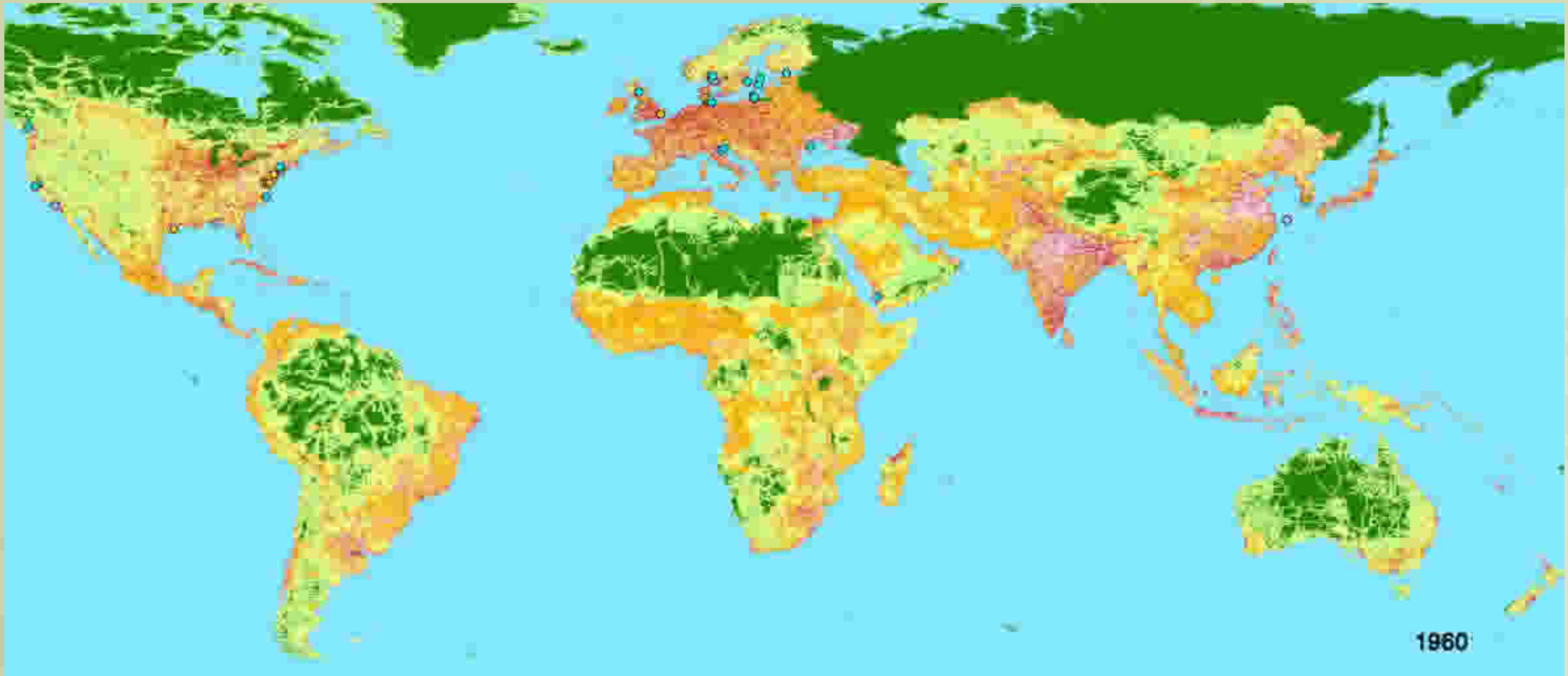
- Doubling of sites first reporting hypoxia started in 1960s.
- >400 systems with reports of hypoxia/anoxia
- >100 eutrophic sites in danger of developing hypoxia/anoxia.
- OMZ and Upwelling areas not included.

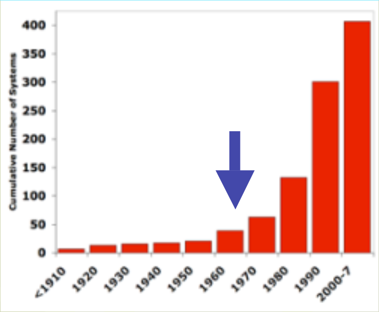


Boesch 2002 Estuaries

Spread of Hypoxia

In the 1960s the number of systems with reports of hypoxia-related problems increased.

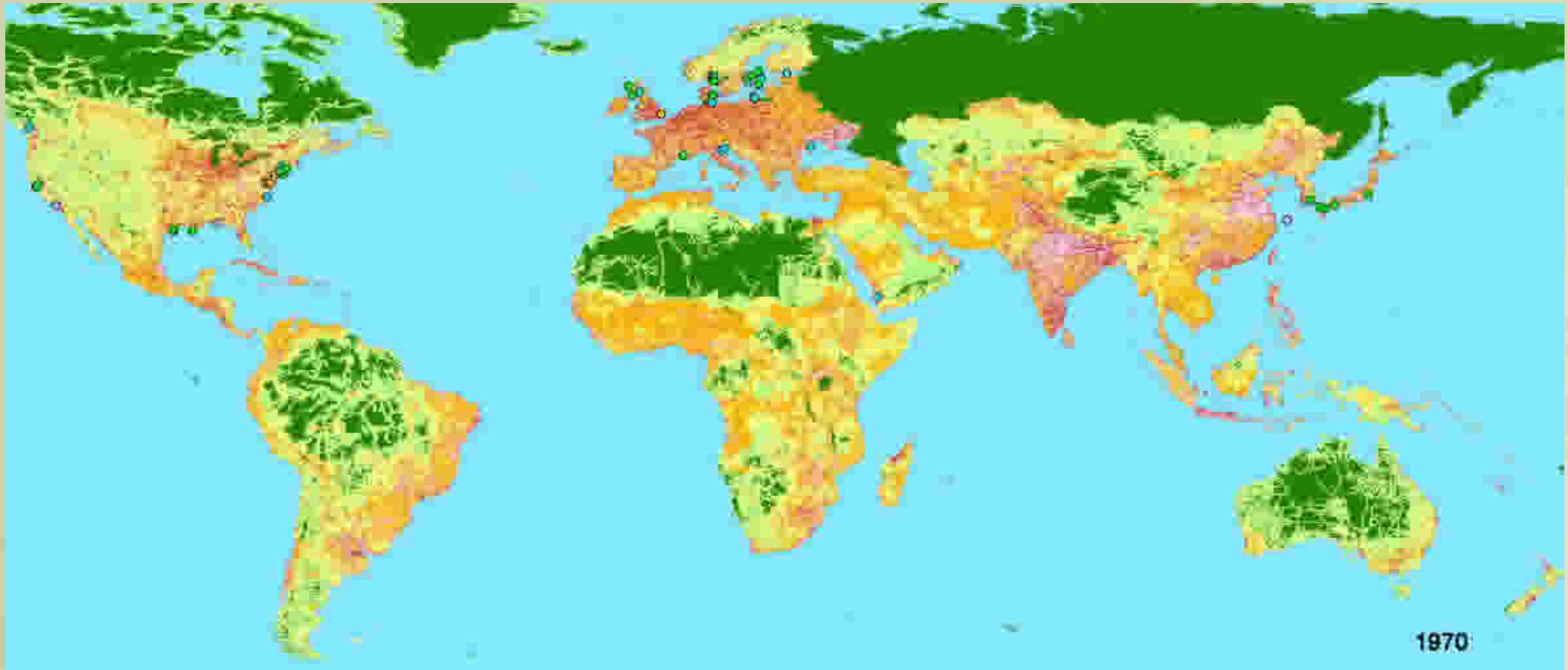


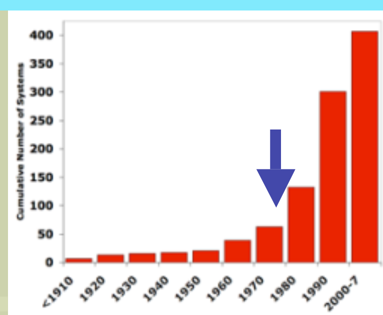


Sanderson et al. 2002 Bioscience;
Global Human Footprint

Spread of Hypoxia

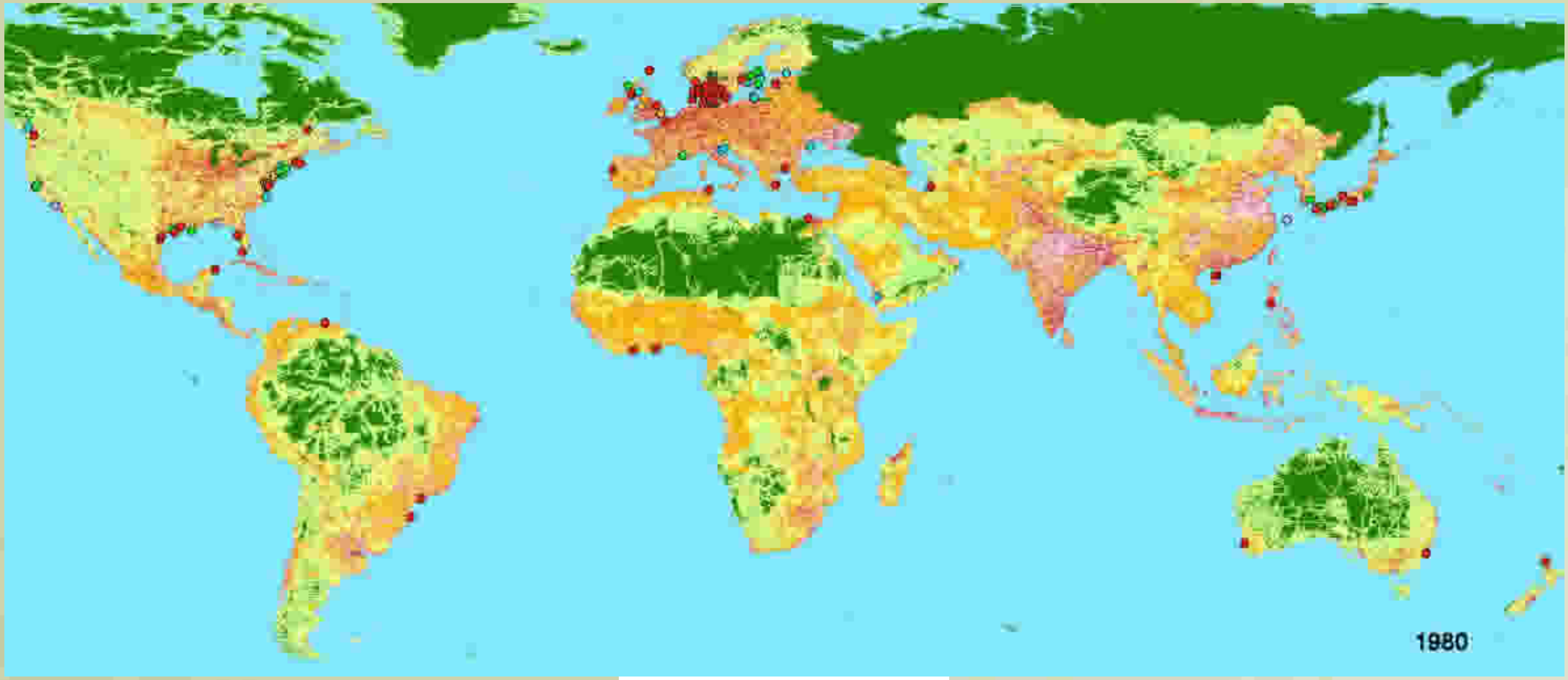
1970s more increase in the number of hypoxic systems.

