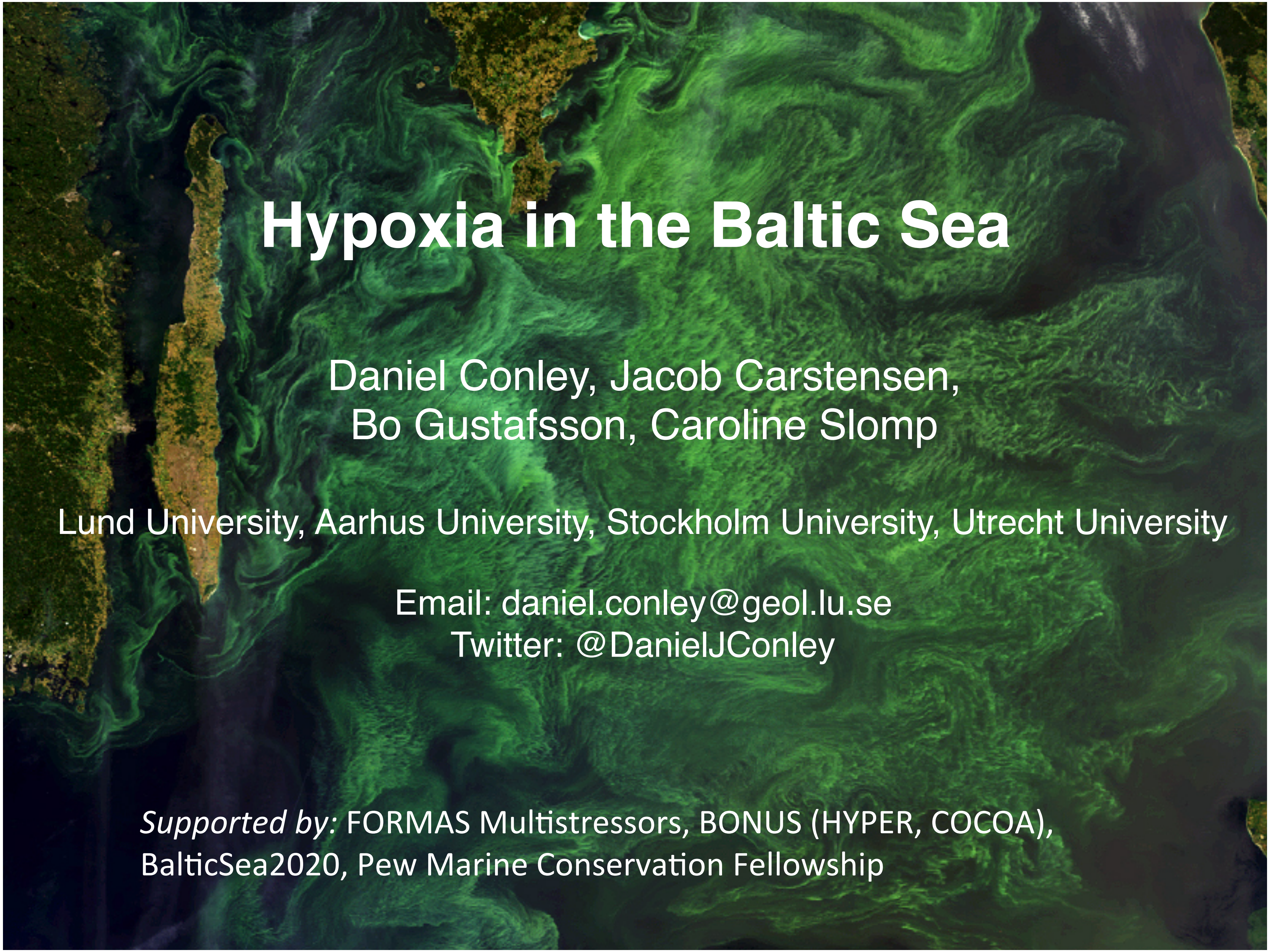

Hypoxia in the Baltic Sea

Daniel Conley, Jacob Carstensen,
Bo Gustafsson, Caroline Slomp

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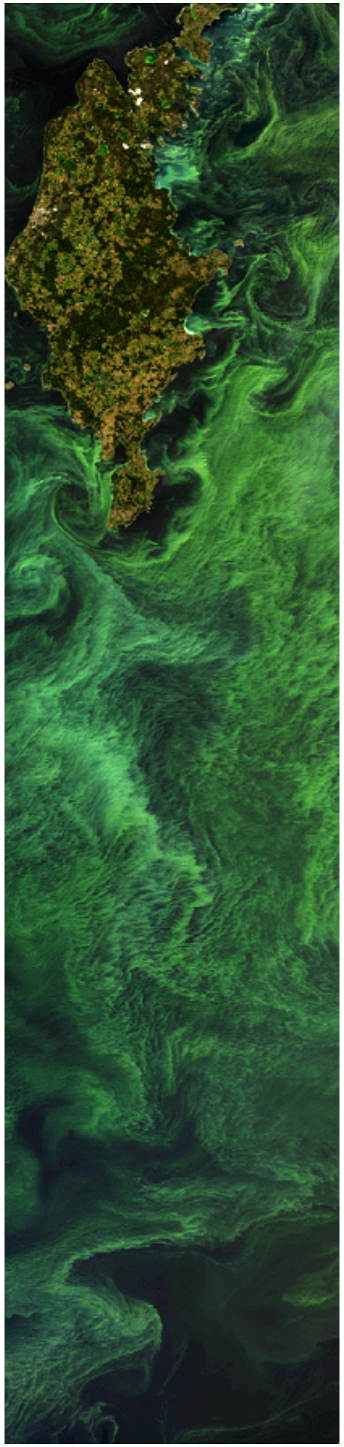
Twitter: @DanielJConley

Supported by: FORMAS Multistressors, BONUS (HYPER, COCOA), BalticSea2020, Pew Marine Conservation Fellowship



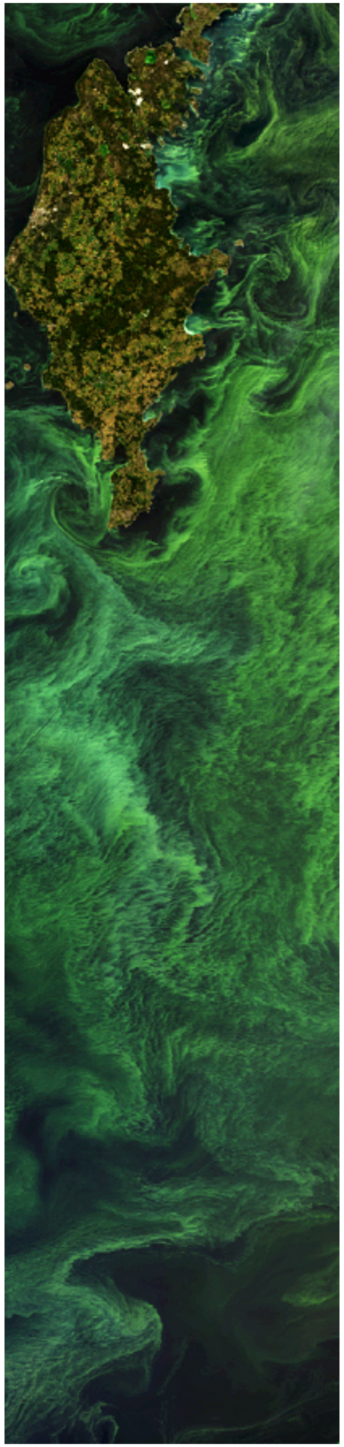
Introduction

Hypoxia: When, where and why

Effect of major Baltic inflows on hypoxia

Consequences of hypoxia in the Baltic

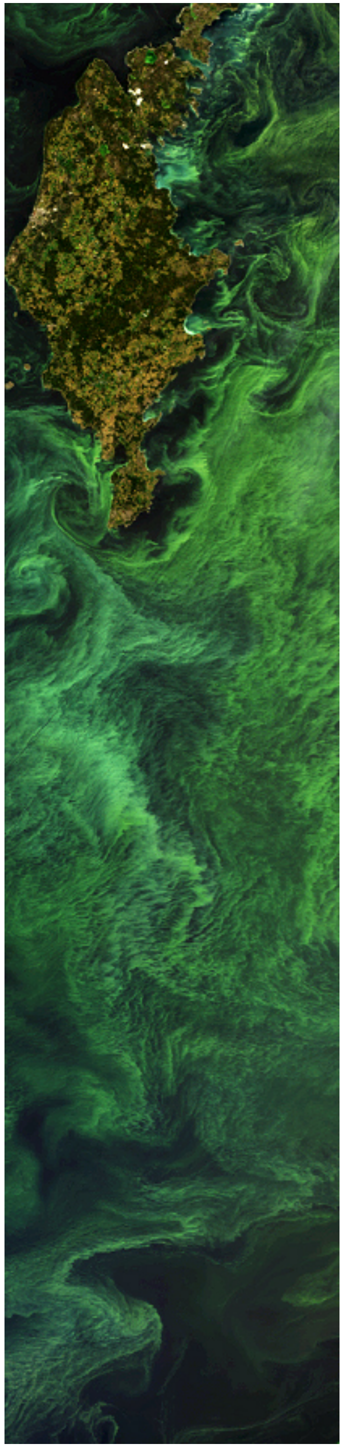
Perspectives for the future



What are the conditions necessary hypoxia to occur?

Stratification of the water column from temperature, salinity or circulation (lack of oxygen renewal)

Organic matter (oxygen consuming material)



Question

Where does hypoxia occur in the Baltic Sea?

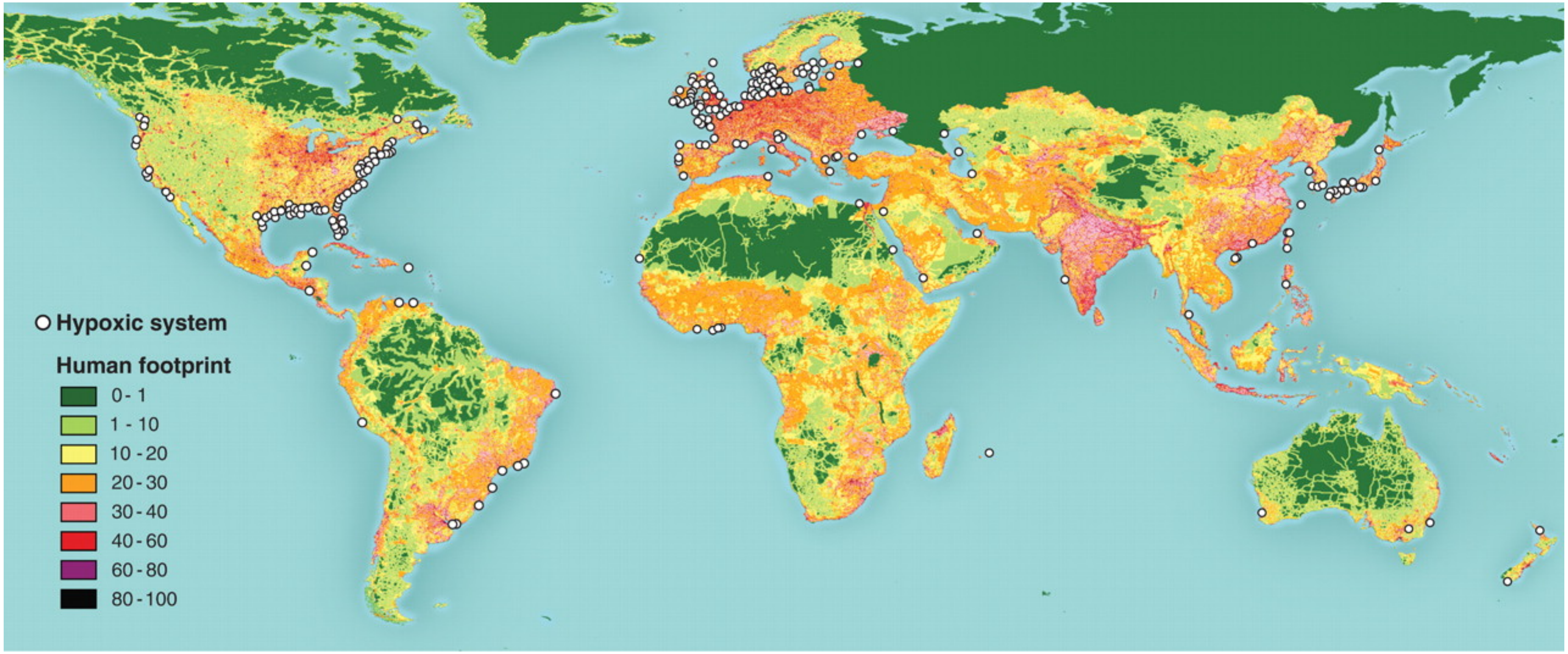
When you can't breathe, nothing else matters!

American Lung Association (via Bob Diaz)

How long can you hold your breath?

Mariager Fjord, Denmark
25 August 1997

Spreading dead zones



Reported from more than 400 coastal systems
The number of reports of hypoxia are increasing

Diaz and Rosenberg 2008

Eutrophication

Definition of eutrophication: An increase in the supply of organic matter to an ecosystem (Nixon 1995).

This emphasizes that eutrophication is a fundamental change in the energetic base that may propagate through the system in various ways and produce a variety of changes