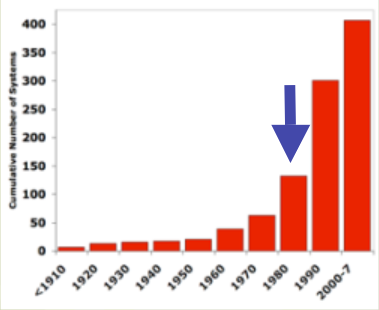




Spread of Hypoxia

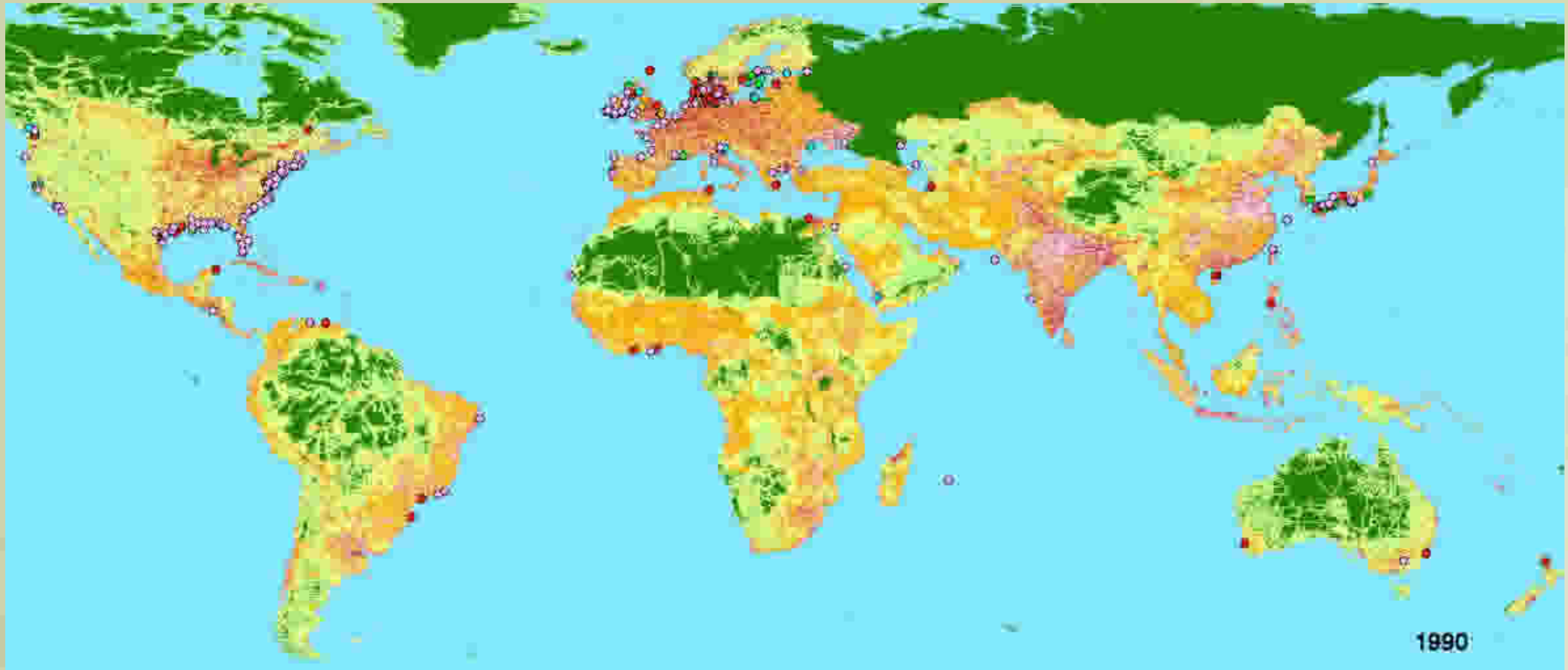
1980s explosive increase in the number of hypoxic systems.

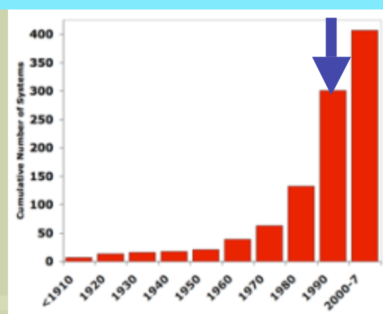




Spread of Hypoxia

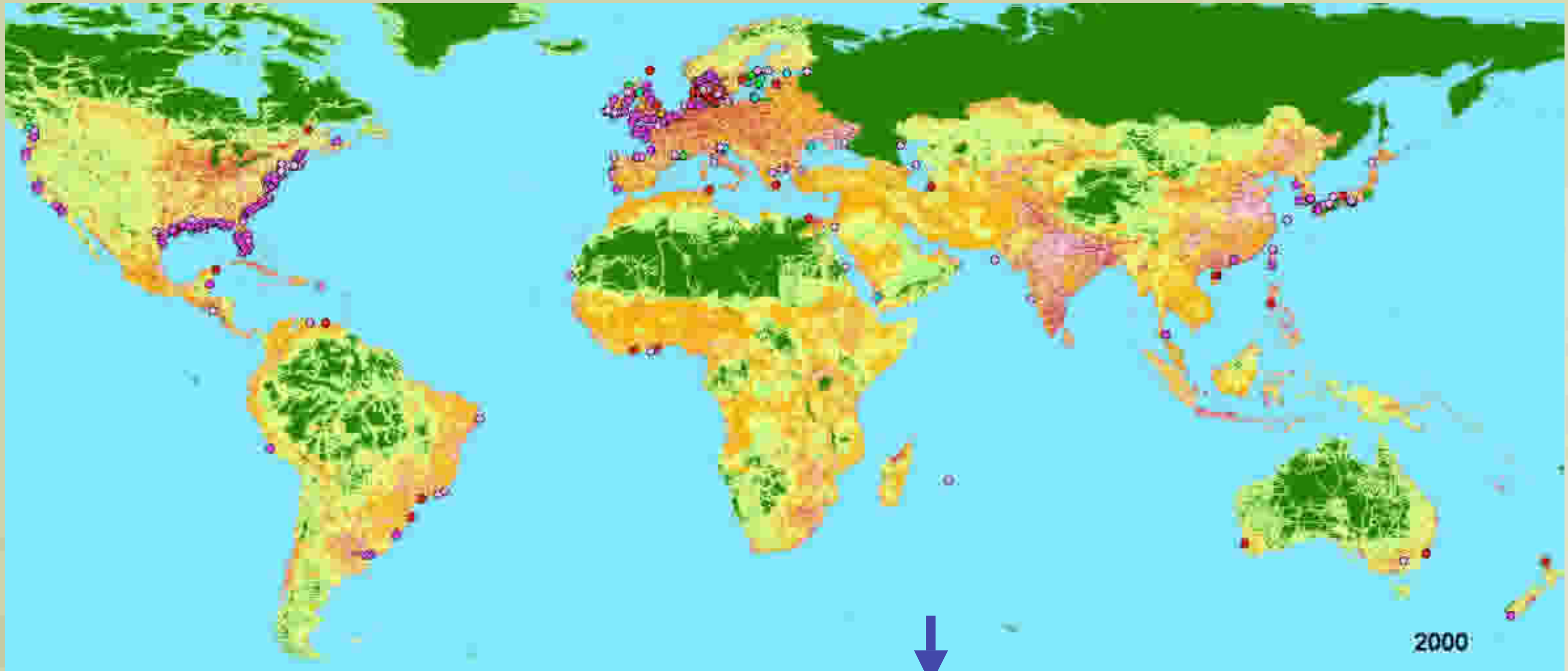
By the 1990s most estuarine and marine systems in close proximity to population centers had reports of hypoxia or anoxia.

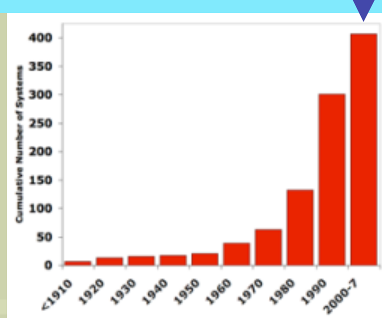




Spread of Hypoxia

2000s numbers continue to expand.





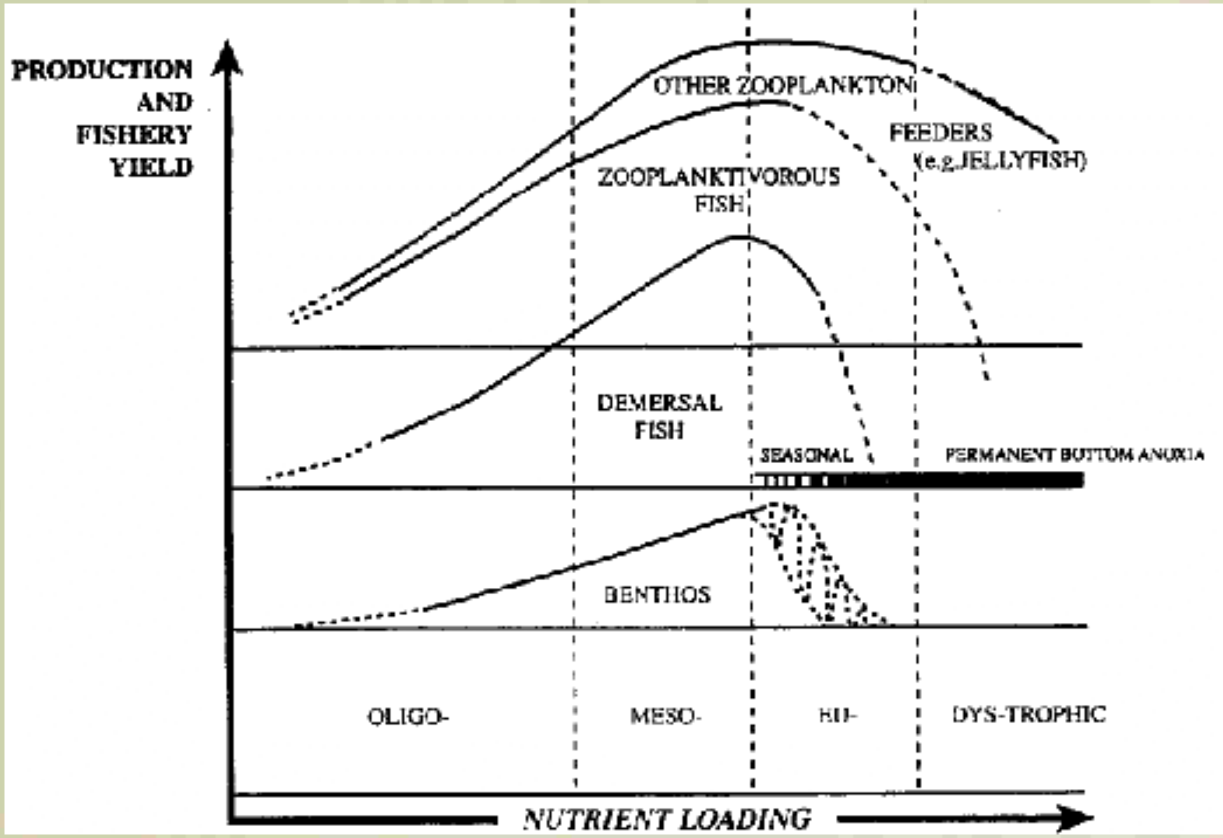
Hypoxia a Paradox of Eutrophication

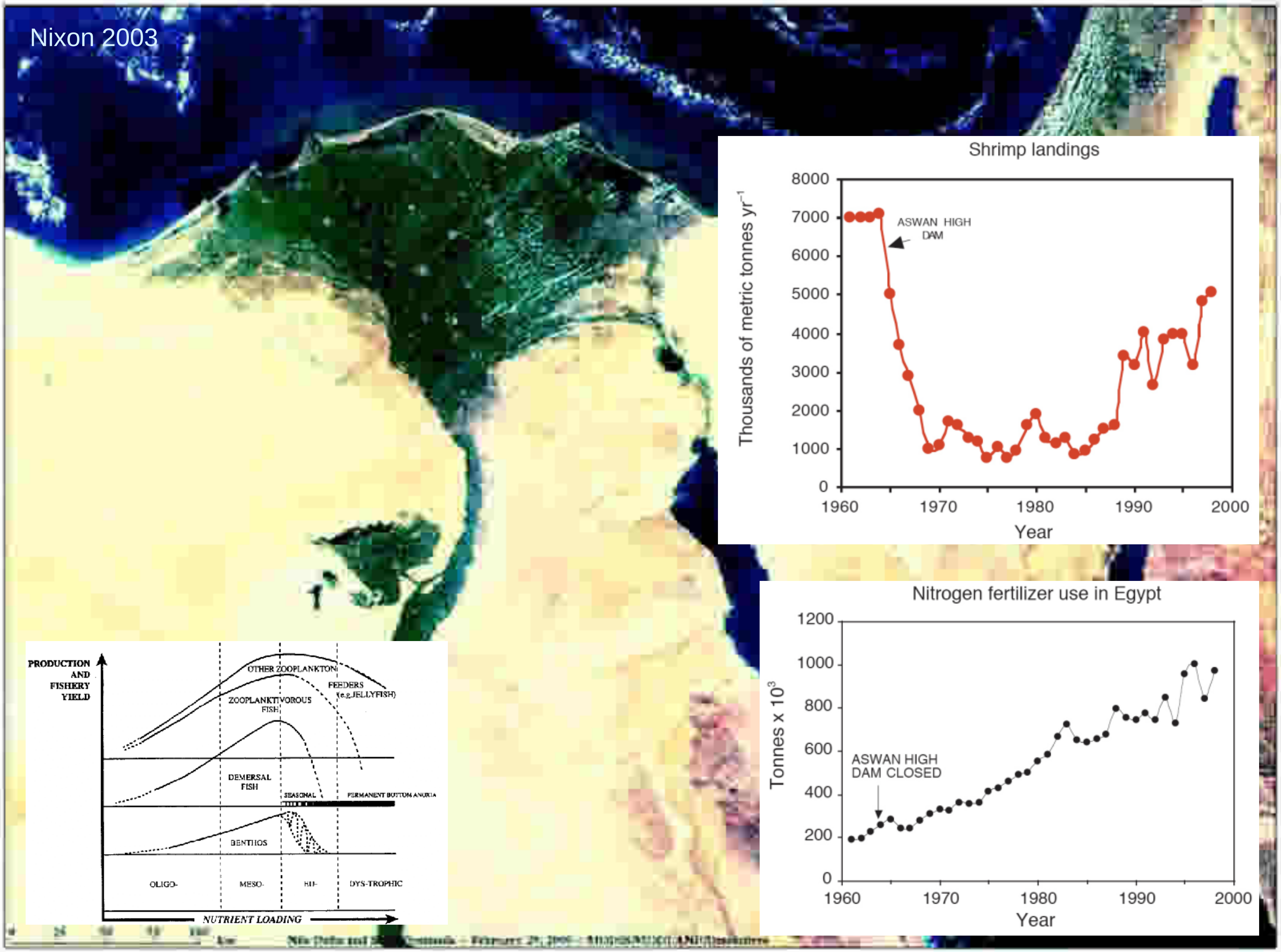
- Initial increase in nutrient loading leads to an initial increase in fisheries production.