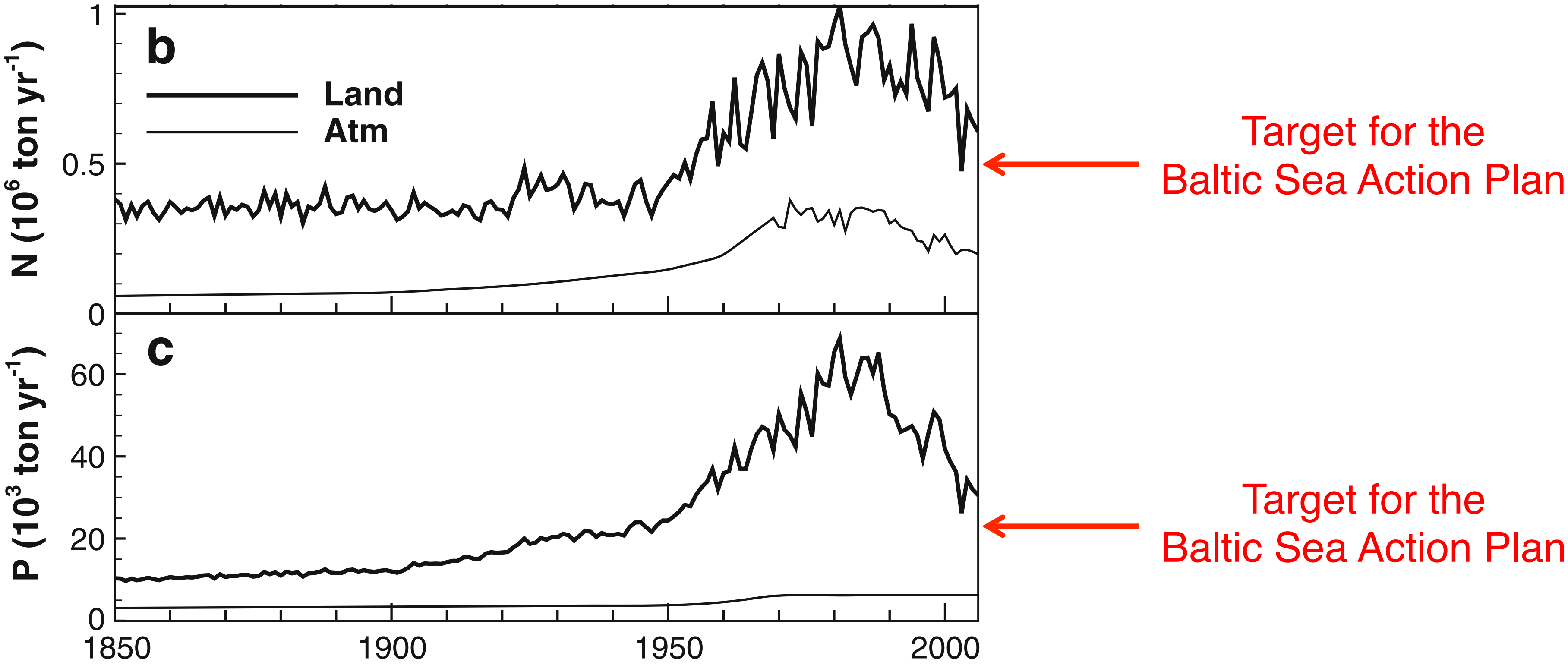
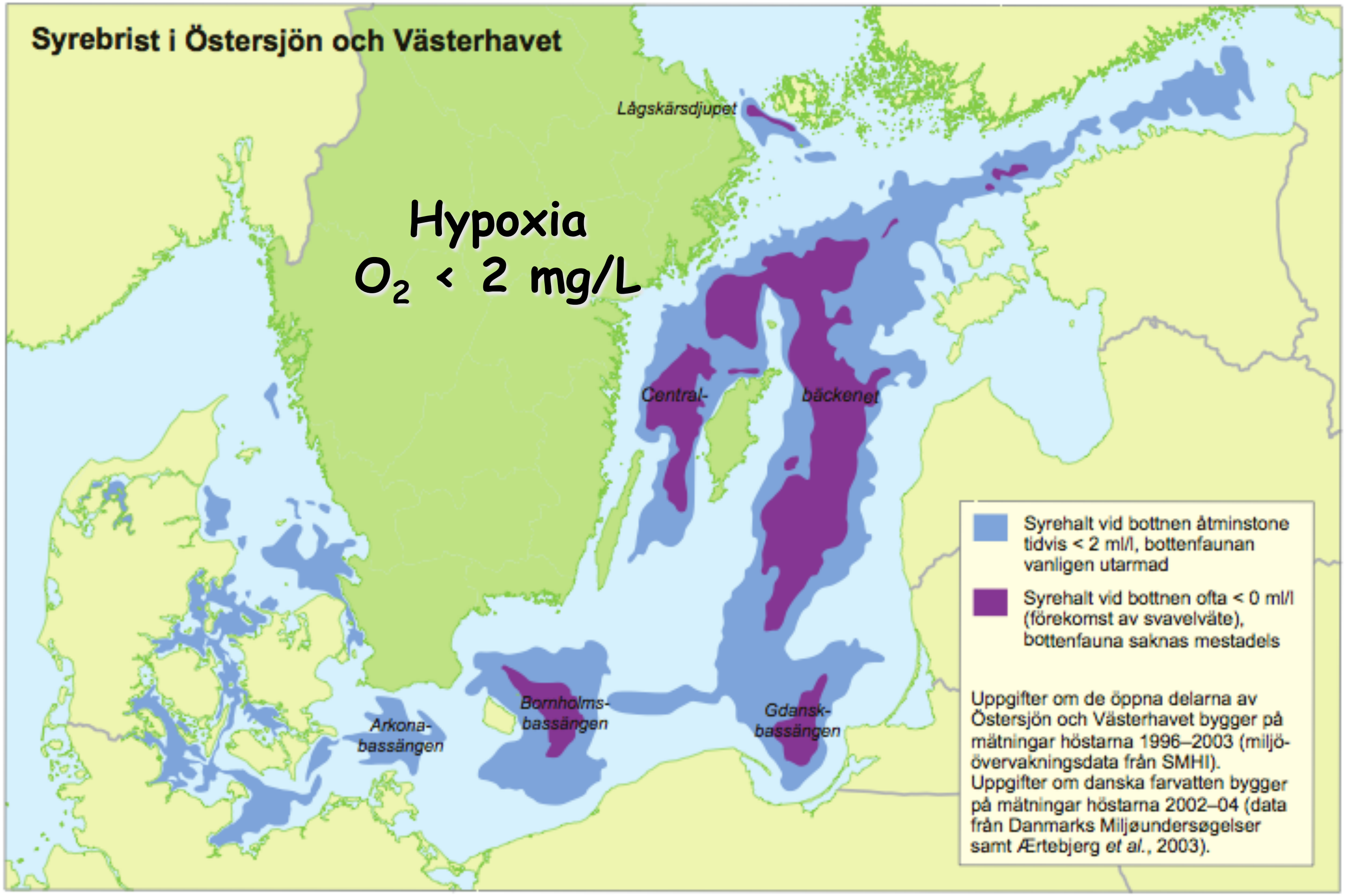


Fig. 2 Time series of annual average total river runoff (Q), nitrogen (N), and phosphorus (P) loads from land and atmosphere to the whole Baltic Sea

Gustafsson et al. 2012

Area with hypoxia averages ca. 49,000 km^2



Från *Förändringar under ytan* (Monitor 19).

Larger than the size of Denmark (43,000 km^2)

Methodology developed in 1888 by Ludwig Wilhelm Winkler at Budapest University
(First measurements of dissolved oxygen in the Baltic Sea are from 1898)

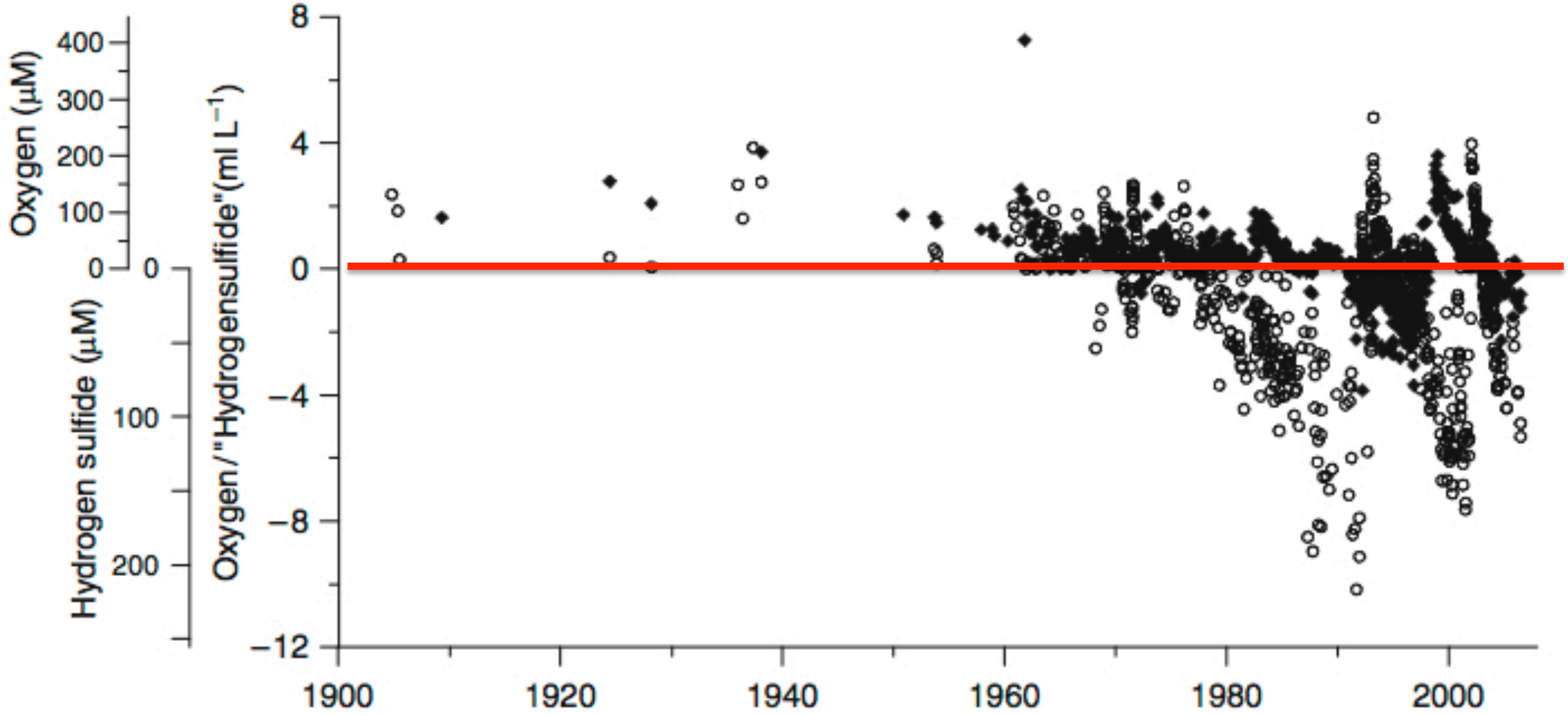
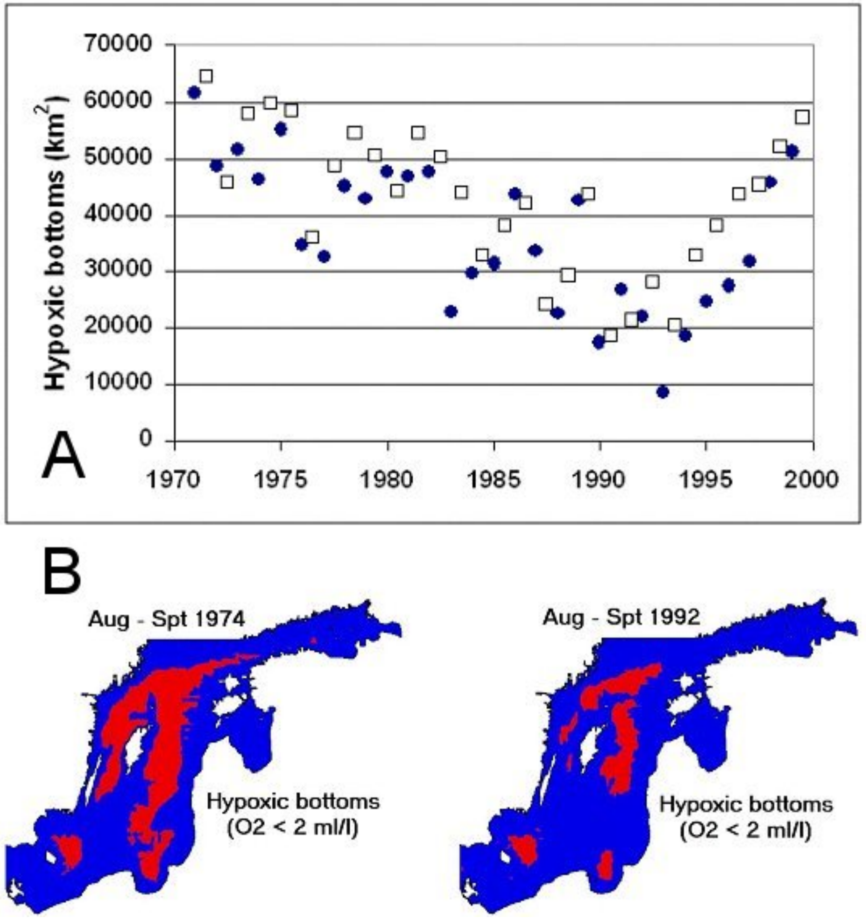


Fig. 3 Long-term variation of oxygen and hydrogen sulfide (shown as negative oxygen equivalents, mL L^{-1}) in the layers 145–155 m (*filled*) and below 230 m (*open*) at oceanographic station BY15 in the Gotland Deep (57° 15′–57° 25′ N and 19° 50′–20° 10′E). For comparisons, 10 mL O_2 L^{-1} = 446 μM of oxygen; –10 mL O_2 L^{-1} correspond to 213 μM of hydrogen sulphide

Savchuk (2010)

Changes in hypoxia area with time

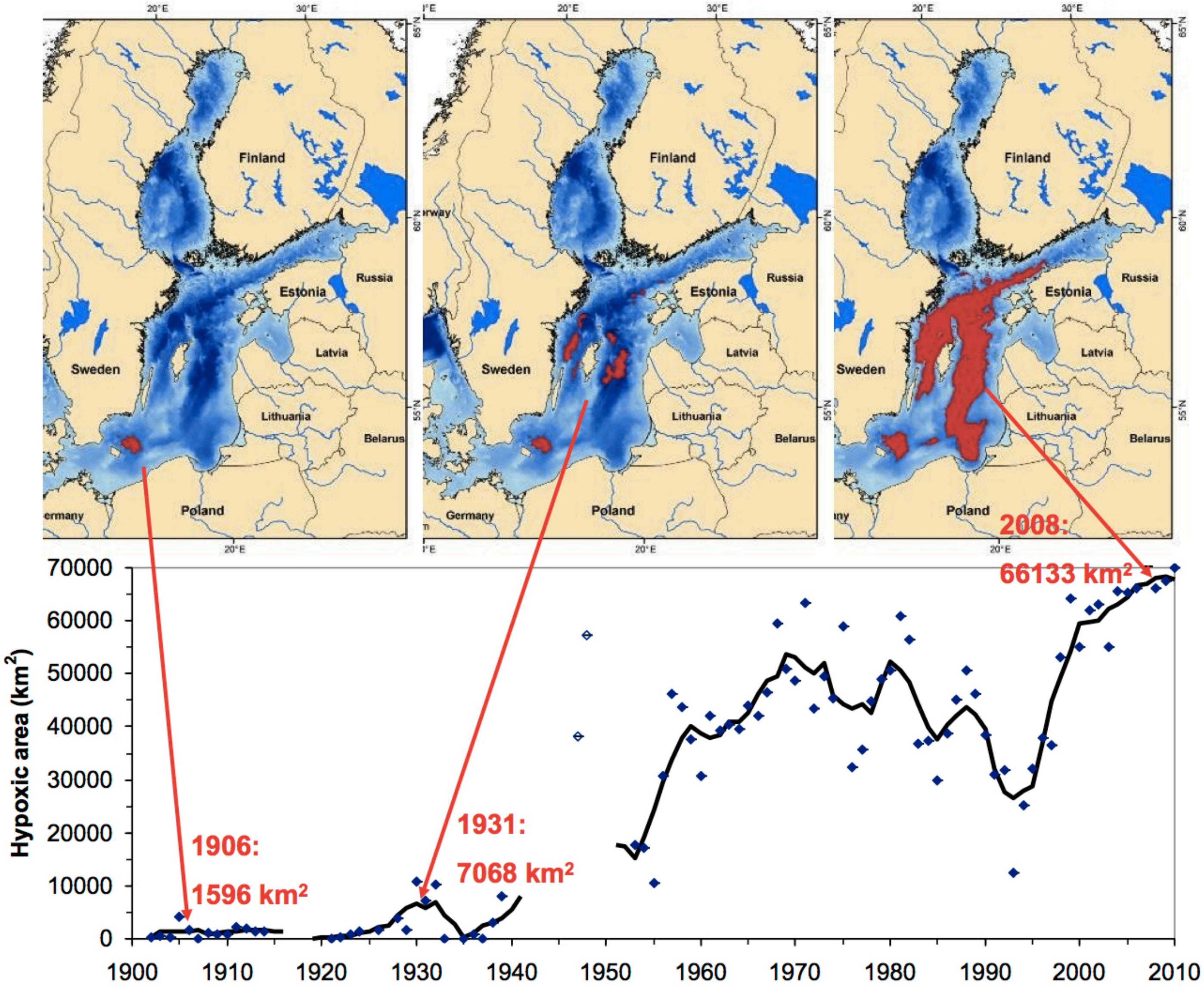


- Highest basin-wide oxygen occurs during periods of low salt water input, e.g. major inflows
- Salt water input leads to more stratification and reduced mixing increasing residence time and reducing oxygen concentrations

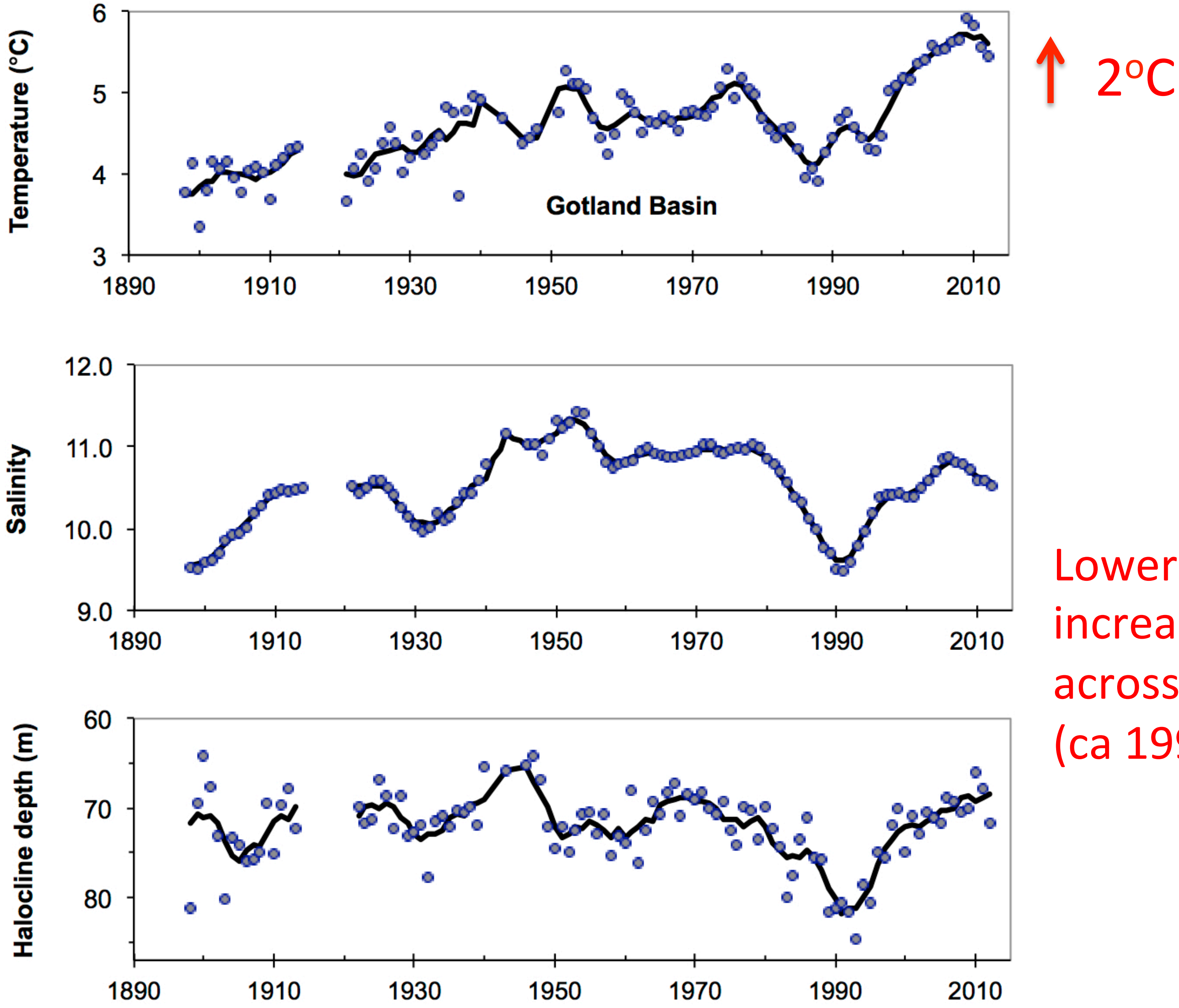
Prior to 1970?