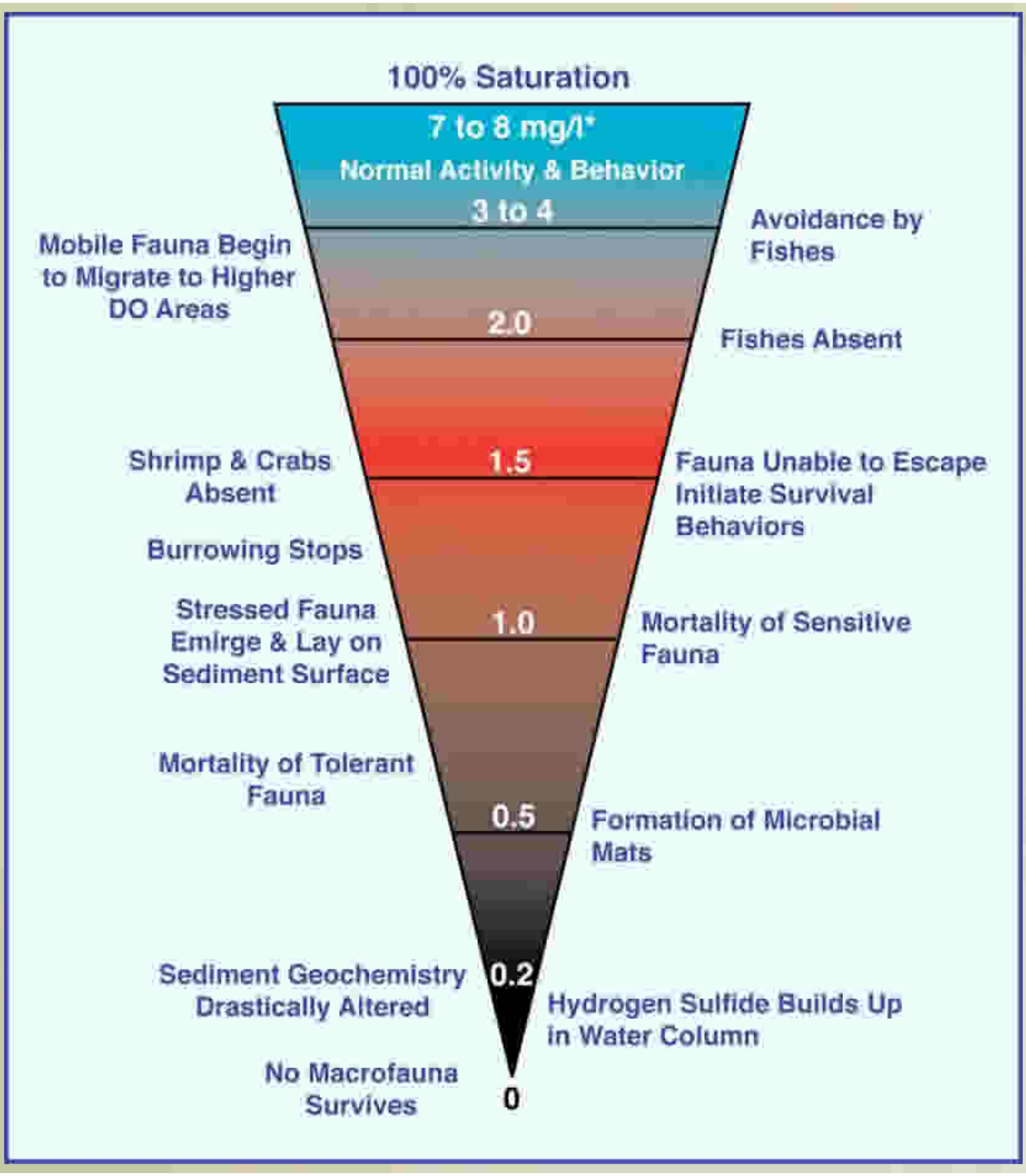
- As nutrient loading continues to increase the system approaches an organic matter saturation point.

- At some point,
- organic matter is
- not efficiently
- processed
- through
- fishery species.

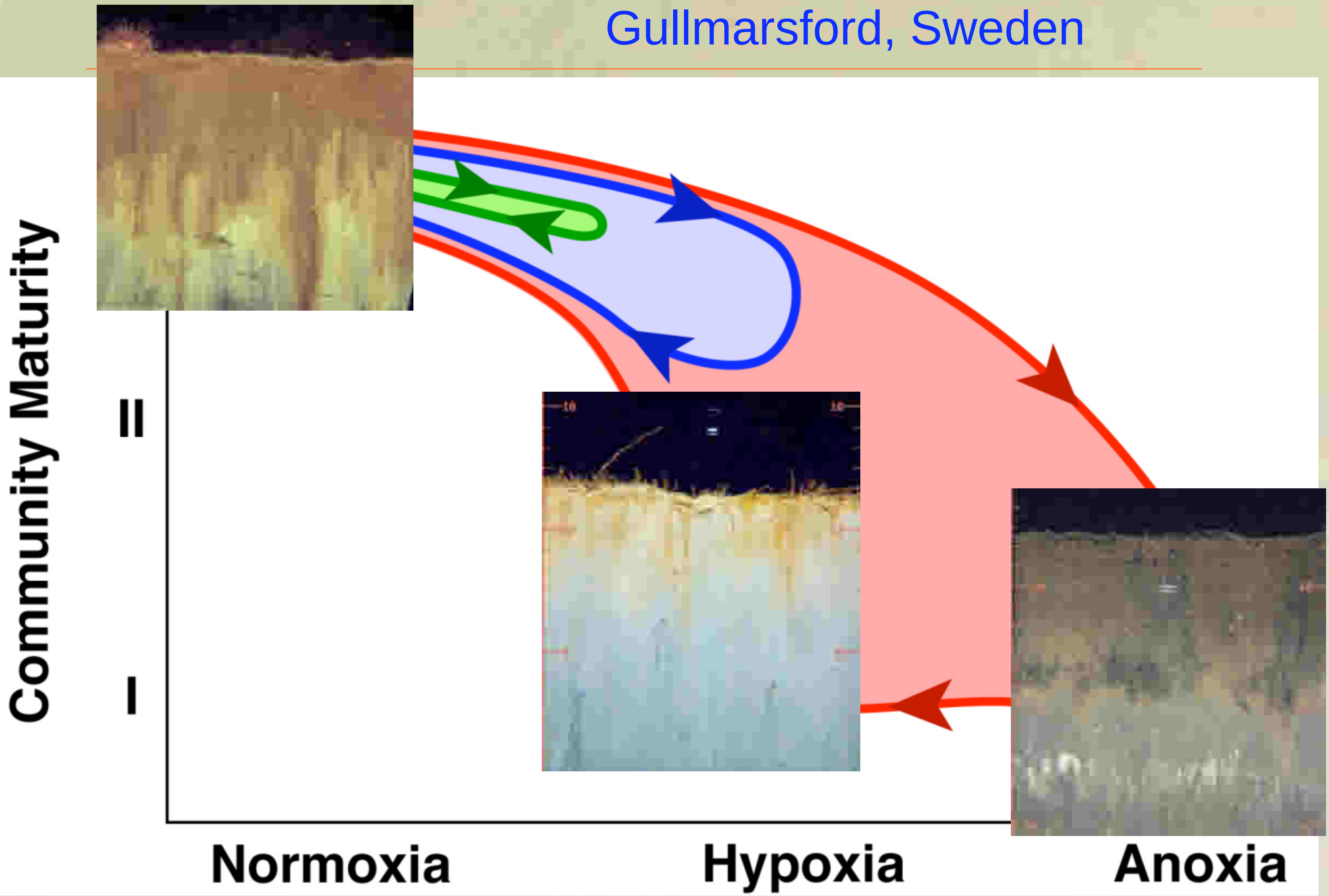
Caddy 1993




Nixon 2003
Shrimp landings
Thousands of metric tonnes yr^{-1}
8000
7000
6000
5000
4000
3000
2000
1000
0
ASWAN HIGH
DAM
1960
1970
1980
1990
2000
Year
Nitrogen fertilizer use in Egypt
Tonnes x 10^3
1200
1000
800
600
400
200
0
ASWAN HIGH
DAM CLOSED
1960
1970
1980
1990
2000
Year
PRODUCTION
AND
FISHERY
YIELD
OTHER ZOOPLANKTON
FEEDERS
(e.g. JELLYFISH)
ZOOPLANKTIVOROUS
FISH
DEMERSAL
FISH
SEASONAL
PERMANENT BOTTOM ANOXIA
BENTHOS
OLIGO-
MESO-
EU-
DYS-TROPHIC
NUTRIENT LOADING


100% Saturation
7 to 8 mg/l*
Normal Activity & Behavior
3 to 4
Avoidance by Fishes
Mobile Fauna Begin to Migrate to Higher DO Areas
2.0
Fishes Absent
Shrimp & Crabs Absent
1.5
Fauna Unable to Escape Initiate Survival Behaviors
Burrowing Stops
Stressed Fauna Emirge & Lay on Sediment Surface
1.0
Mortality of Sensitive Fauna
Mortality of Tolerant Fauna
0.5
Formation of Microbial Mats
Sediment Geochemistry Drastically Altered
0.2
Hydrogen Sulfide Builds Up in Water Column
No Macrofauna Survives
0