Conley et al. 2002

Changes in hypoxia area with time

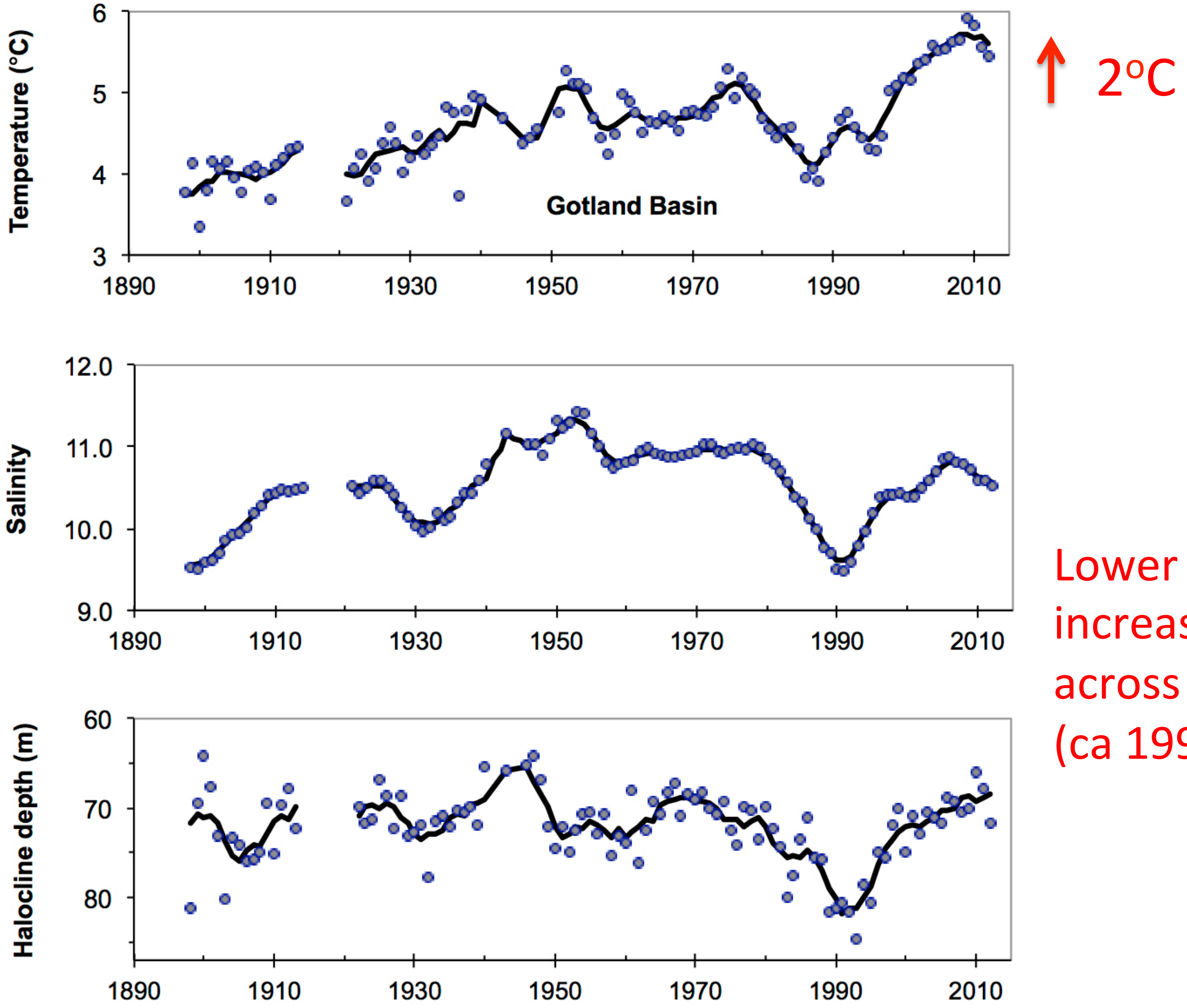


Carstensen et al. 2014 PNAS



Lower salinity and increased mixing across halocline (ca 1990)

Carstensen et al. (2014)



Lower salinity and increased mixing across halocline (ca 1990)

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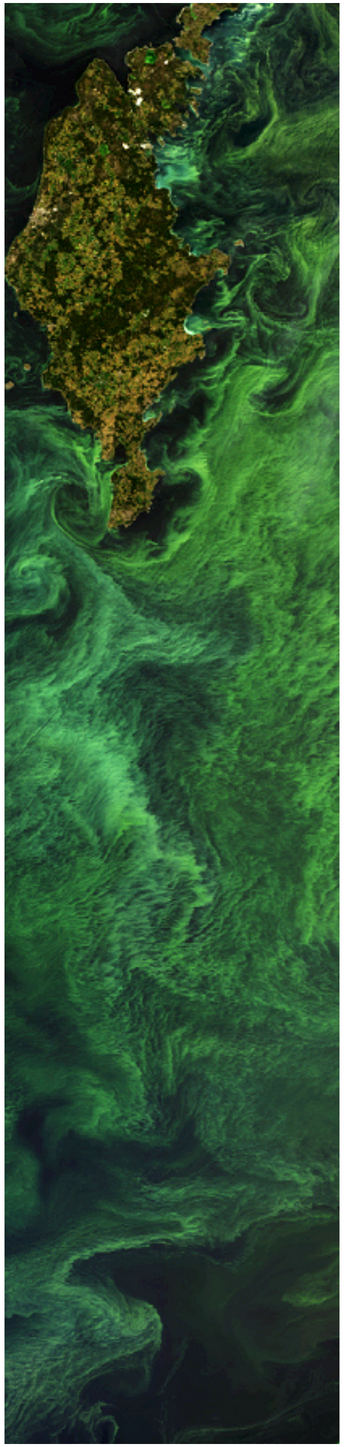
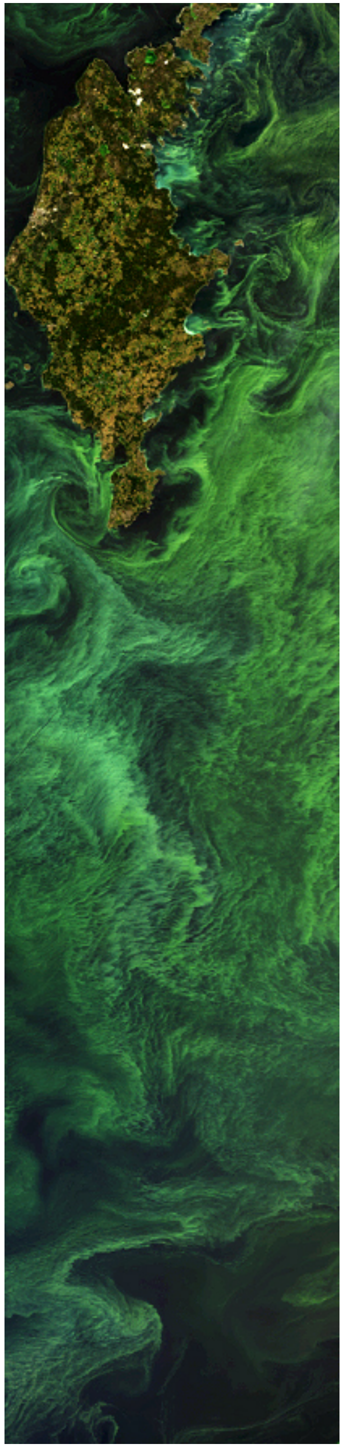


Question

What do we know about coastal hypoxia?

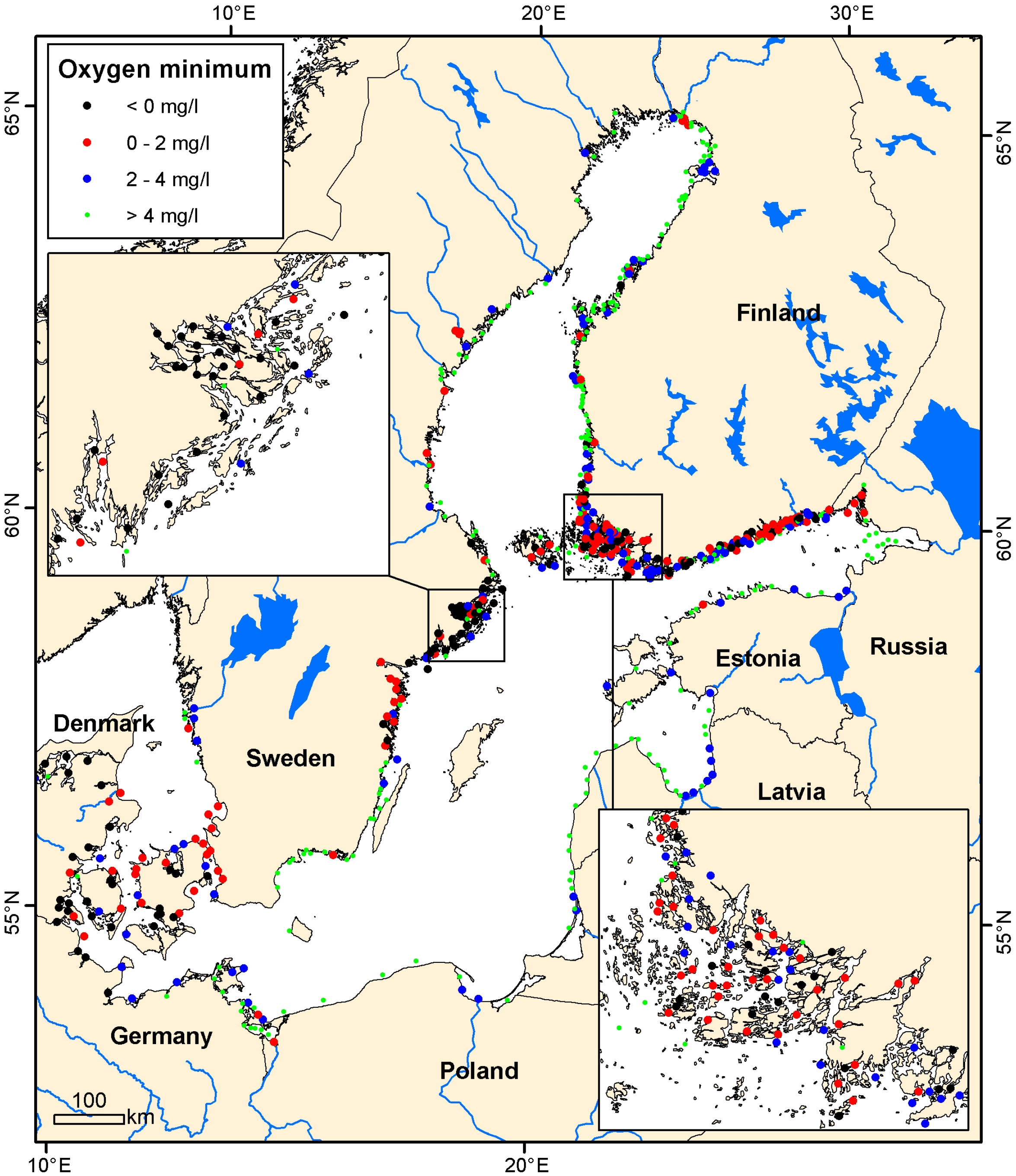


What do we know about coastal hypoxia?

Classic examples permanently anoxic (Mariager Fjord)

Summer hypoxia (Gullmar Fjord, Stockholm Archipelago)

Episodic



Mininum oxygen concentrations (1955-2009)

215 sites out of 613 coastal units have experienced hypoxia (O_2 < 2 mg/l)

...and there is a trend for decreasing O_2

Conley et al. 2011 ES&T

Categories of hypoxia (2000-2009)

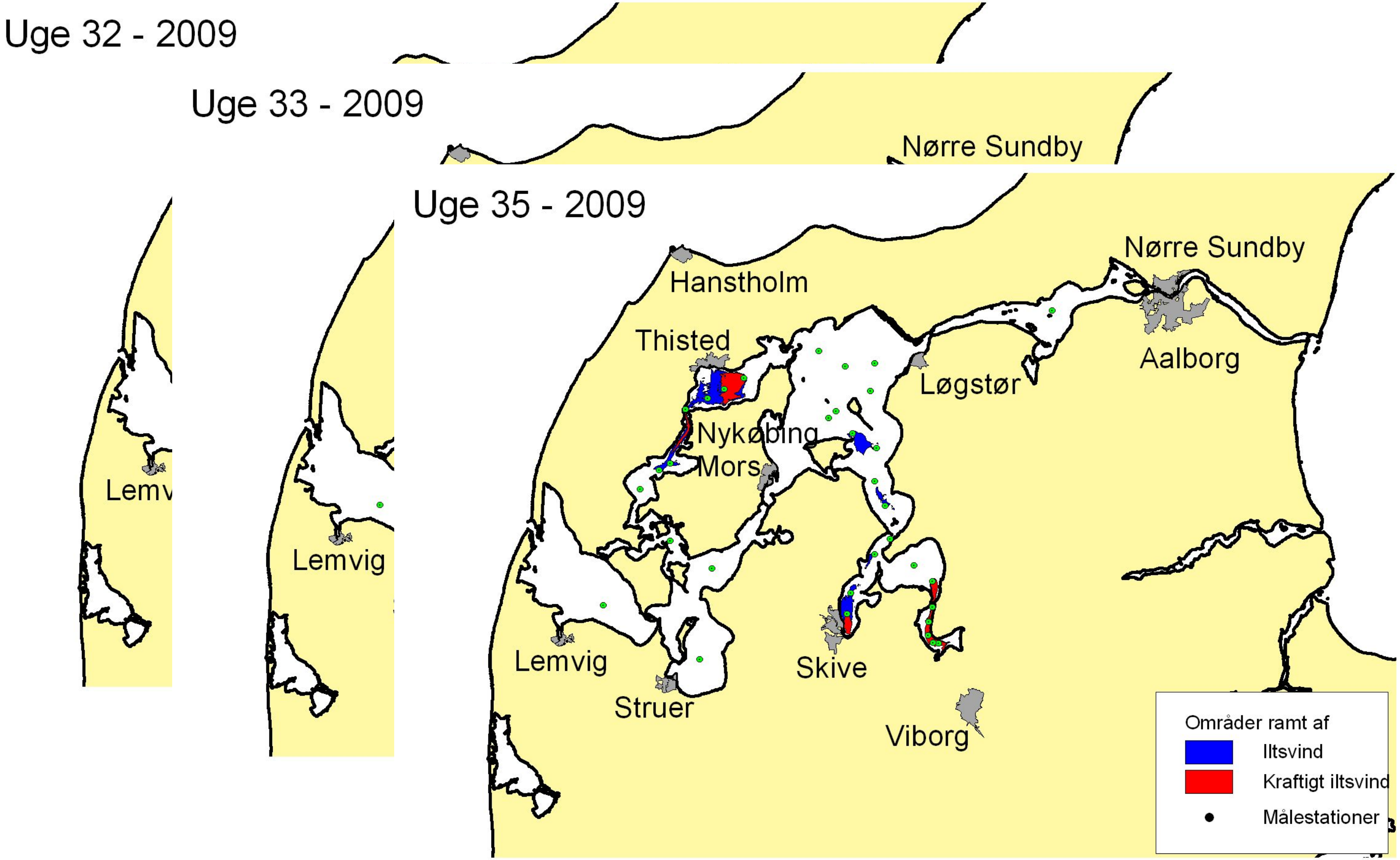
Never - 63%

Persistent - 1.5% (7 coastal units)

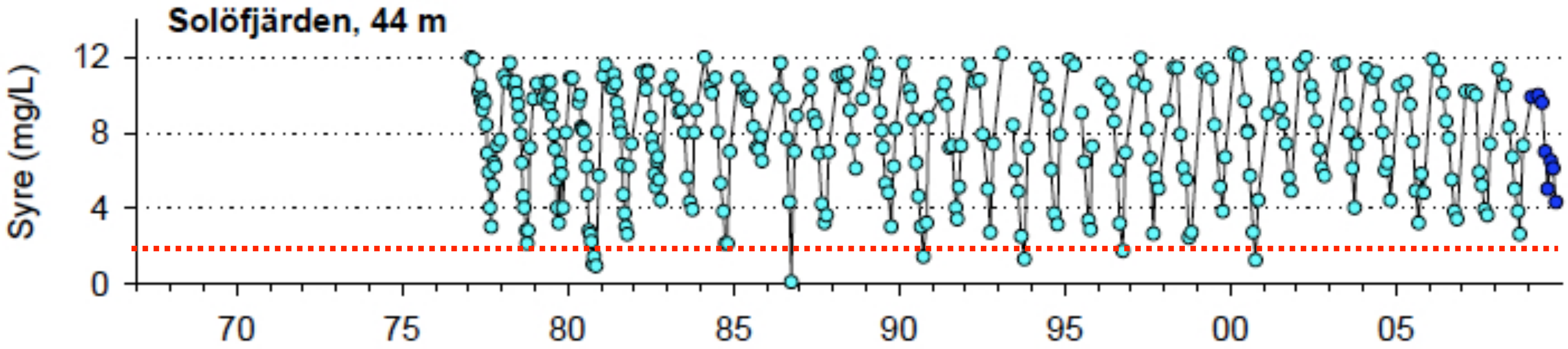
Seasonal - ca. 4%

Episodic - 30%

Limfjorden: Hypoxia changes rapidly

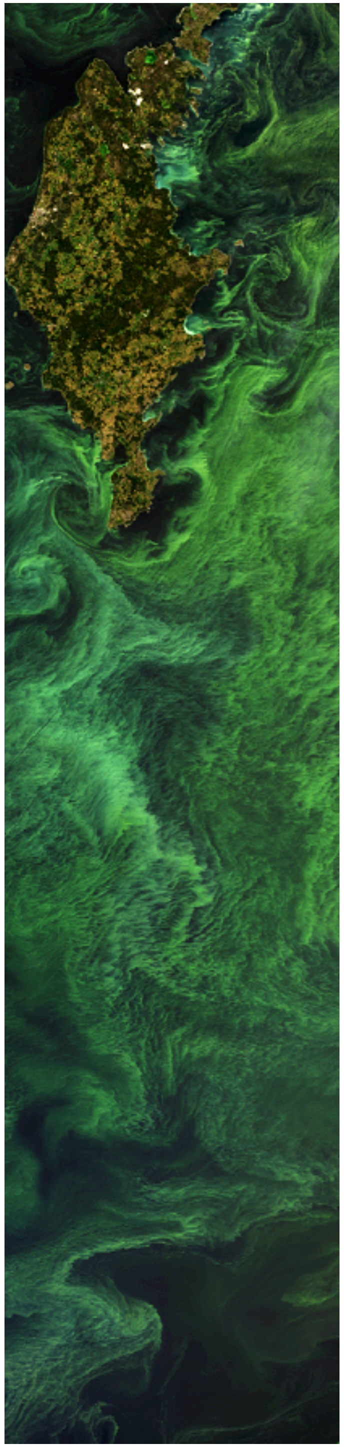


Oxygen concentrations from Solöfjarden, Stockholm Archipeligo



Lännergren 2010

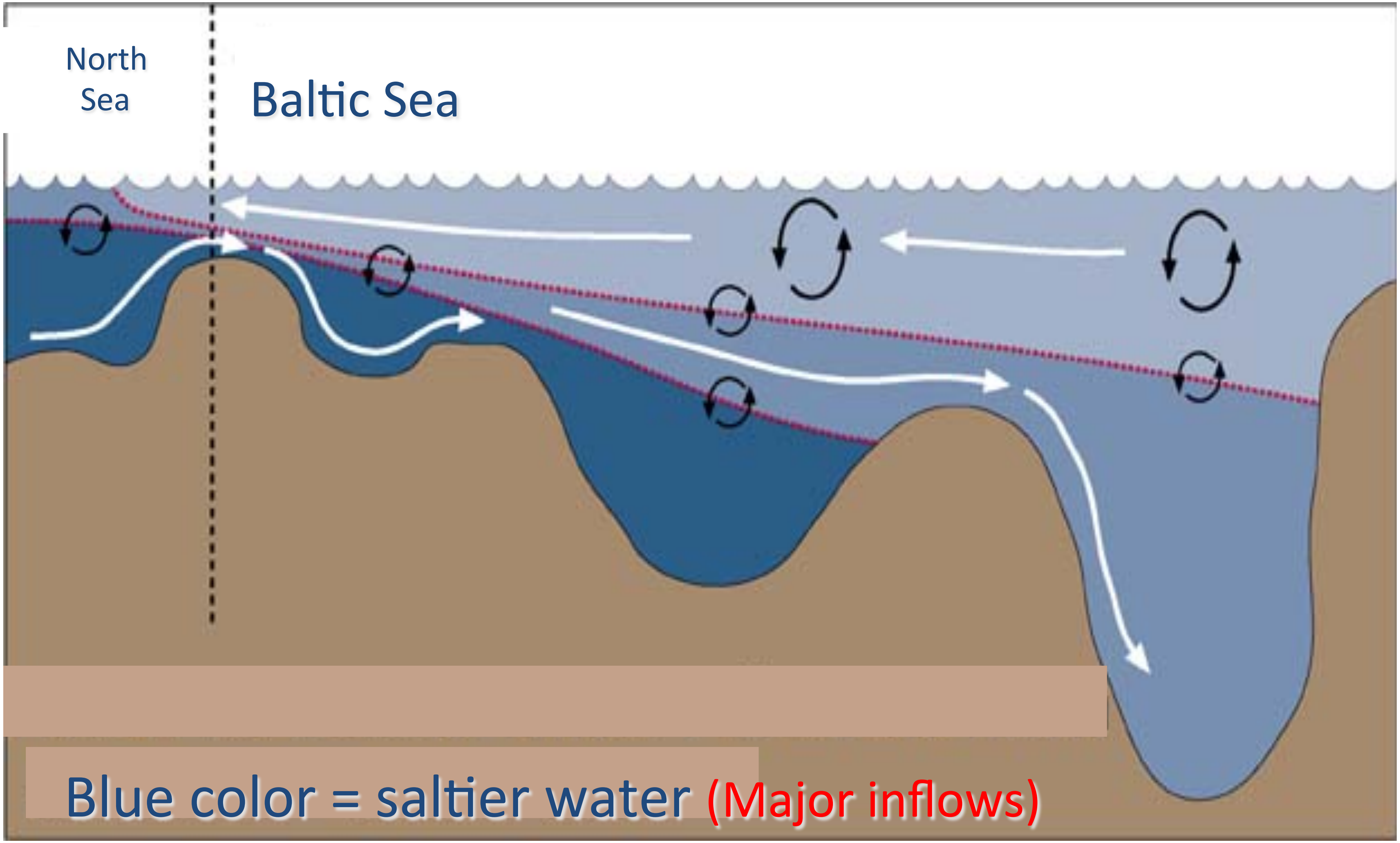
Although Solöfjarden has a strong seasonal cycle in oxygen concentrations it is classified as experiencing ”episodic hypoxia”



Question

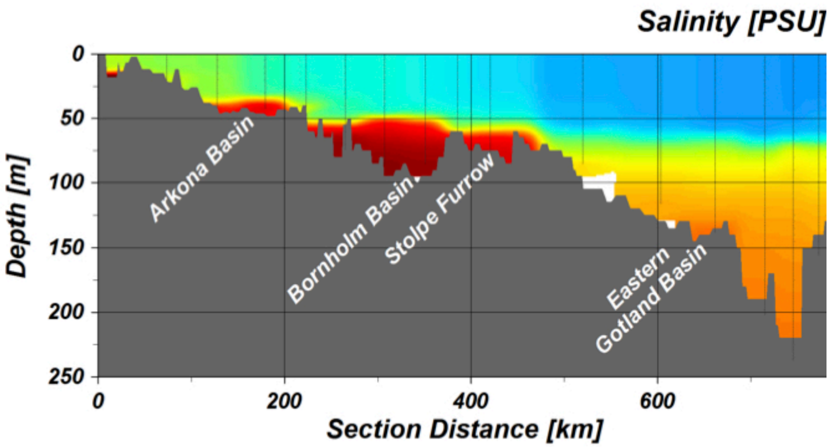
What are the effects of major saltwater inflows into the Baltic Sea?