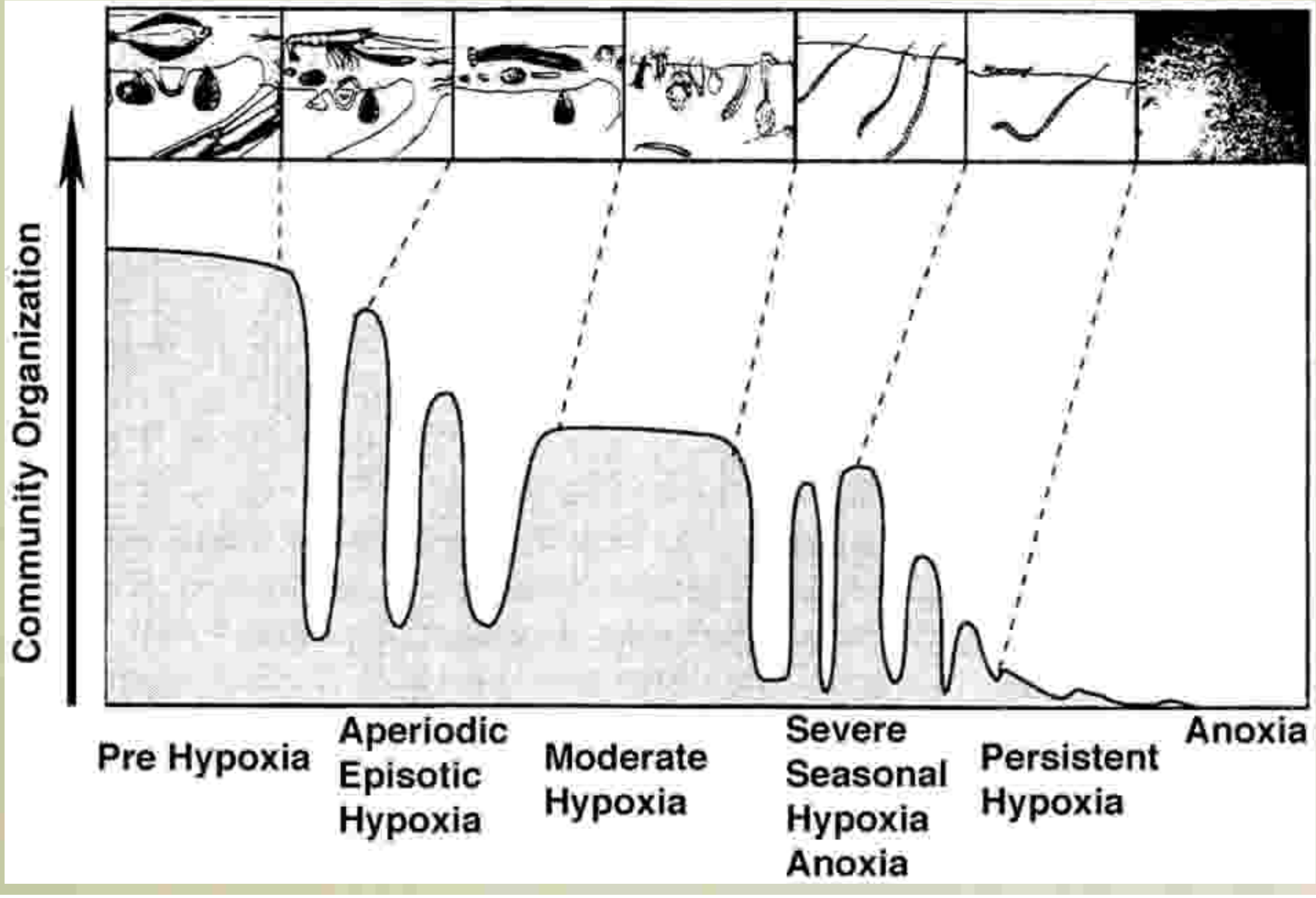
Gullmarsford, Sweden



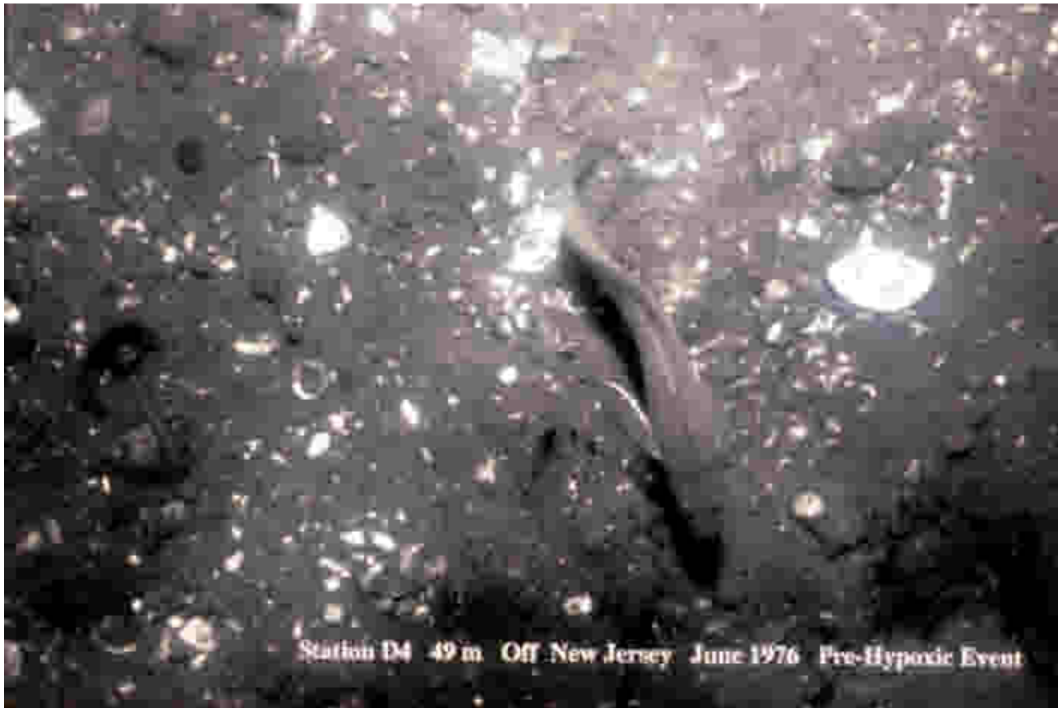
Rosenberg et al. 2002

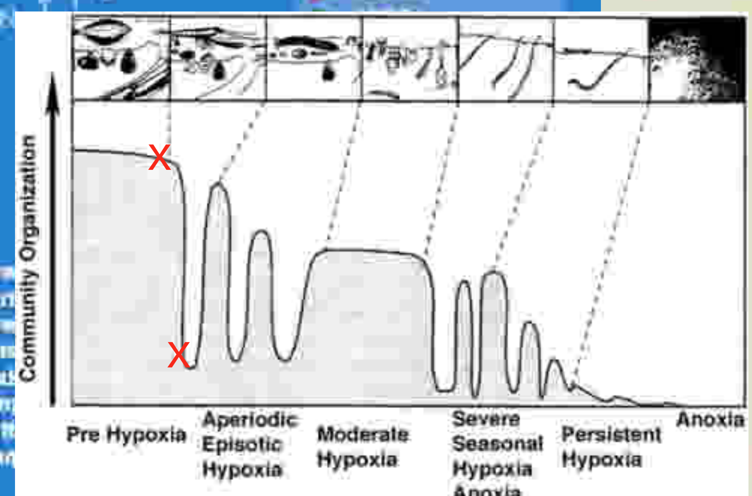
Energy Pulsing to Reduction

As hypoxia develops it becomes a key factor in regulating energy flow by forcing ecosystem to pulse.



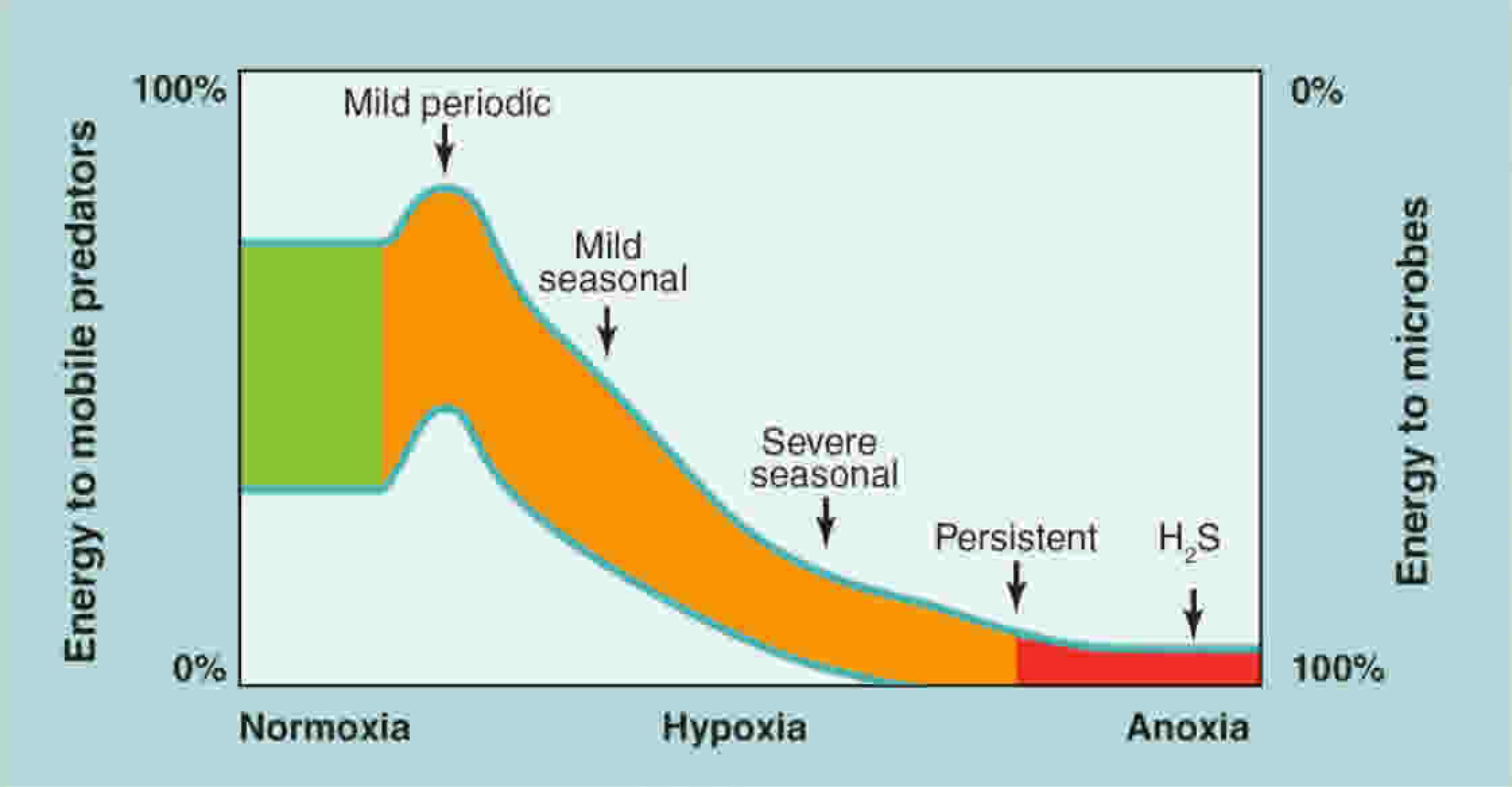
NY/NJ Bight
987 Km^2
Single Episode
Summer 1976
Mass Mortality





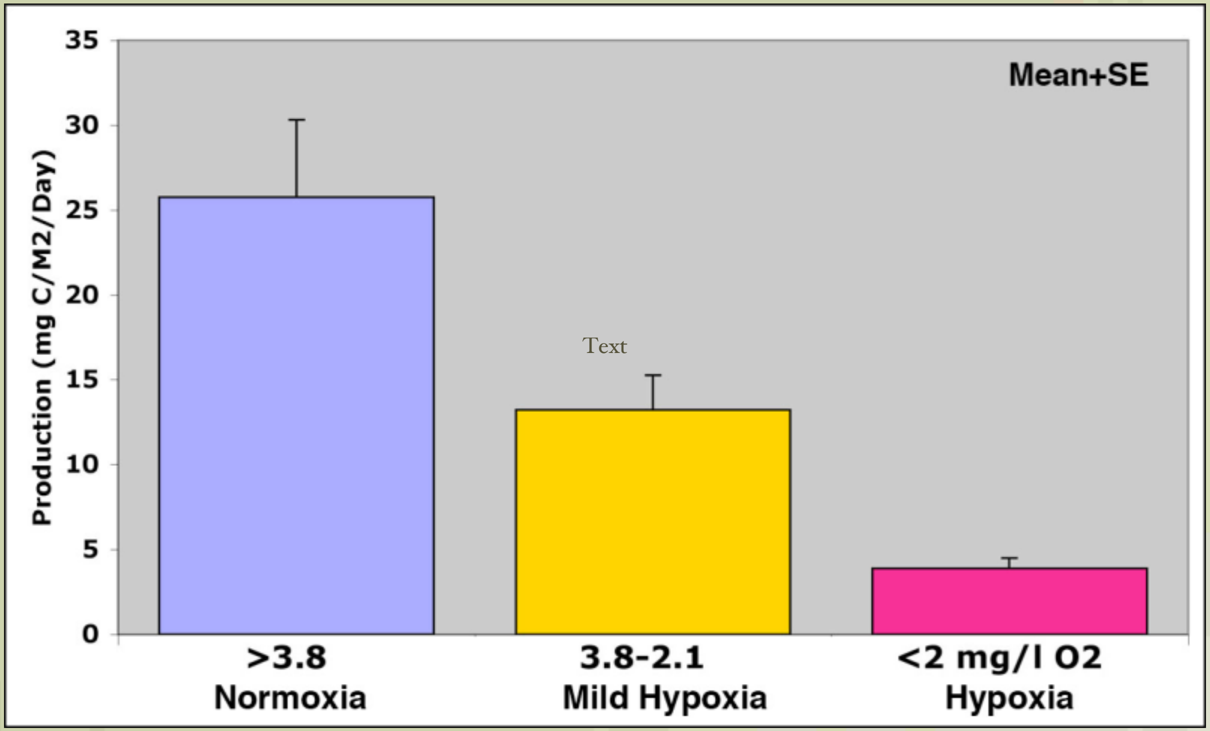
Ecosystem Energy Flows

Processes and pathways that are favored by hypoxic conditions taking larger portions of ecosystem's energy. Ultimately, microbes dominate.



Interaction of Eutrophication/Hypoxia and Energy

Daily production in Chesapeake Bay is related to DO concentration.
Average year Bay has 2,000 km2 dead zone.