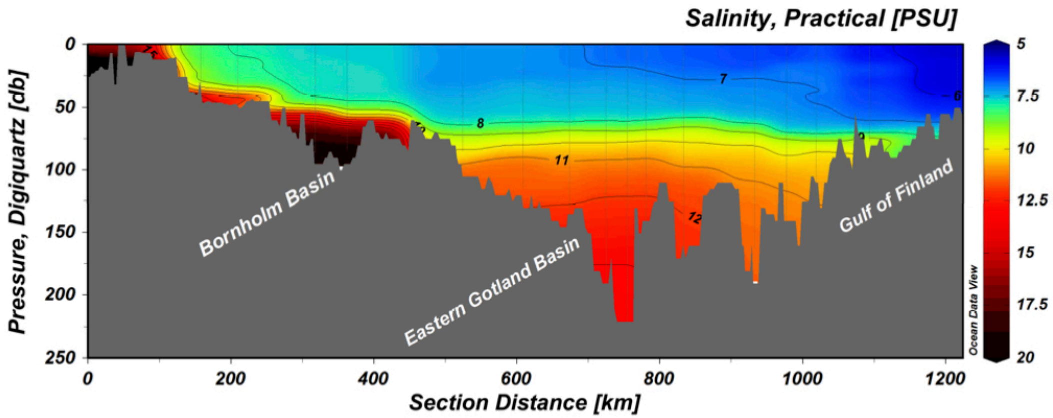
Saltwater inputs into the Baltic Sea

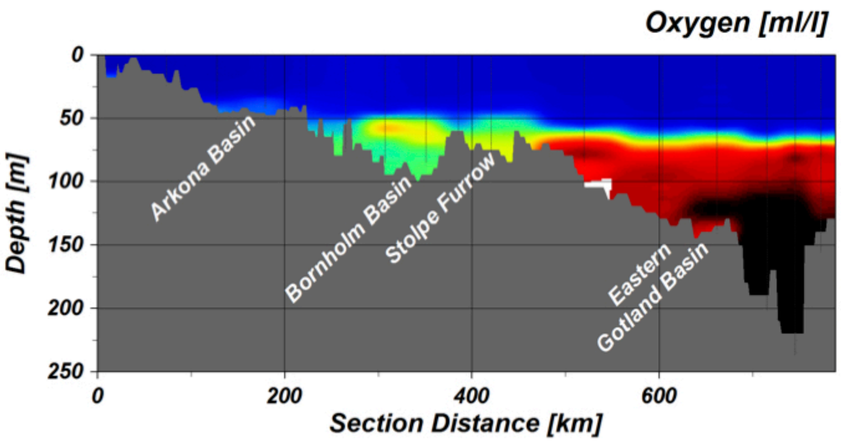


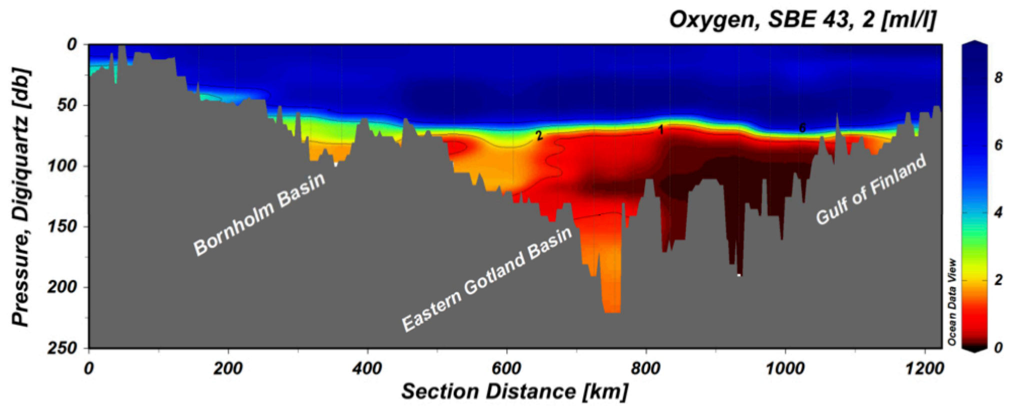
February 2015

July 2015



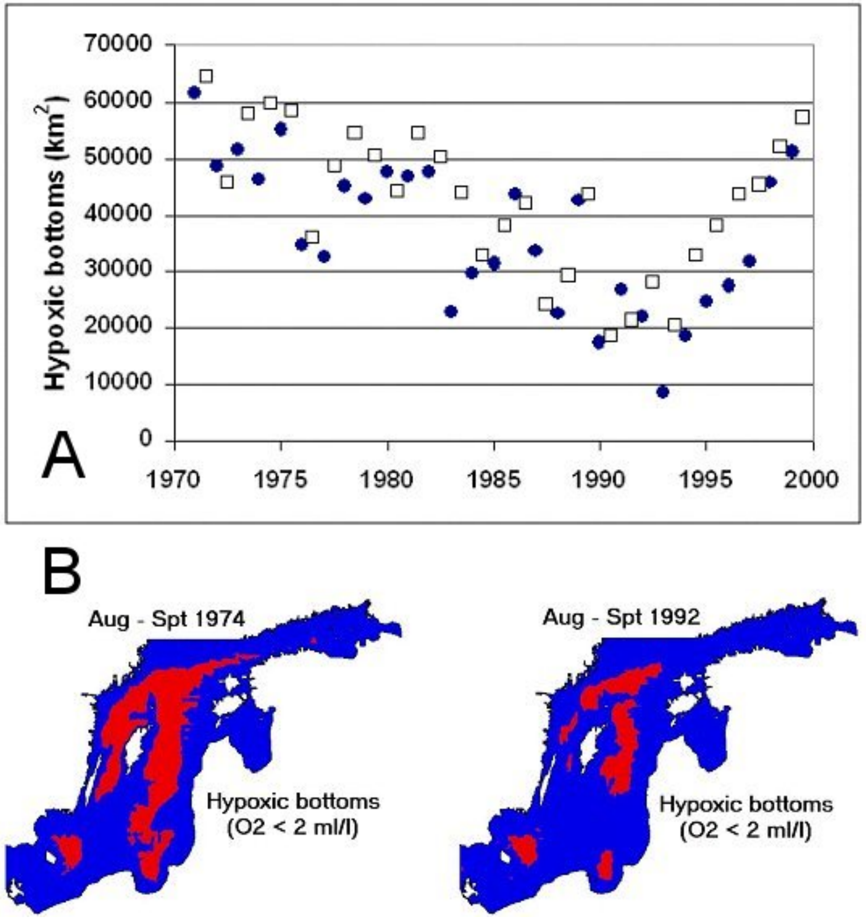






Data from SMHI

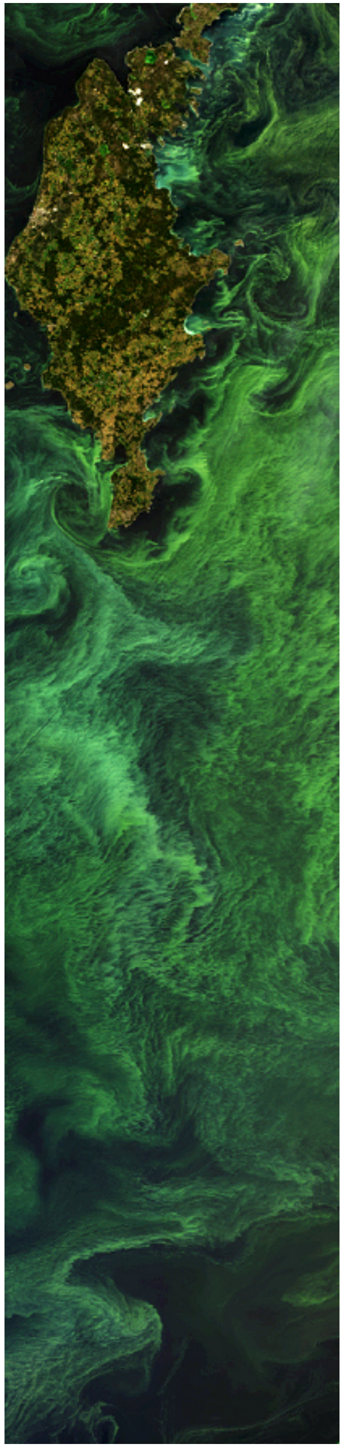
Changes in hypoxia area with time



Conley et al. 2002

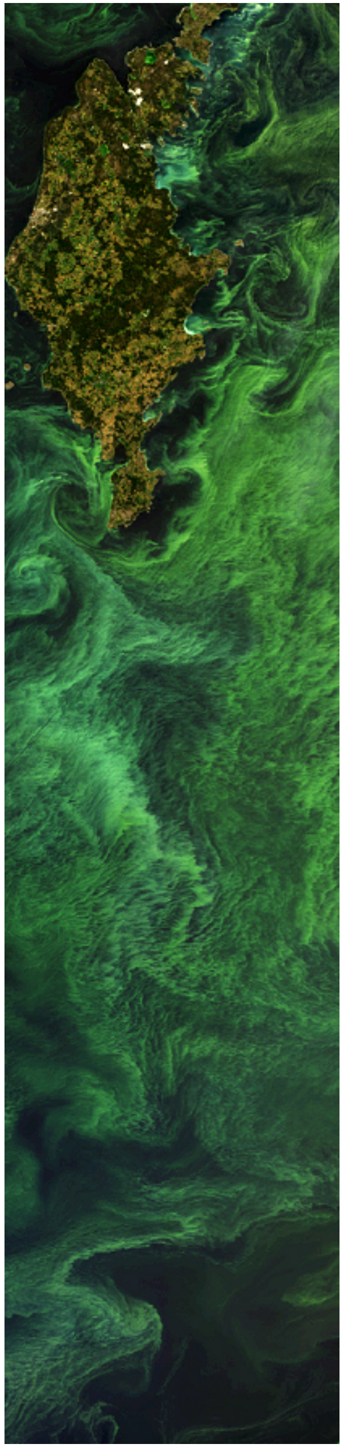
- Highest basin-wide oxygen occurs during periods of low salt water input, e.g. major inflows

- Salt water input leads to more stratification and reduced mixing increasing residence time and reducing oxygen concentrations



Question

Is hypoxia a natural feature of the Baltic Sea?

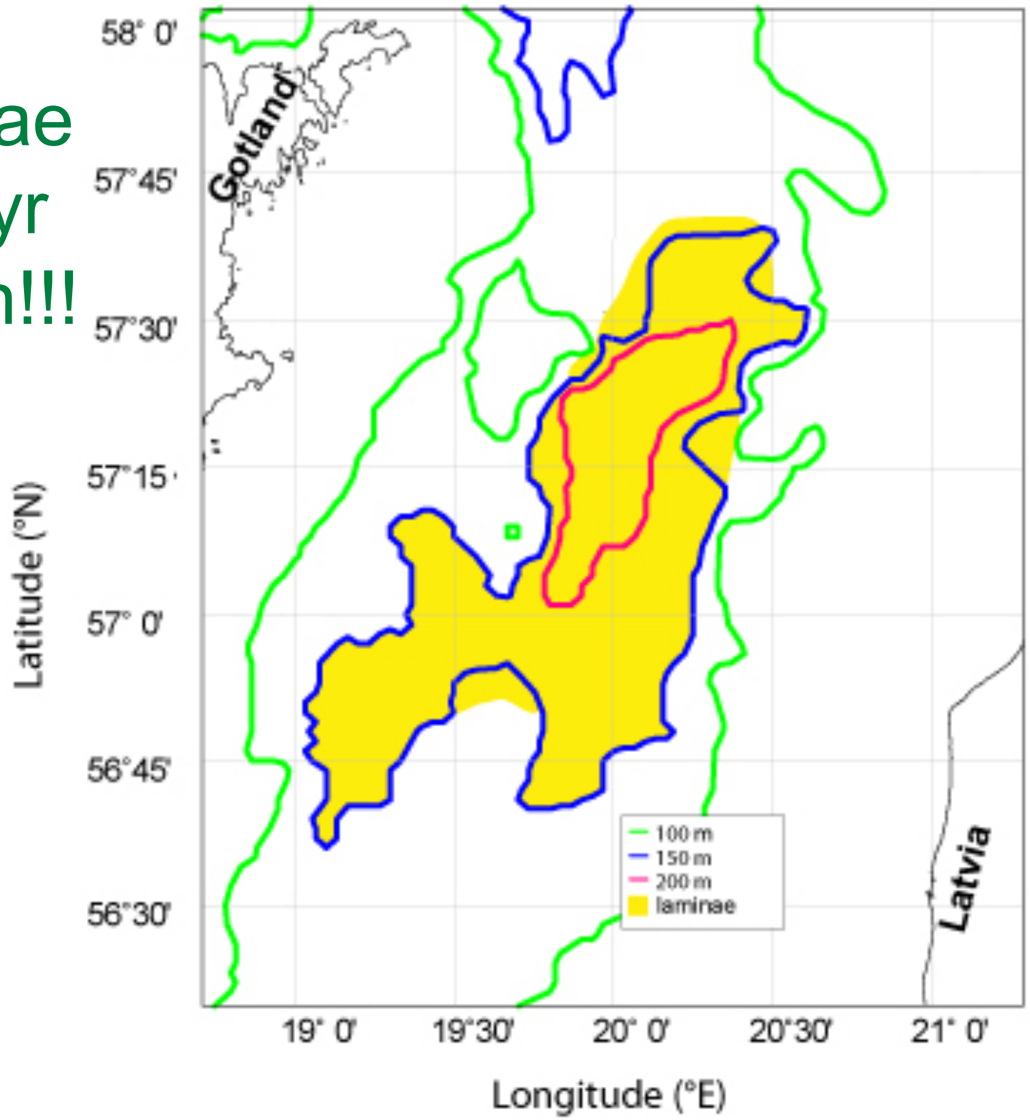


Is hypoxia a natural feature of the Baltic Sea?

Hypoxia in the recent past from geological data
(laminated sediments)

Laminated sediments in the Gotland Basin

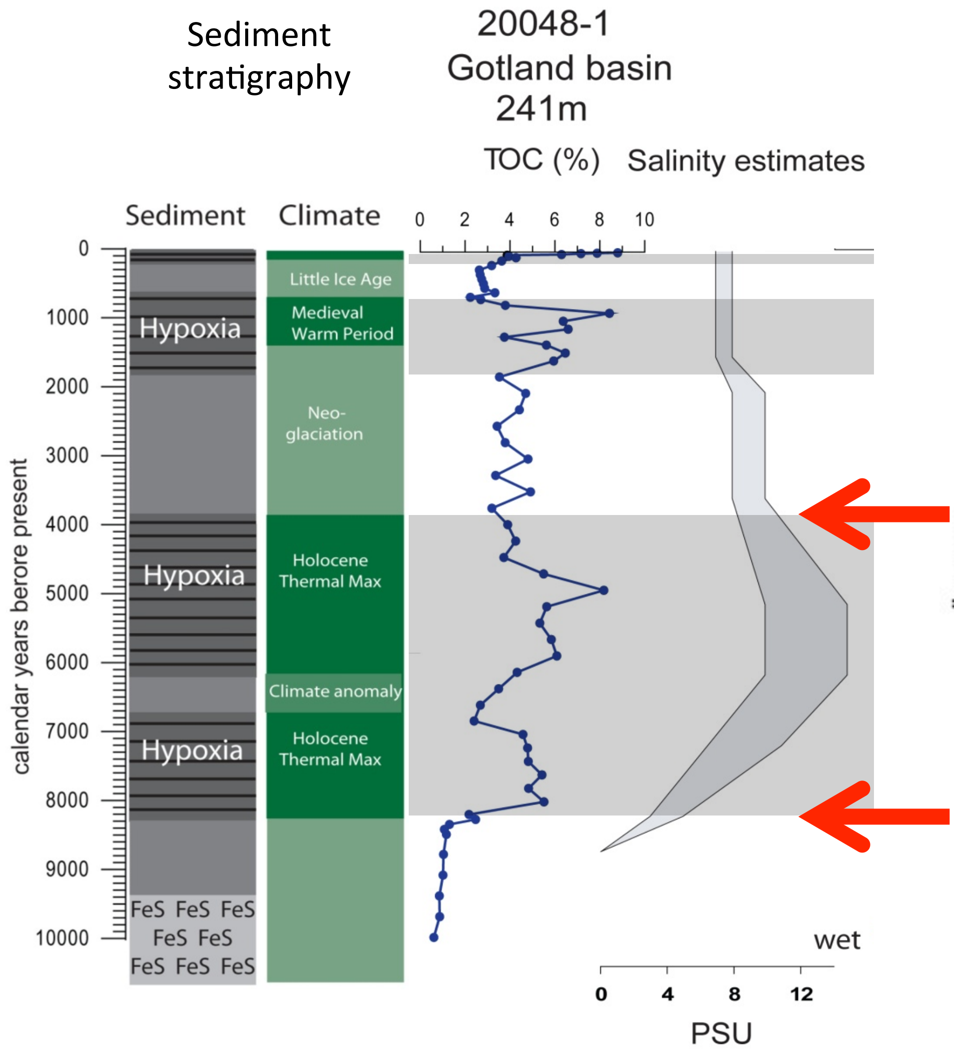
At depths >150 m laminae deposition started 100 yr ago in the Gotland Basin!!!

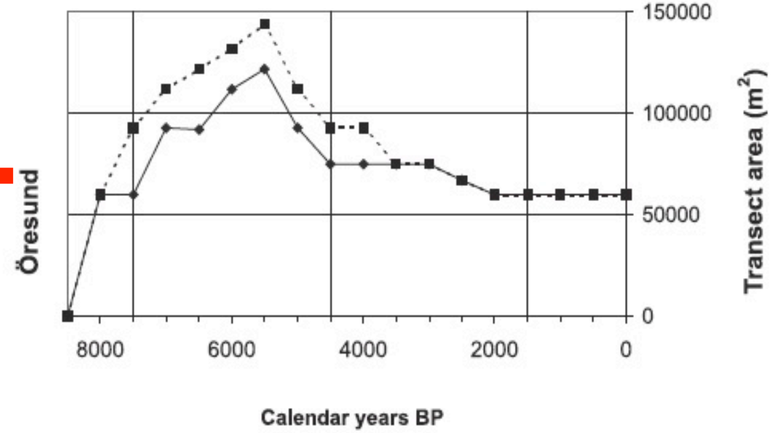


Hille et al. 2006

Hypoxia during the Holocene

(the last c. 10 000 yrs)





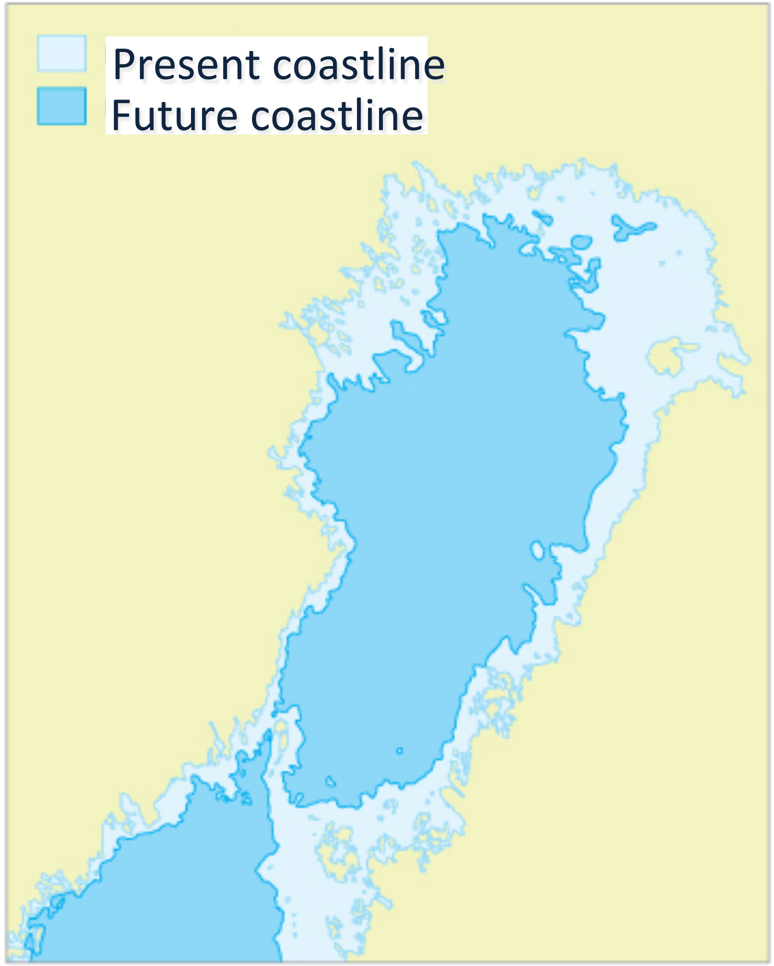
Zillén et al. 2008

Zillén and Conley 2010

The "Littorina Sea" began ca. 8000 yr BP

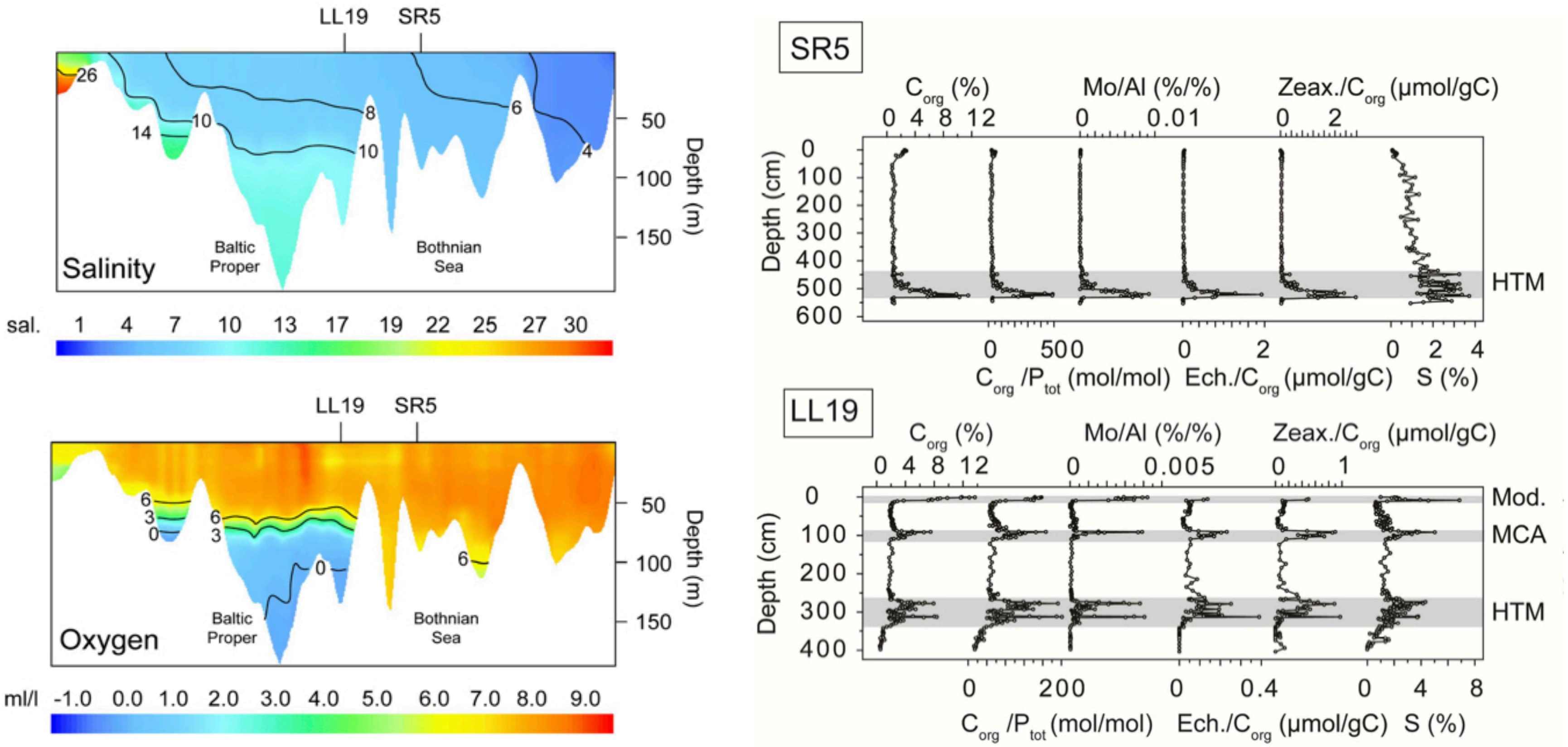
Land uplift/subsidence

Bothnian Bay in 3000 years?



Land uplift will continue for the next 10 000 years = 50-100 m

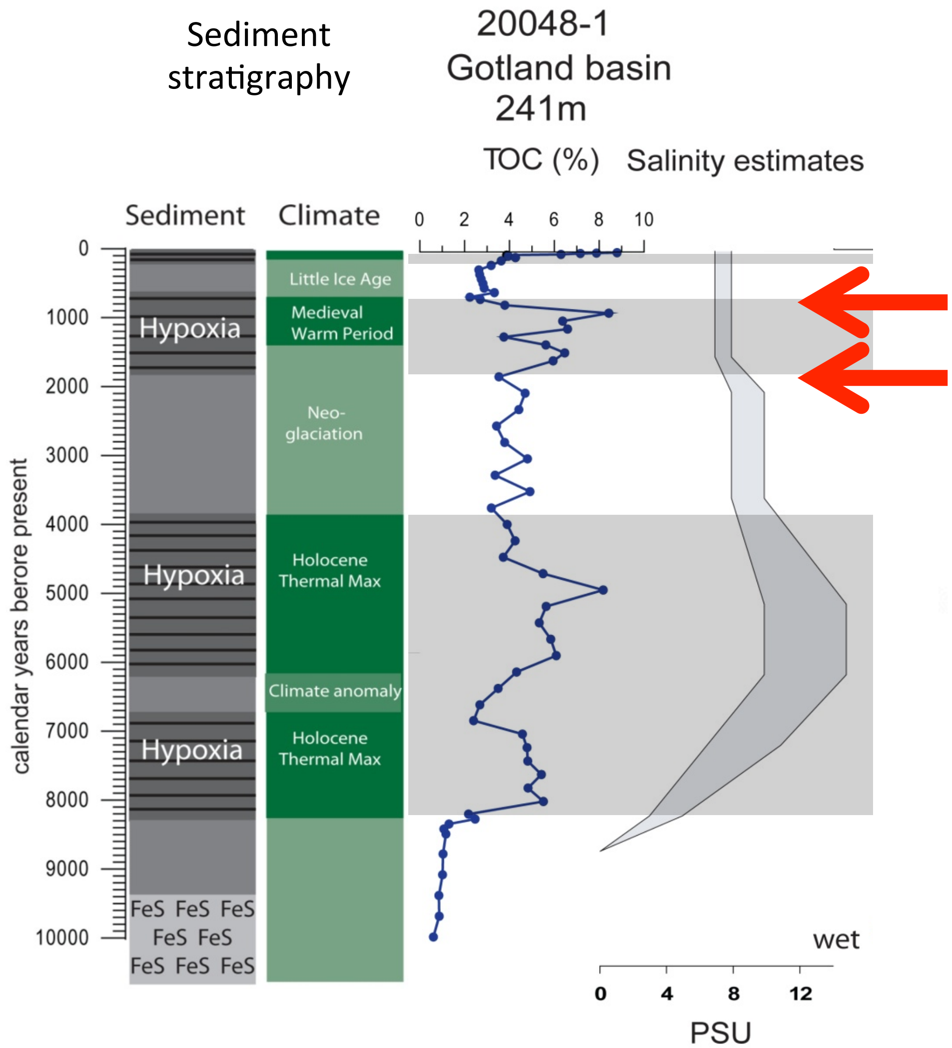
Effects of isostatic uplift on Baltic Sea hypoxia



Jilbert, Conley, Gustafsson, Funkey and Slomp (2005)

Hypoxia during the Holocene

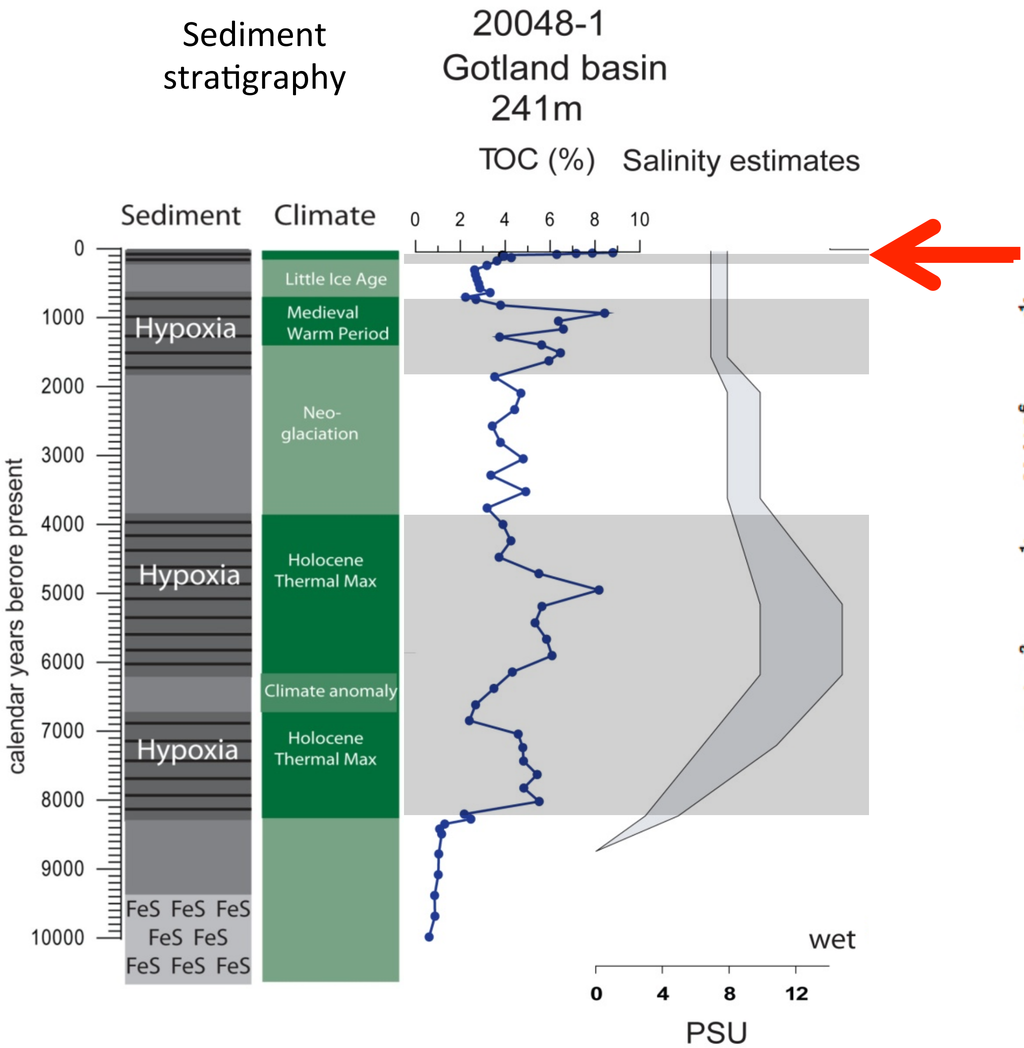
(the last c. 10 000 yrs)

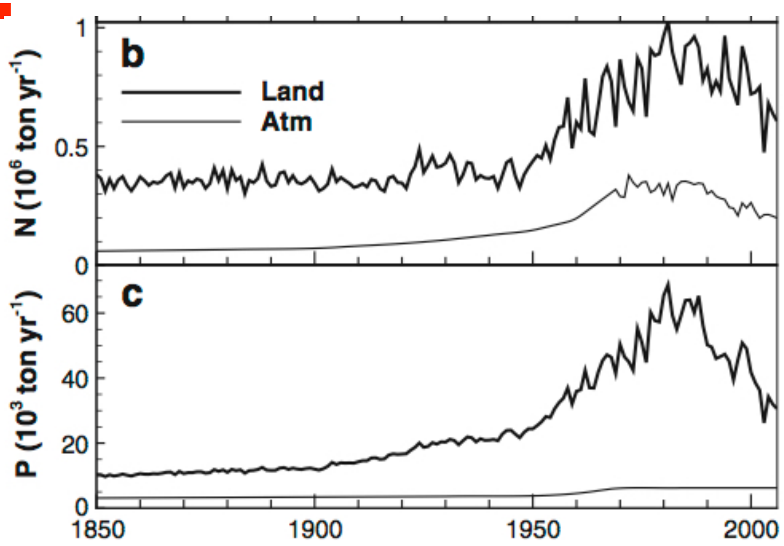


Zillén et al. 2008

Zillén and Conley 2010

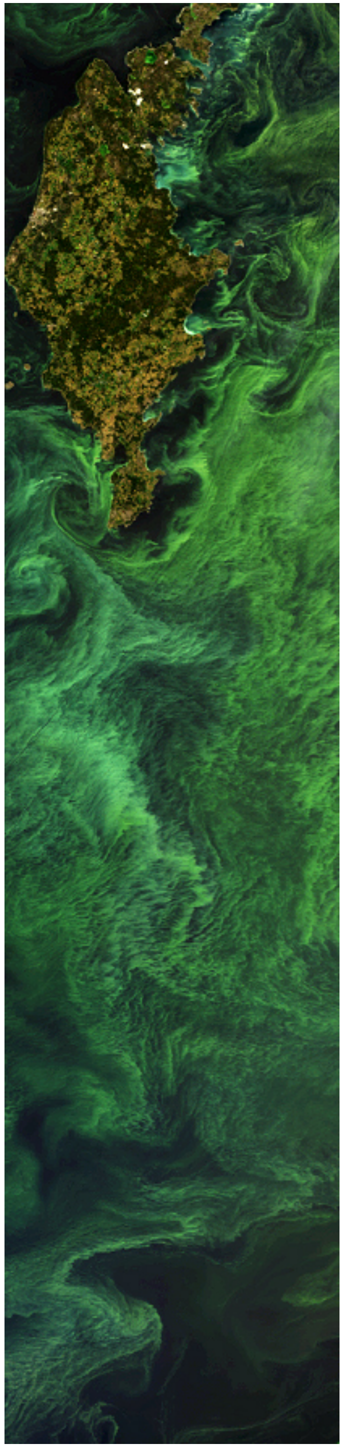
Hypoxia during the Holocene
(the last c. 10 000 yrs)





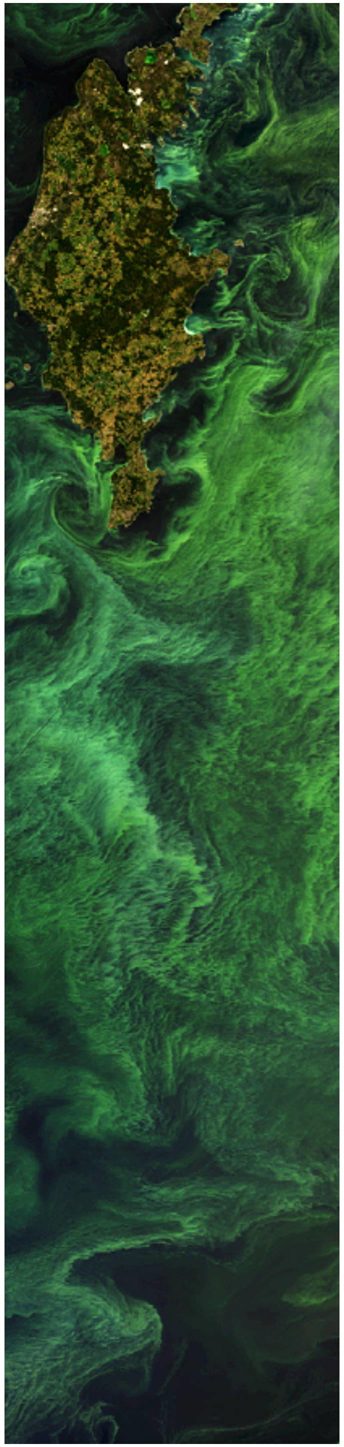
Zillén et al. 2008

Zillén and Conley 2010



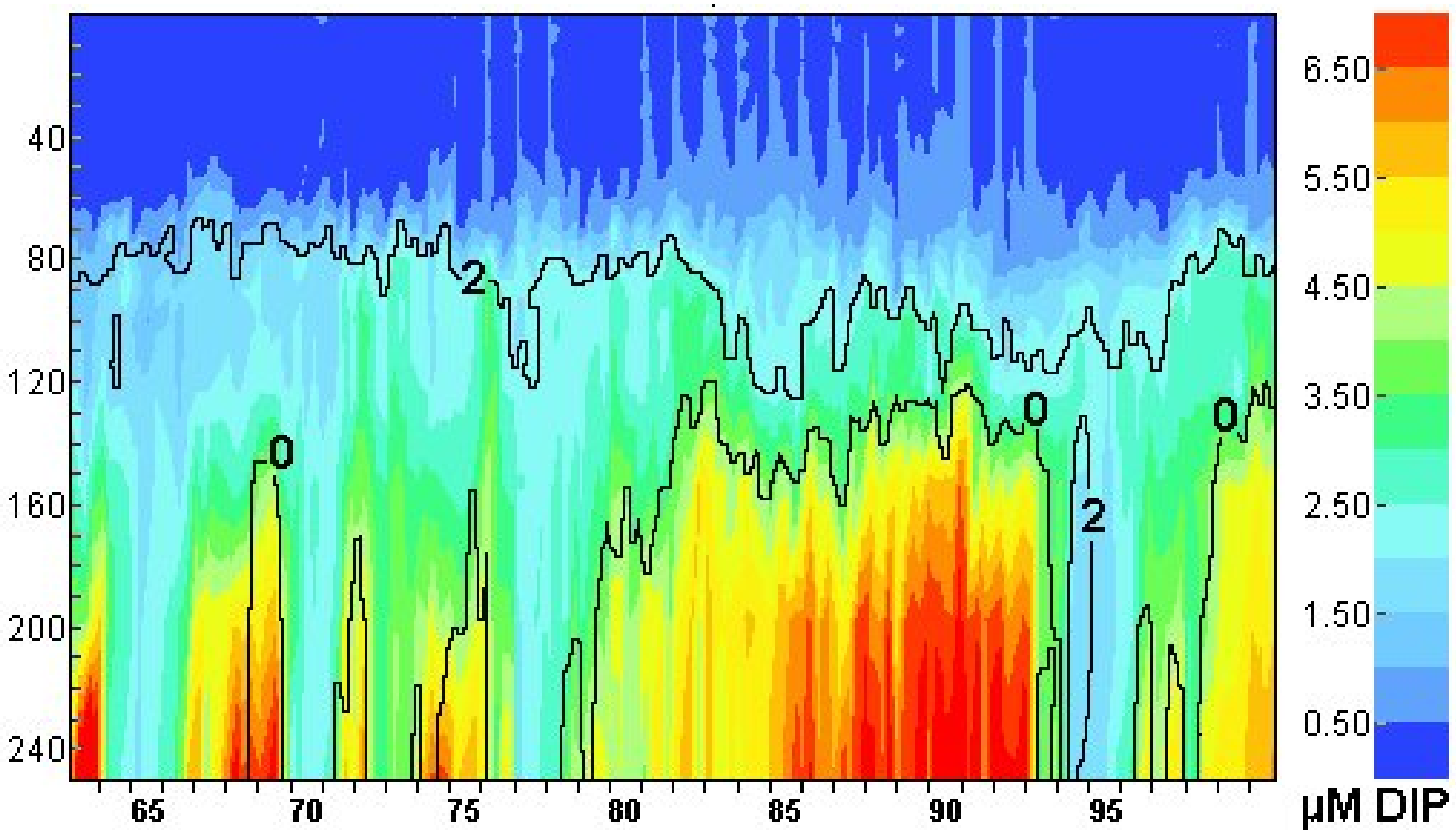
Question

What are the consequences of hypoxia?