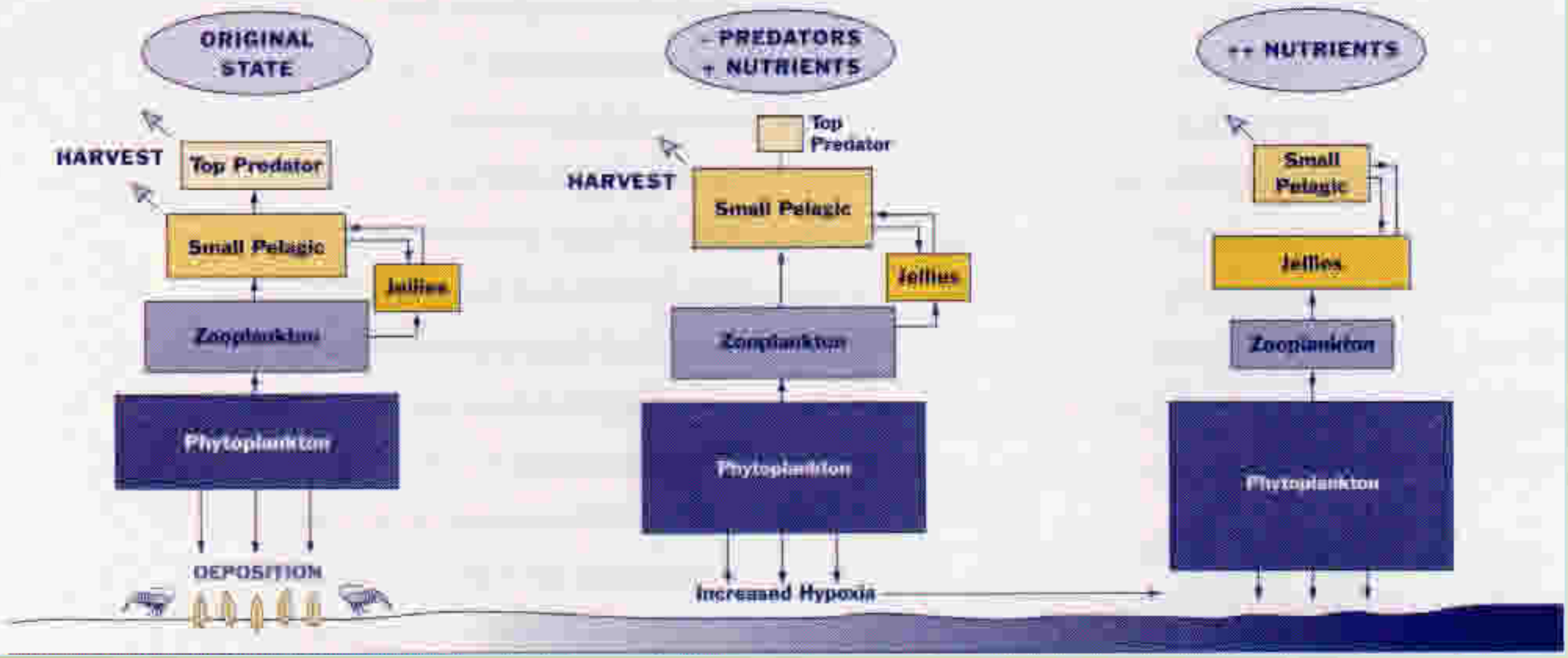
Difference	mg C/m2/day	% Reduction
Normoxia-Mild Hypoxia	13	49
Normoxia-Hypoxia	22	85

This is 3-5% of Bay’s annual secondary production.
75,000 metric tons of worms and clams.

Figure 6

Caddy 2000

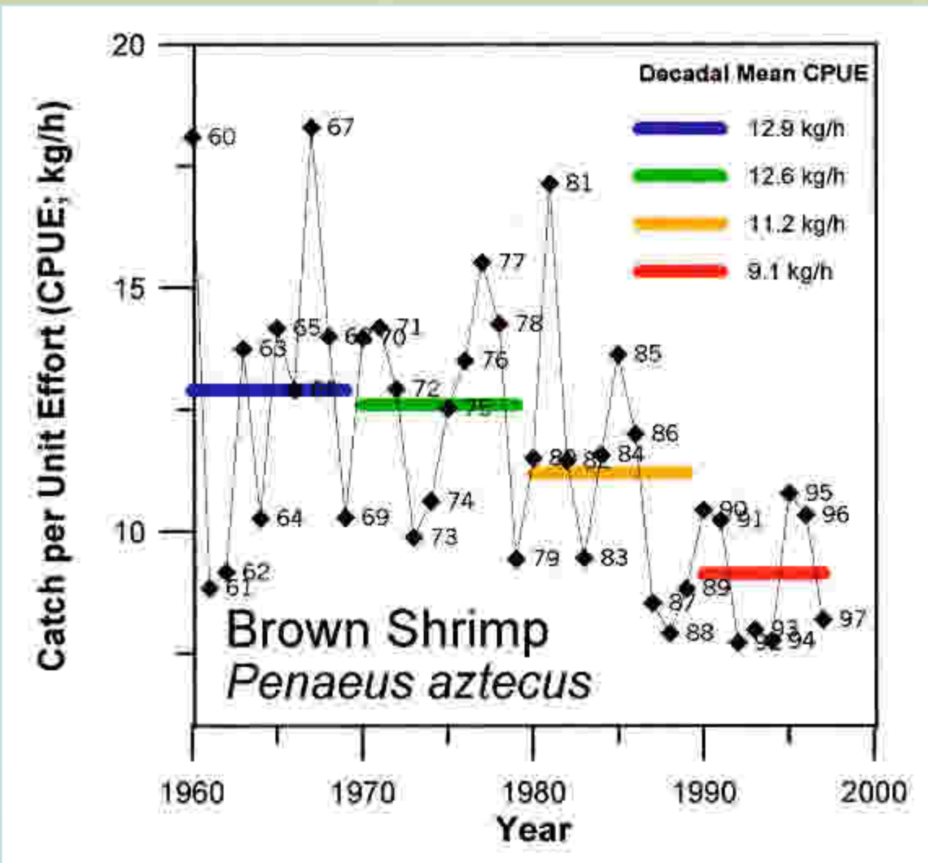
Simultaneous Effects of Eutrophication and Fishery Harvest on Marine Food Chains

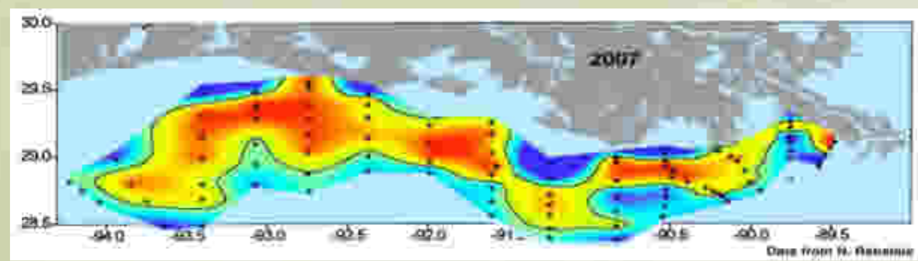


Multiple Stressors Involved:

- •Fishing pressure
- •Trophic shifts in PP species
- •Habitat degradation/loss
- •Mortality/stress from hypoxia

www.saletseafoods.com





Rabalais unpublished

Downing et al. 1999

Response to Eutrophication/Hypoxia

- Increased input of organic matter leads to increase biomass, but Hypoxia/Anoxia tend to reduce biomass.
- Favors opportunistic species, lower species diversity, and increased importance of microbes.
- Eutrophication preconditioned fauna to lessen response to hypoxia when it occurs.
  - Lack of benthic response to short-term periodic hypoxia.
  - Pulsed recolonization with annual hypoxia.

Figure 3. The Yangtze River drainage basin and the estimated hypoxy areas in the ECS (35).

Nutrients do not act alone, but are a major stressor of ecosystems and the key human factor in development of oxygen depletion.

Li and Daler 2004

For marine systems
Nitrogen is primary problem.

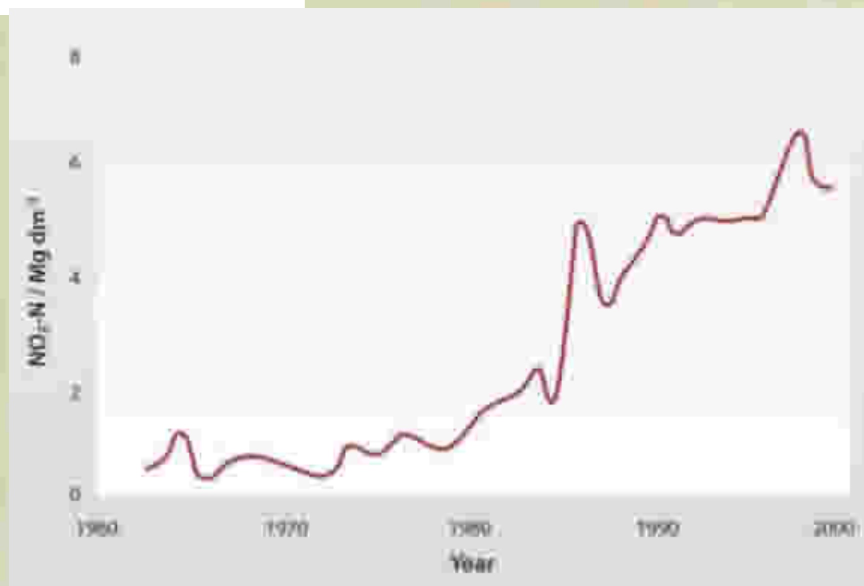
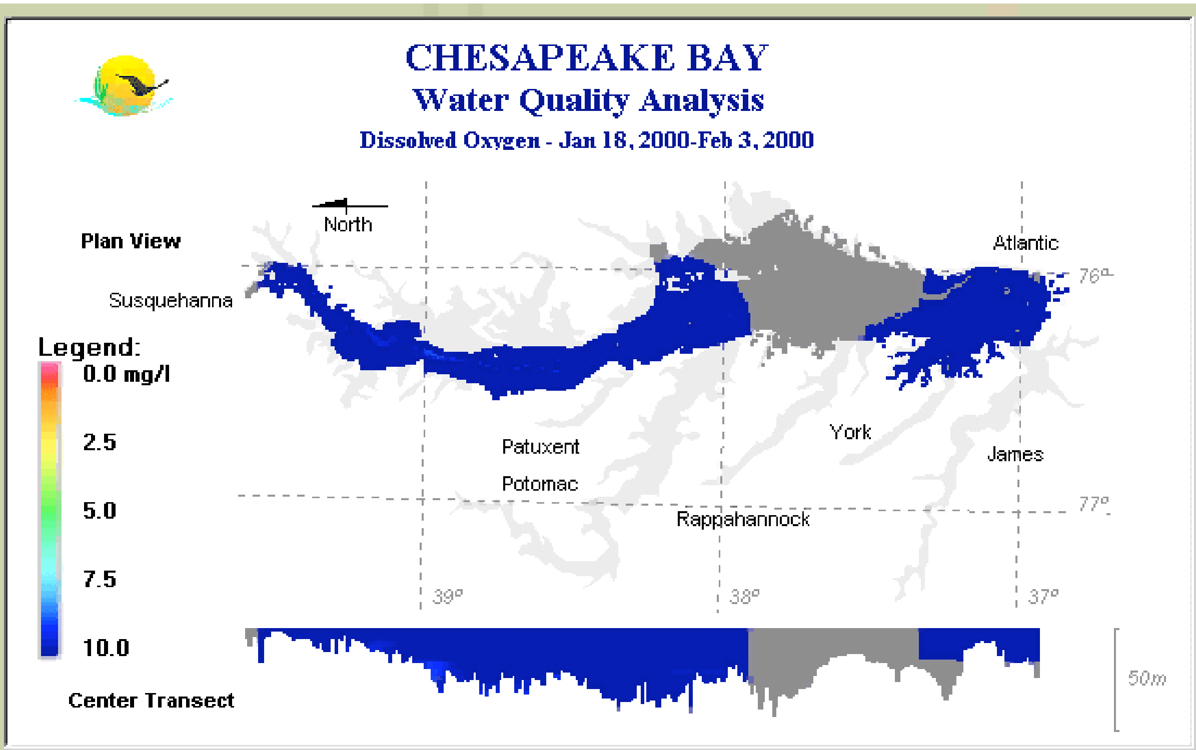
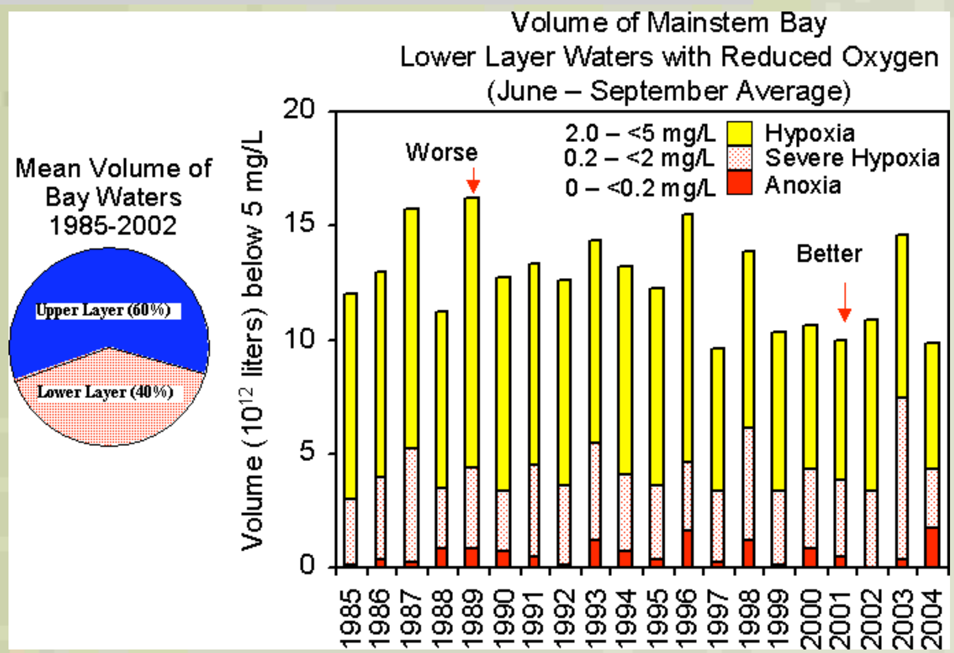


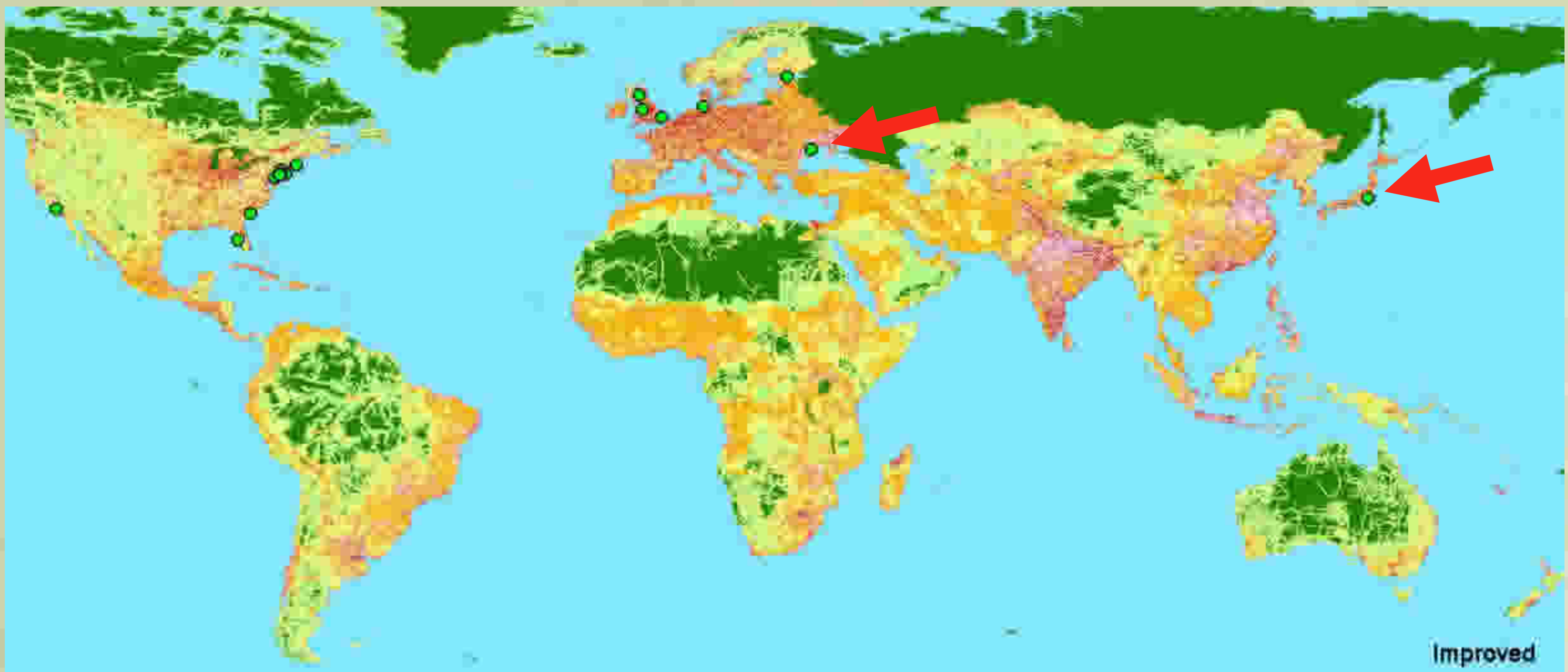
Figure 5. Historical variations of nitrate concentrations at Datong station (33).



Red = <1 mg/l
Yellow = 1-3 mg/l
Greens/Blues = >3 mg/l



Remission from Economic Reduction in Nutrient Loading



Black Sea (Mee et al. 2005)

Time	Fisheries & WQ
<1960	↑
1970s	↓
1990s	↑
2000s	??

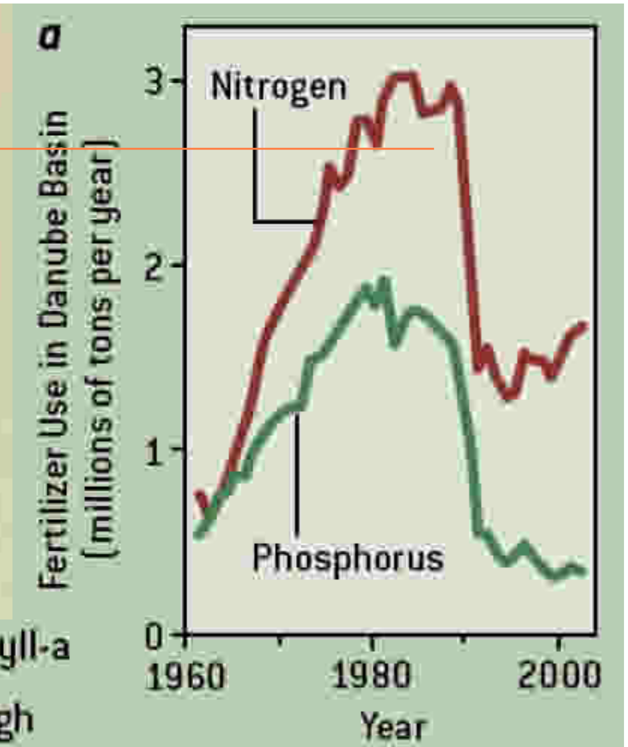
Tokyo Bay (Kodama et al. 2002)

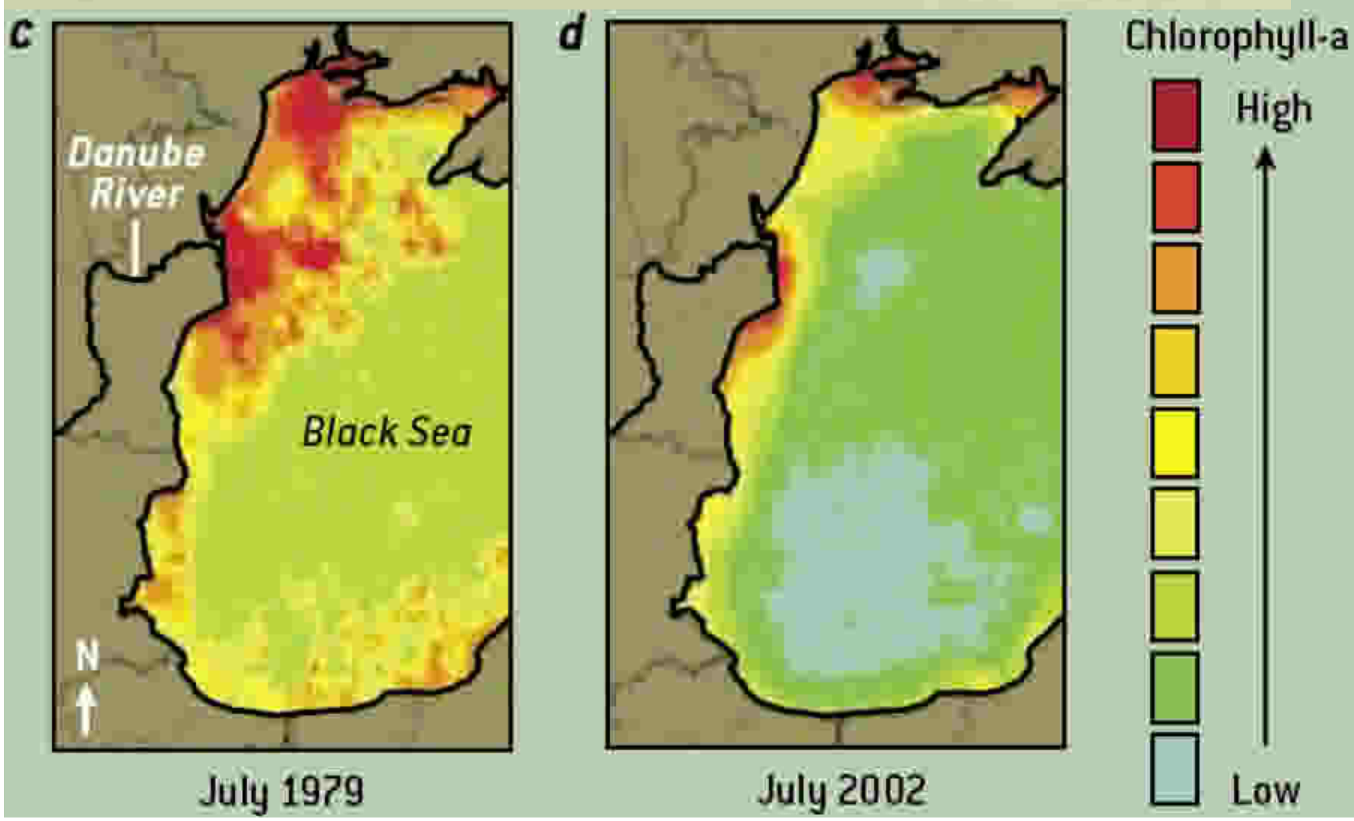
Time	Fisheries & WQ
<1930	↑
Mid 30s	↓
Late 40s	↑
Early 70s	↓ ↓

Black Sea

Black Sea **(Mee et al. 2005)**

Time	Fisheries & WQ
<1960	↑
1970s	↓
1990s	↑
2000s	**??**

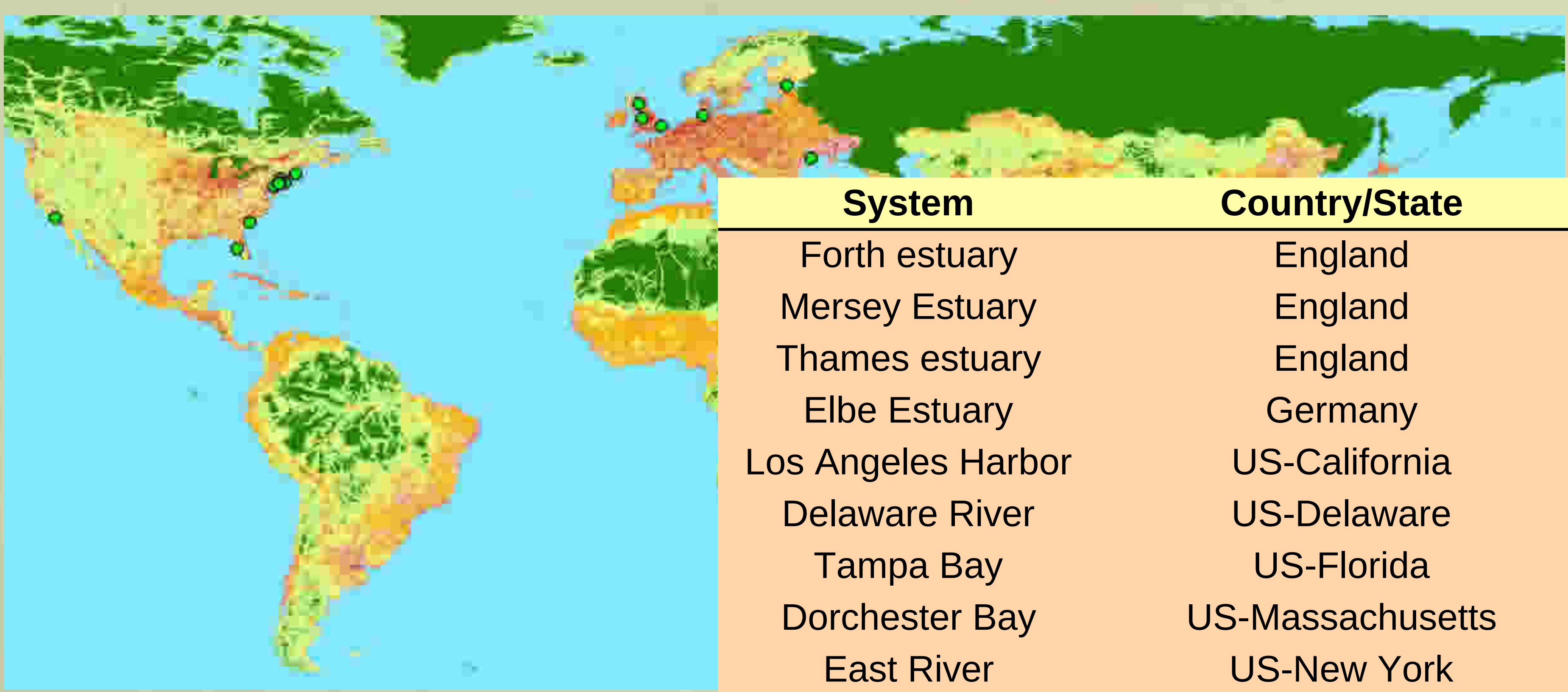




Mee 2006

Recovered with Nutrient Management

14 systems have responded positively.