Impact on biogeochemical cycles

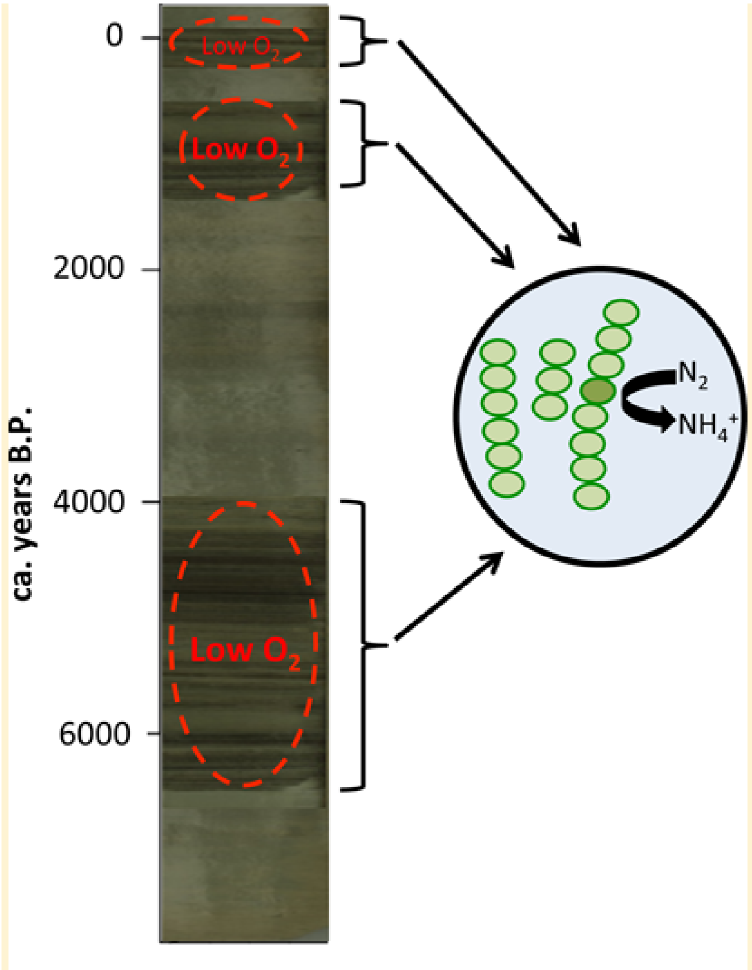
DIP and hypoxia through time in the Baltic



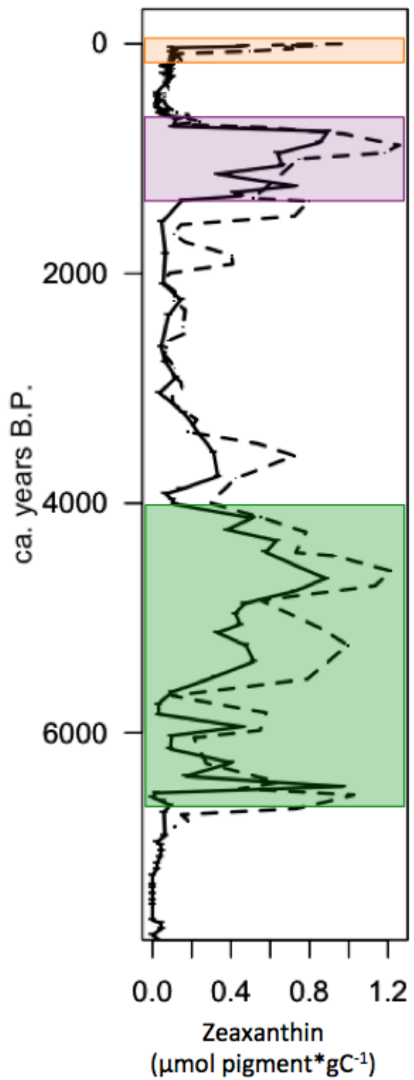
Note: Colors are DIP
Isopleths are oxygen concentrations

Conley et al. 2002

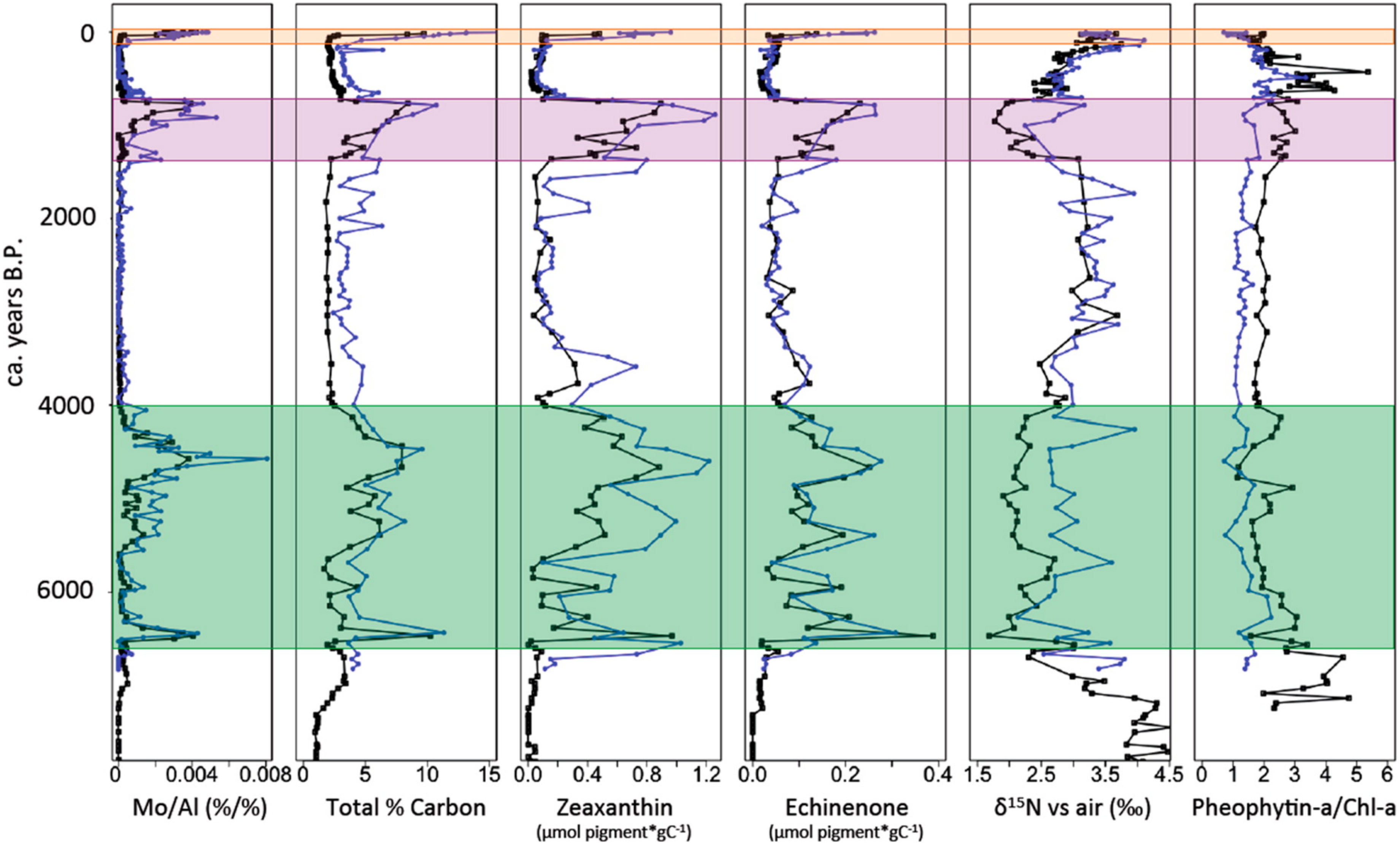
Cyanobacteria are most prevelant during periods of hypoxia



Sediment core from the Baltic Sea.



Funkey et al. 2014, ES&T

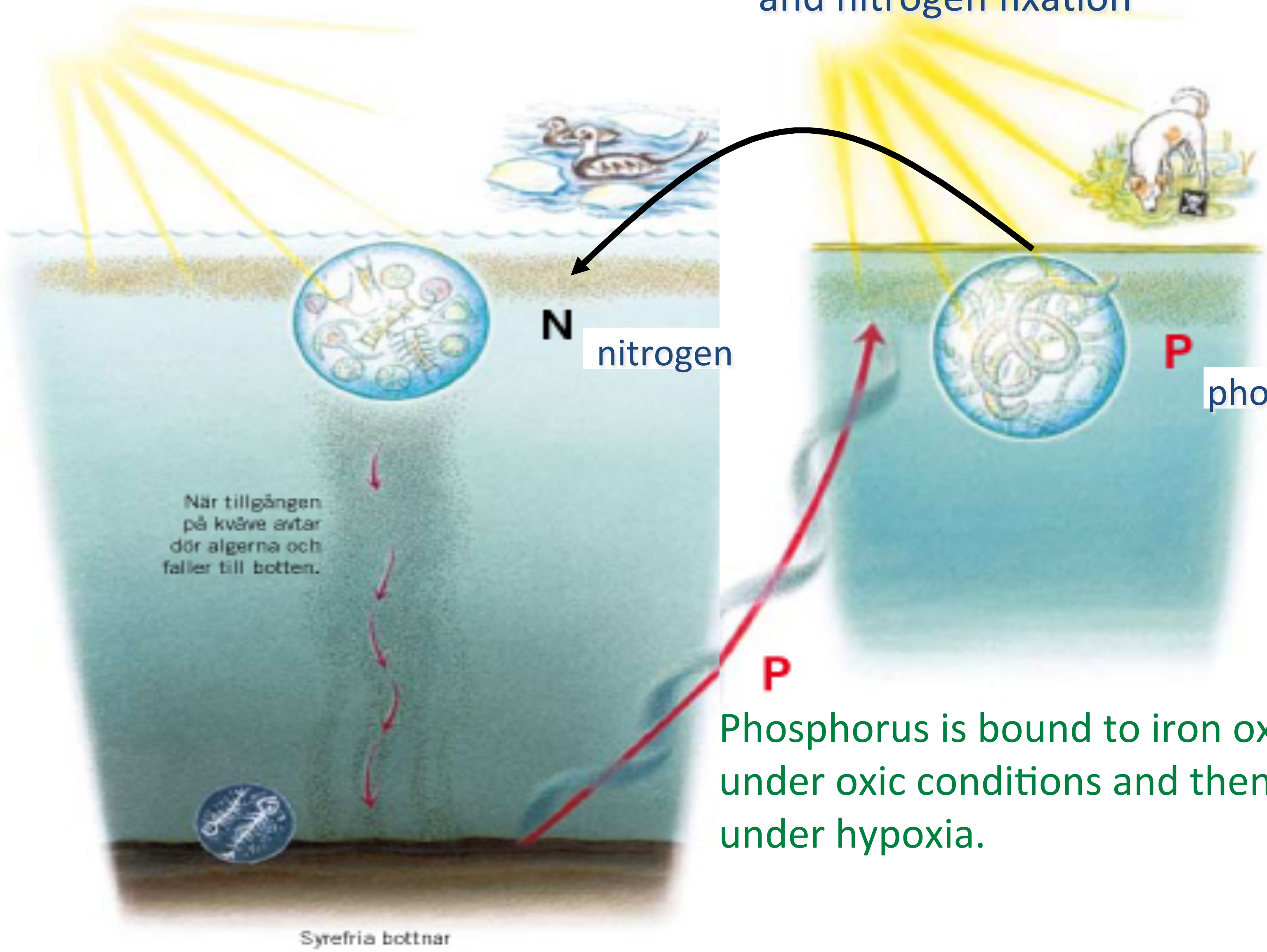


Published in: Carolina P. Funkey; Daniel J. Conley; Nina S. Reuss; Christoph Humborg; Tom Jilbert; Caroline P. Slomp; *Environ. Sci. Technol.* **2014,** 48, 2598-2602. DOI: 10.1021/es404395a

The ”viscious circle”

Spring bloom

Summer cyanobacteria blooms and nitrogen fixation



Phosphorus is bound to iron oxides under oxic conditions and then released under hypoxia.

Blooms Like It Hot

Hans W. Paerl[1] and Jef Huisman[2]

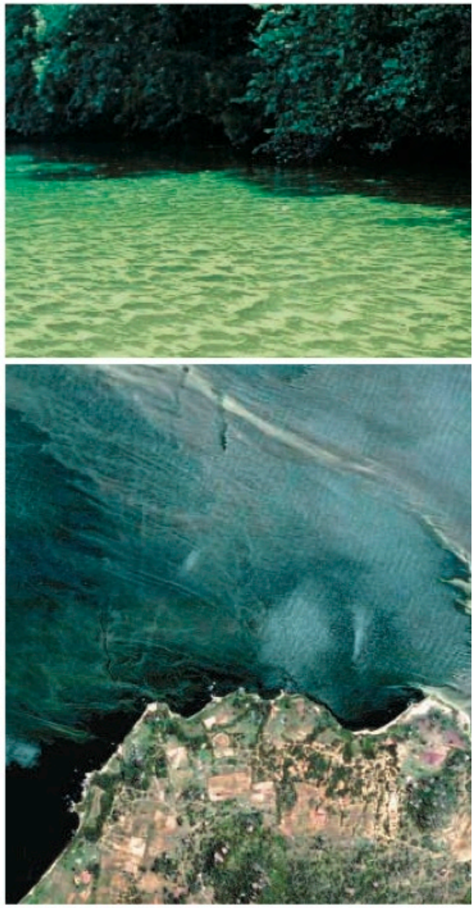
A link exists between global warming and the worldwide proliferation of harmful cyanobacterial blooms.

Nutrient overenrichment of waters by urban, agricultural, and industrial development has promoted the growth of cyanobacteria as harmful algal blooms (see the figure) (*1*, *2*). These blooms increase the turbidity of aquatic ecosystems, smothering aquatic plants and thereby suppressing important invertebrate and fish habitats. Die-off of blooms may deplete oxygen, killing fish. Some cyanobacteria produce toxins, which can cause serious and occasionally fatal human liver, digestive, neurological, and skin diseases (*1*–*4*). Cyanobacterial blooms thus threaten many aquatic ecosystems, including Lake Victoria in Africa, Lake Erie in North America, Lake Taihu in China, and the Baltic Sea in Europe (*3*–*6*). Climate change is a potent catalyst for the further expansion of these blooms.

Rising temperatures favor cyanobacteria in several ways. Cyanobacteria generally grow better at higher temperatures (often above 25°C) than do other phytoplankton species such as diatoms and green algae (*7*, *8*). This gives cyanobacteria a competitive advantage at elevated temperatures (*8*, *9*). Warming of surface waters also strengthens the vertical stratification of lakes, reducing vertical mixing. Furthermore, global warming causes lakes to stratify earlier in spring and destratify later in autumn, which lengthens optimal growth periods. Many cyanobacteria exploit these stratified conditions by forming intracellular gas vesicles, which make the cells buoyant. Buoyant cyanobacteria float upward when mixing is weak and accumulate in dense surface blooms (*1*, *2*, *7*) (see the figure). These surface blooms shade underlying nonbuoyant phytoplankton, thus suppressing their opponents through competition for light (*8*).

Cyanobacterial blooms may even locally increase water temperatures through the intense absorption of light. The temperatures of surface blooms in the Baltic Sea and in Lake IJsselmeer, Netherlands, can be at least 1.5°C above those of ambient waters (*10*, *11*). This positive feedback provides additional competitive dominance of buoyant cyanobacteria over nonbuoyant phytoplankton.