System	Country/State
Forth estuary	England
Mersey Estuary	England
Thames estuary	England
Elbe Estuary	Germany
Los Angeles Harbor	US-California
Delaware River	US-Delaware
Tampa Bay	US-Florida
Dorchester Bay	US-Massachusetts
East River	US-New York
Great South Bay	US-New York
Hudson River	US-New York
New York City Harbor	US-New York
Raritan Bay	US-New York/New Jersey
Charleston Harbor	US-South Carolina

Climate Change and Coastal Oxygen

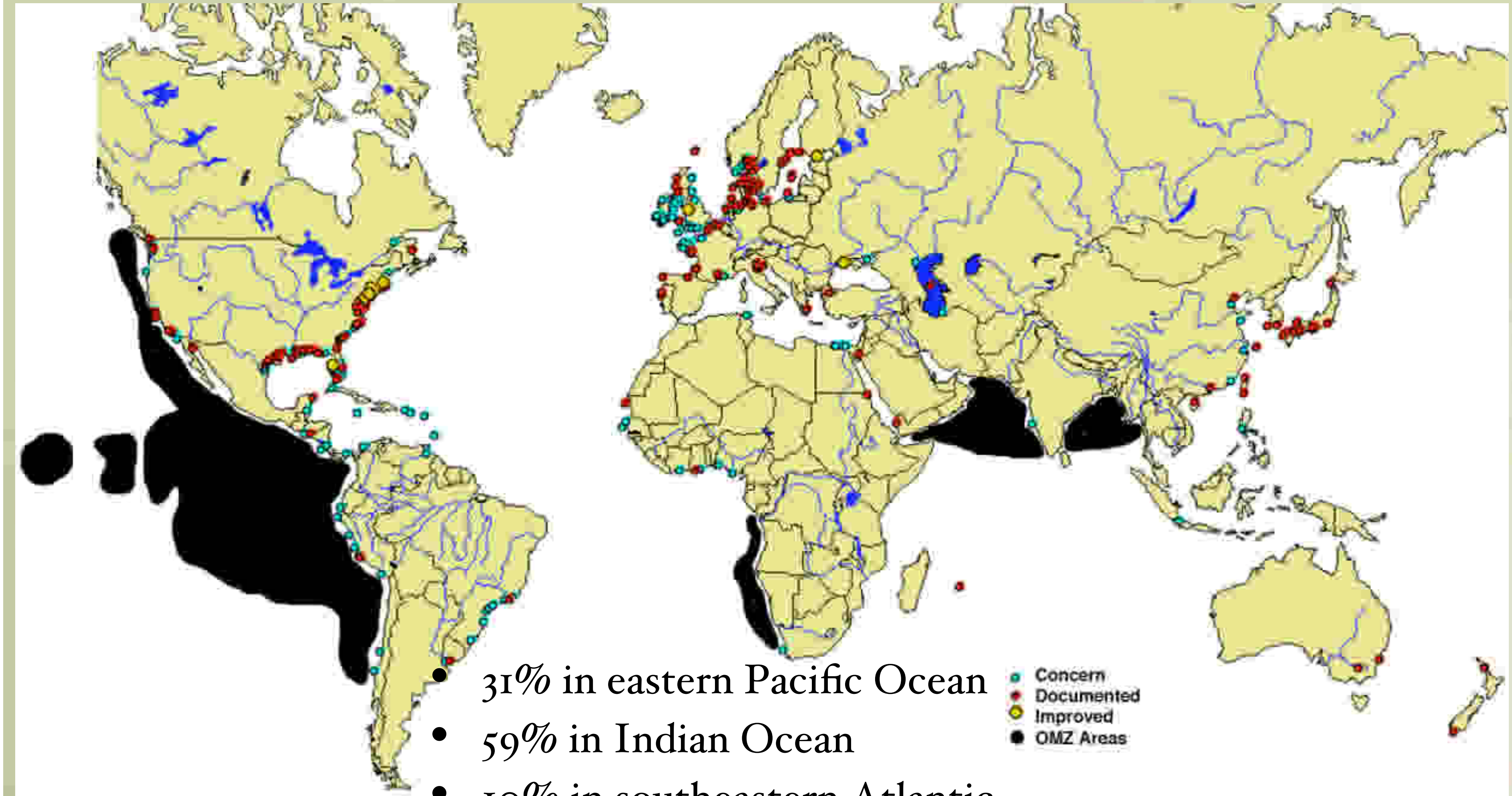
- Predictors for future oxygen budgets are not good:

- Lower dissolved oxygen content of world oceans (Keeling and Garcia 2002 Proc Nat Acad Sci)

- Expansion of Oxygen Minimum Zones and upwelling (Helly and Levin 2004 Deep-Sea Res)

- Expansion of anthropogenic hypoxia (Diaz & Rosenberg 2008 Science, Rabalais et al. 2007 Estuaries & Coasts)

OMZ at <0.5 ml/l Touch 1,148,000 km² of Seafloor Along Continental Margins.



- 31% in eastern Pacific Ocean
- 59% in Indian Ocean
- 10% in southeastern Atlantic

Helly & Levin 2004 Deep-Sea Res

Eutrophication Driven Hypoxia Covers Over 207,000 km^2 of Seafloor.

- This is a conservative estimate, only 30% of hypoxic systems have area estimates.

- Coastal systems account for 75% of hypoxia
  - Baltic Sea
  - Mississippi/Atchafalaya River Plume
  - German Bight
  - East China Sea

Expansion OMZ and Upwelling

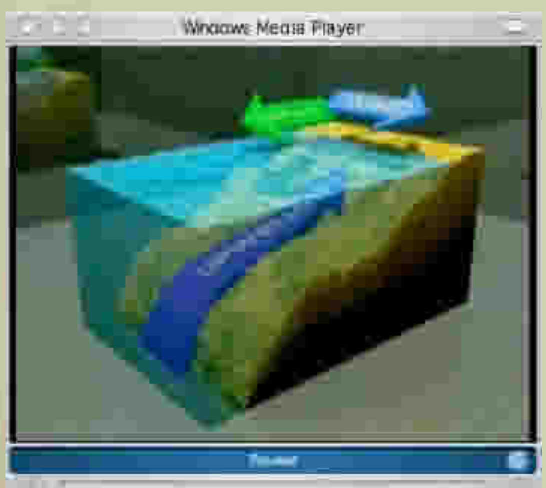
(Grantham et al. 2004 Nature, Chan et al. 2008 Science)

Oregon Coast, USA

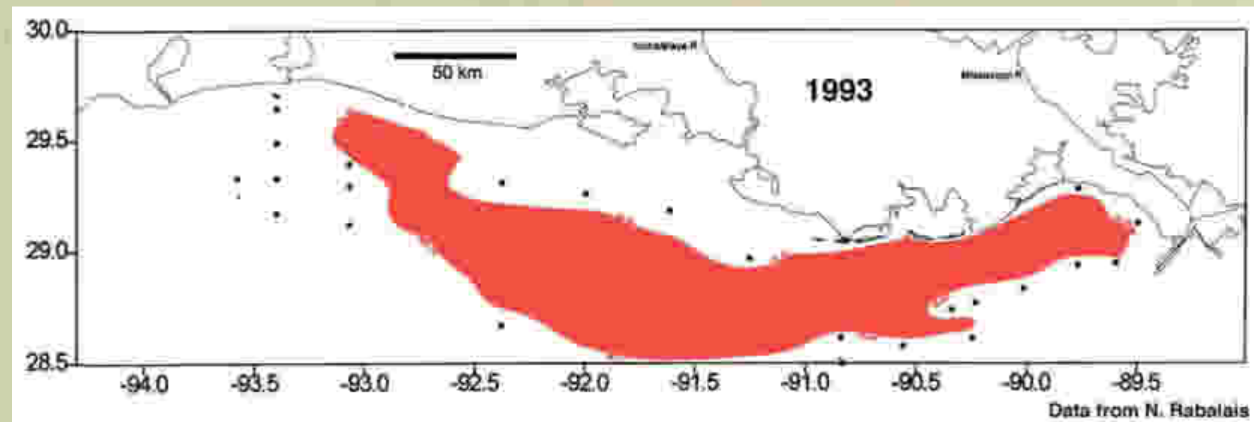
Upwelling increase linked to shifts in regional climate forcing:

- Strong interannual changes in upwelling wind stress
- Nutrient supply to California Coastal Current

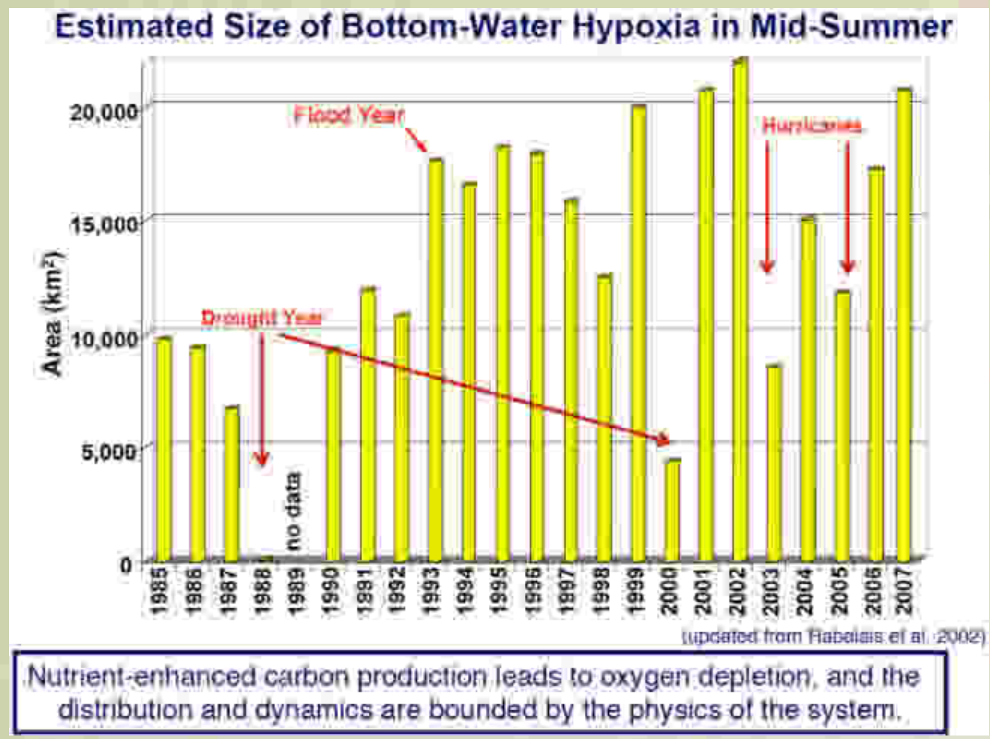
Severe inner-shelf hypoxia and anoxia since 2000, >32,000 km^2 in 2006



Gulf of Mexico - LA Continental Shelf

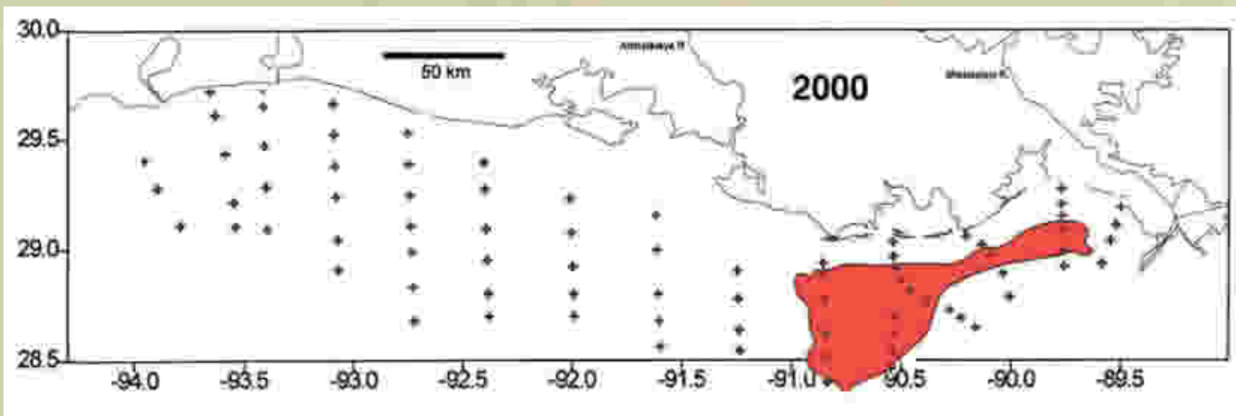


	Years with Hypoxia	% Change Relative to Nominal	
Modeled Nominal Period 1975-2000	19		
River Discharge Down 30%	8	-58%	Dryer
River Discharge Up 20%	26	+37%	Wetter
Water Temp. Up 4 C	25	+32%	Hotter
Discharge 20% & Temp 4 C Up	31	+63%	Wetter & Hotter



Justic et al. 2007 Estuaries & Coasts; Rabalais Poster

Gulf of Mexico - LA Continental Shelf



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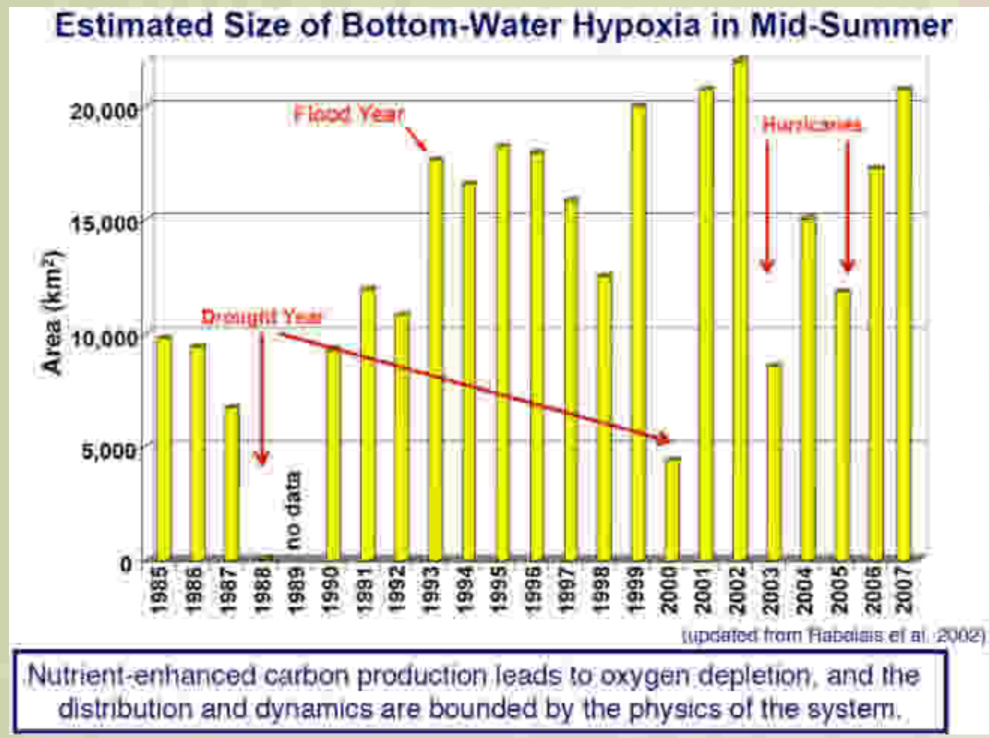
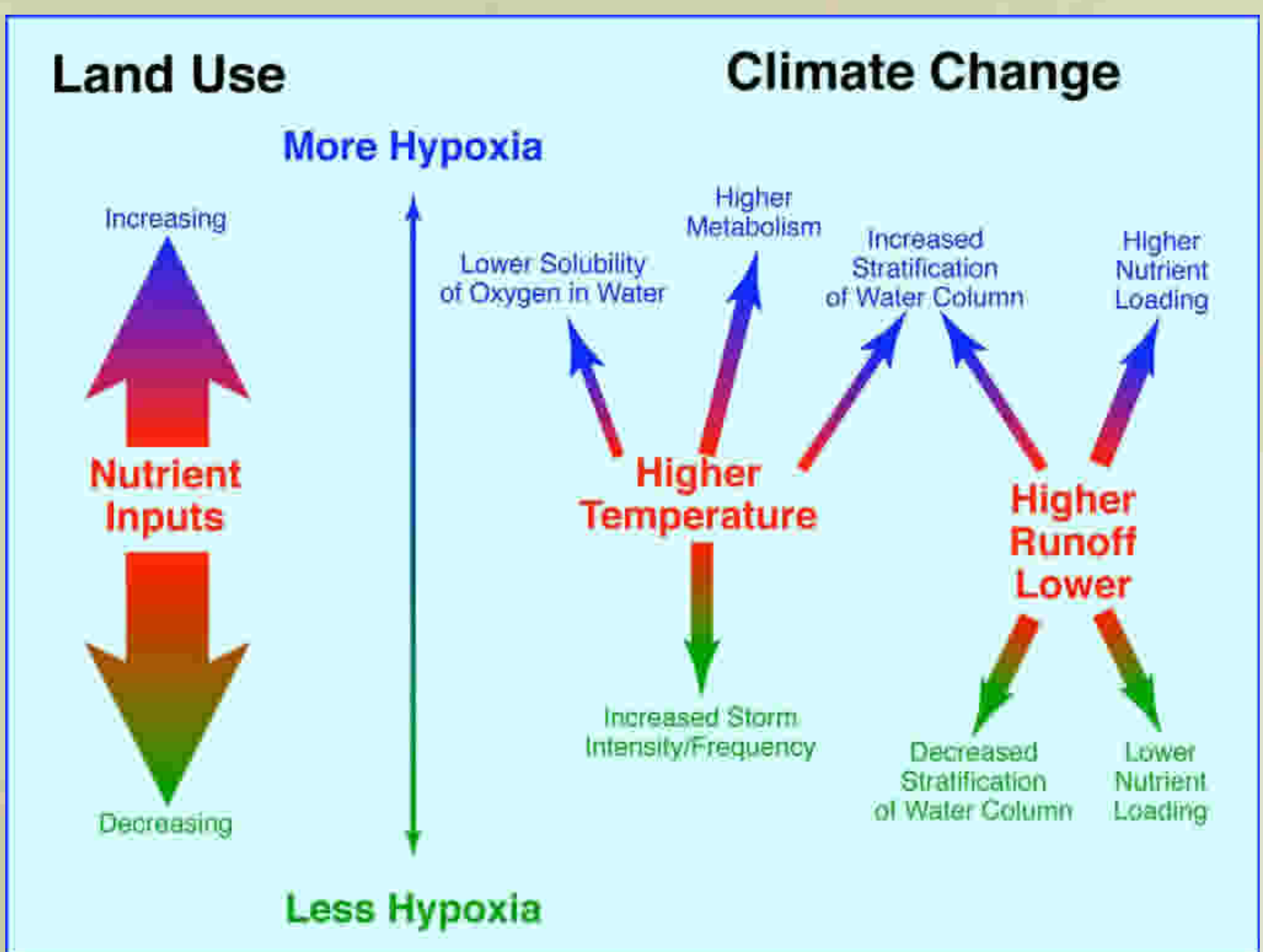


Justic et al. 2007 Estuaries & Coasts; Rabalais Poster

Two Part Key to Future Hypoxia



Summary

- The amount of low dissolved oxygen continues to expand.
- Some improvement in hypoxia was observed in large systems with a return of benthos:
  - Black Sea - Economic Nutrient Reduction
  - Gulf of Finland - Breakup of stratification
- Improvement seen in some systems from nutrient regulation with a return of benthos and fishes:
  - Hudson River, Delaware River, East River
  - Mersey Estuary, Elbe Estuary
- If hypoxia can be eliminated ecosystem functions will return.

How to Reduce Hypoxia

- Action plans all incorporate Nitrogen load reduction
  - Agricultural Best Management Practice (fertilizer reductions)
  - Wetland and buffer strip restoration
- For Gulf of Mexico, a 30% nitrogen load reduction (Rabalais et al. 2007):
  - Reduce fertilizer by 40%
  - Restore 18 million acres of wetlands

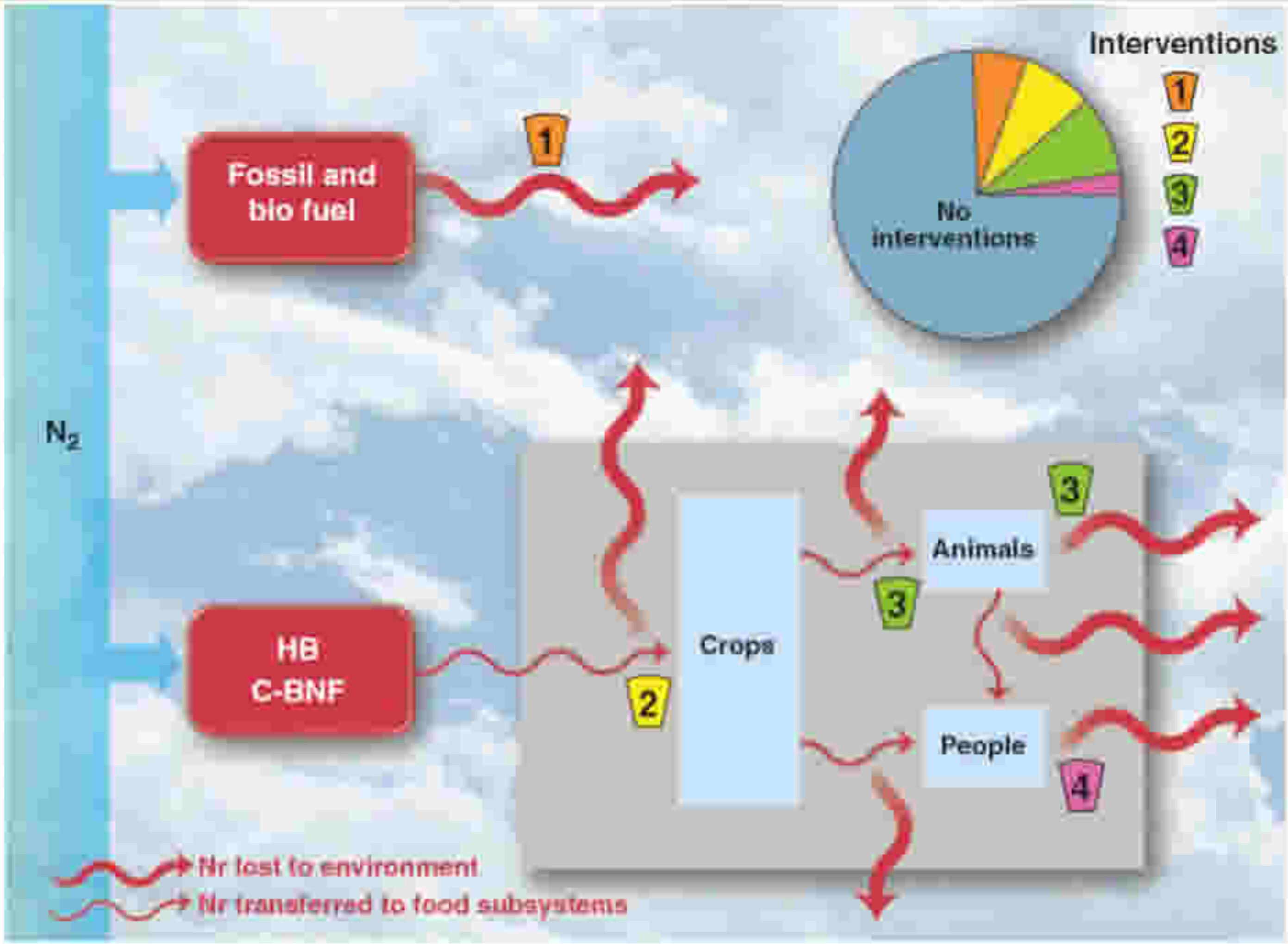


Fig. 3. Conceptual model of where interventions in the N cycle can be used to decrease the amount of Nr created or the amount of Nr lost to the environment. The red boxes represent subsystems where Nr is created. The sky-background space represents the environment. Arrows leaving the red boxes either result in Nr lost to environment (fossil fuel and biofuel combustion) or inputs to the food production system (gray box). The light blue boxes within the gray box represent subsystems within the food production system where Nr is used. Nr can either enter these subsystems (thin red lines), or be lost to the environment (thick red lines). The numbers represent intervention points for N management. The pie chart shows the magnitude of Nr managed by the four interventions relative to the total amount created (187 Tg N) in 2005.

Galloway et al. 2008, Science

Future Hypoxia

National Geographic's, Strange Days on Planet Earth
Episode 6, Dirty Secrets, 2008. Visual by Sea Studios Foundation.