Global warming also affects patterns of precipitation and drought. These changes in the hydrological cycle could further enhance cyanobacterial dominance. For example, more intense precipitation will increase surface and groundwater nutrient discharge into water bodies. In the short term, freshwater discharge may prevent blooms by flushing. However, as the discharge subsides and water residence time increases as a result of drought, nutrient loads will be captured, eventually promoting blooms. This scenario takes place when elevated winter-spring rainfall and flushing events are followed by protracted periods of summer drought. This sequence of

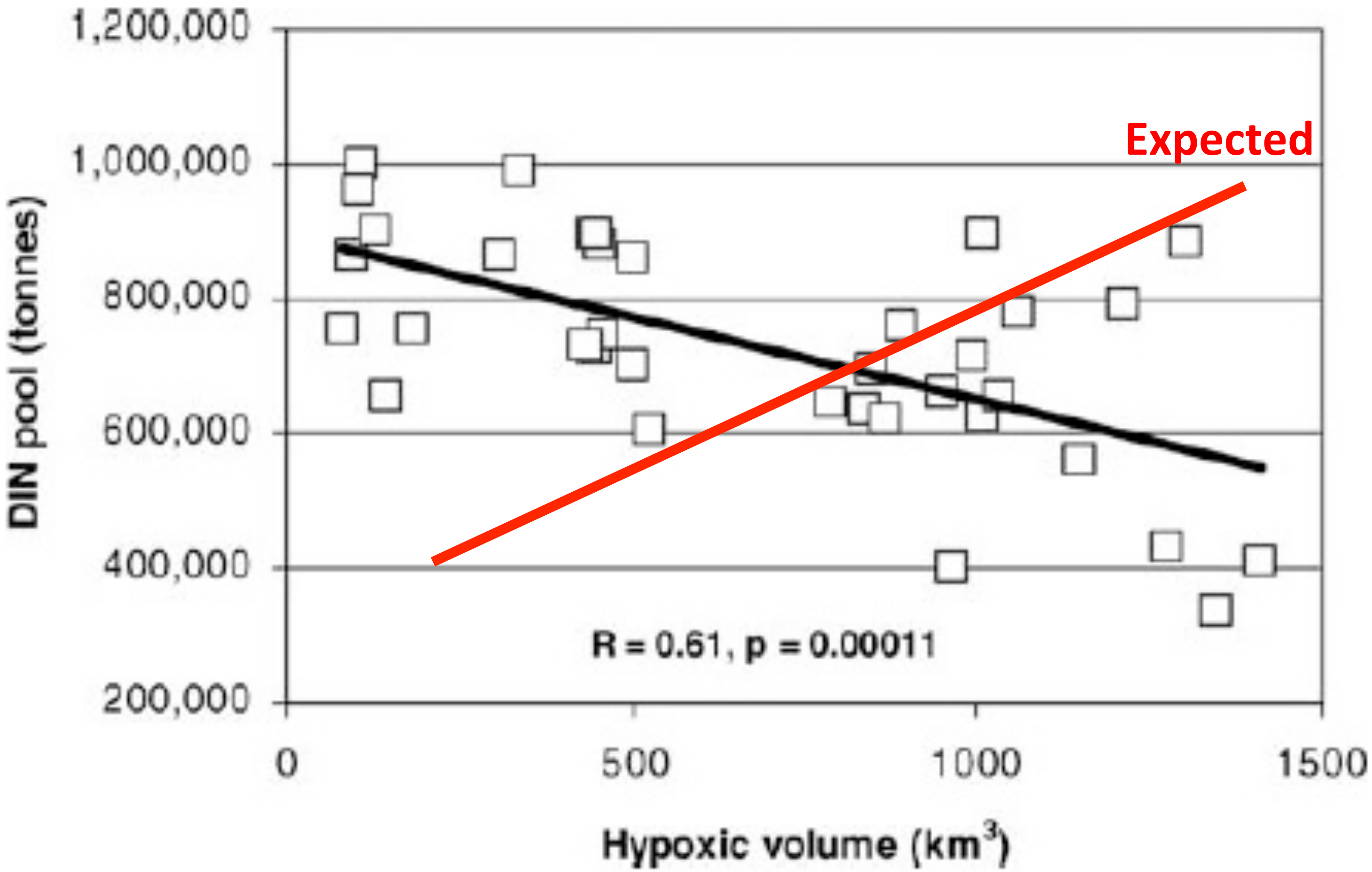


Undesired blooms. Examples of large water bodies covered by cyanobacterial blooms include the Neuse River Estuary, North Carolina, USA (**top**) and Lake Victoria, Africa (**bottom**).

[1]Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC 28557, USA. E-mail: hpaerl@email.unc.edu [2]Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, 1018 WS Amsterdam, Netherlands. E-mail: jef.huisman@science.uva.nl

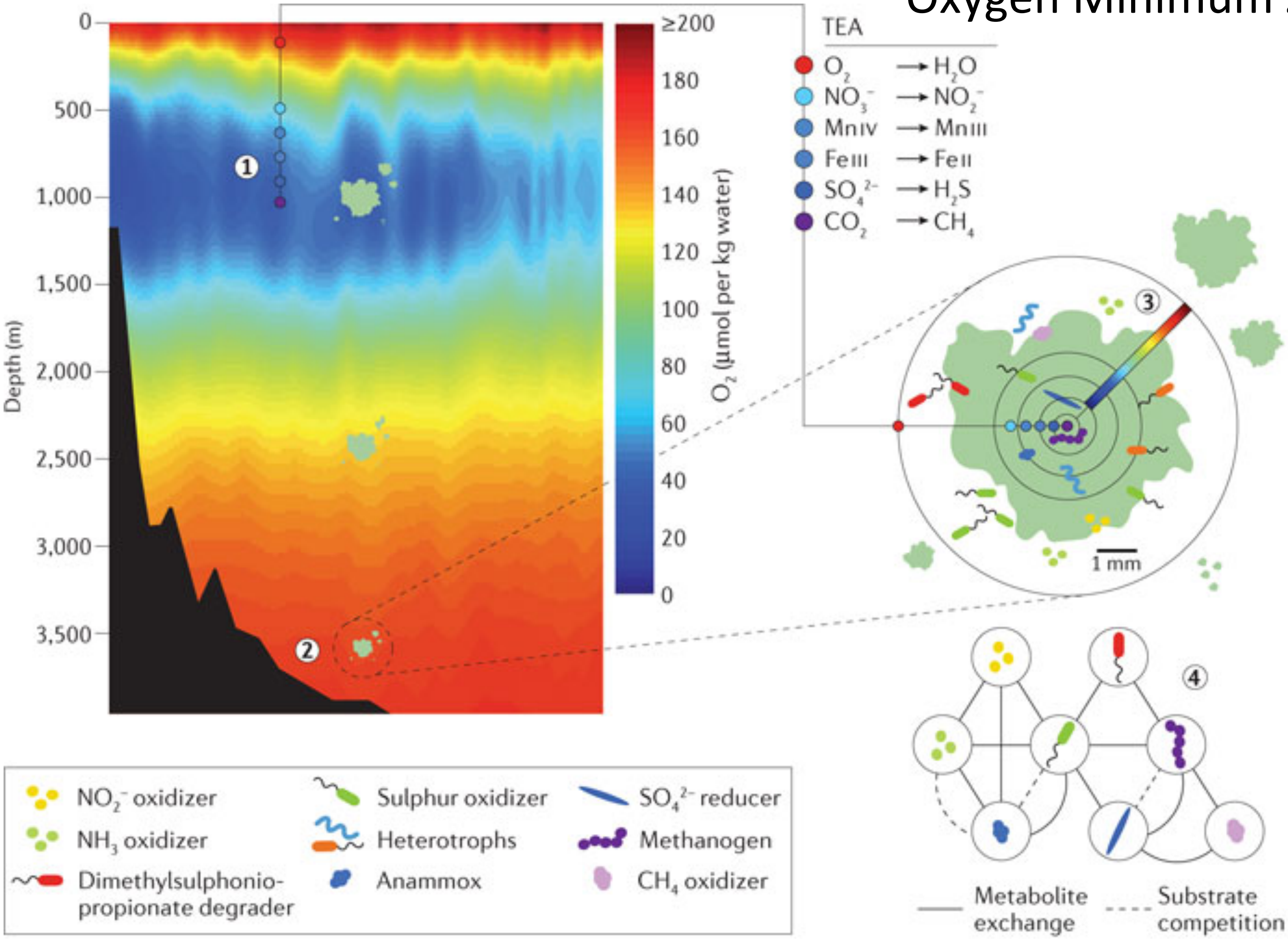
Lower DIN in Baltic hypoxic bottom water

➡ More N losses when hypoxic



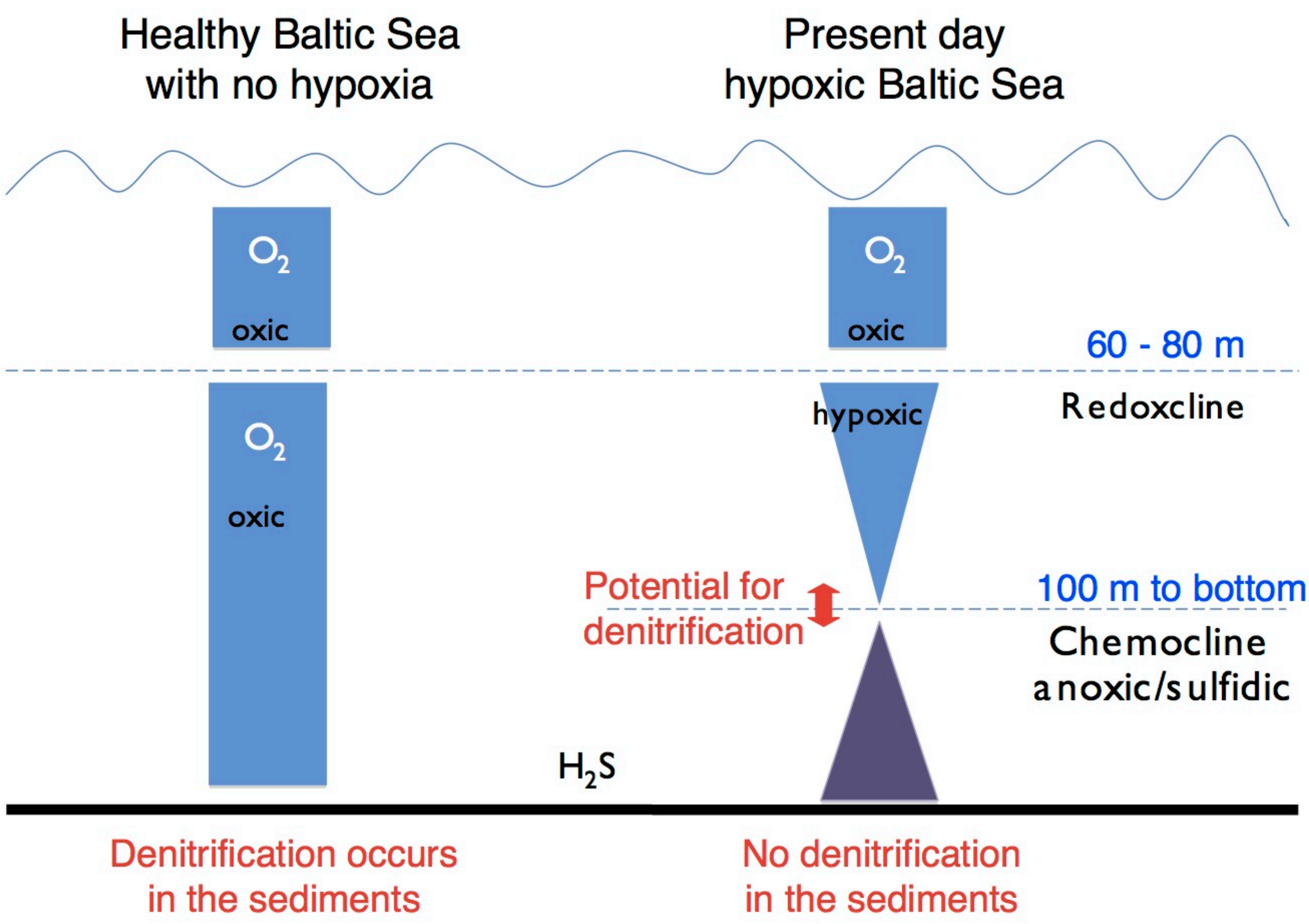
Vahtera et al. 2007

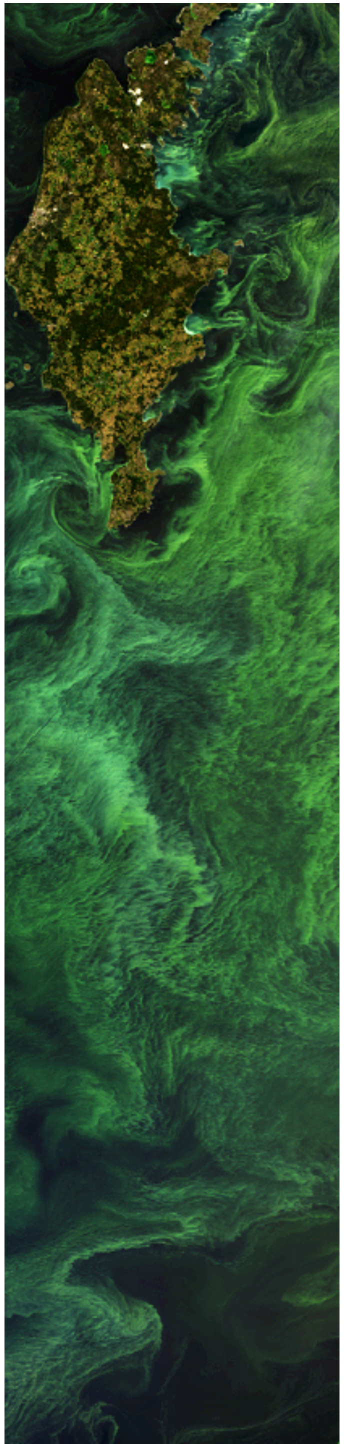
Oxygen Minimum Zones OMZs



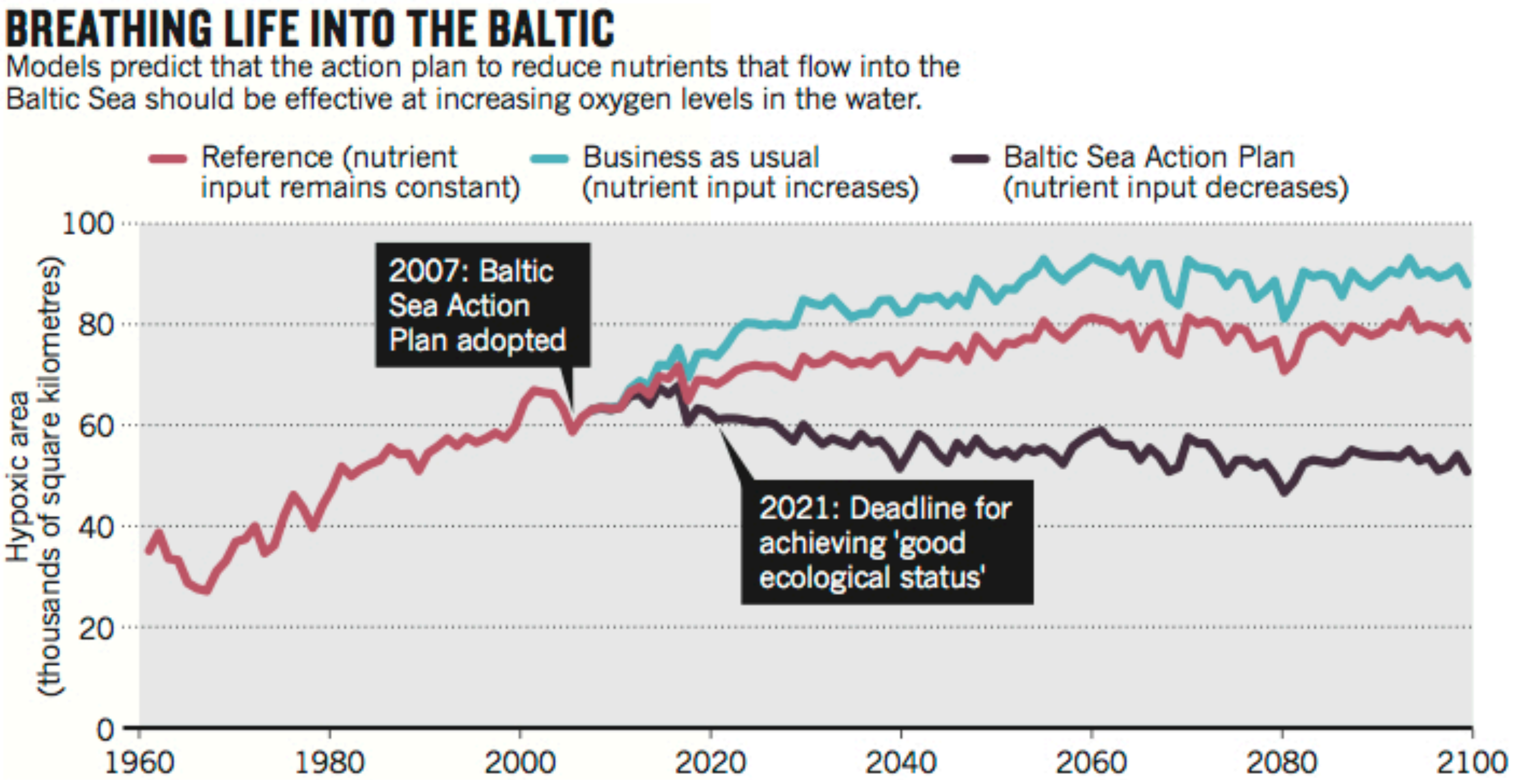
Wright et al. 2012

Nature Reviews | Microbiology

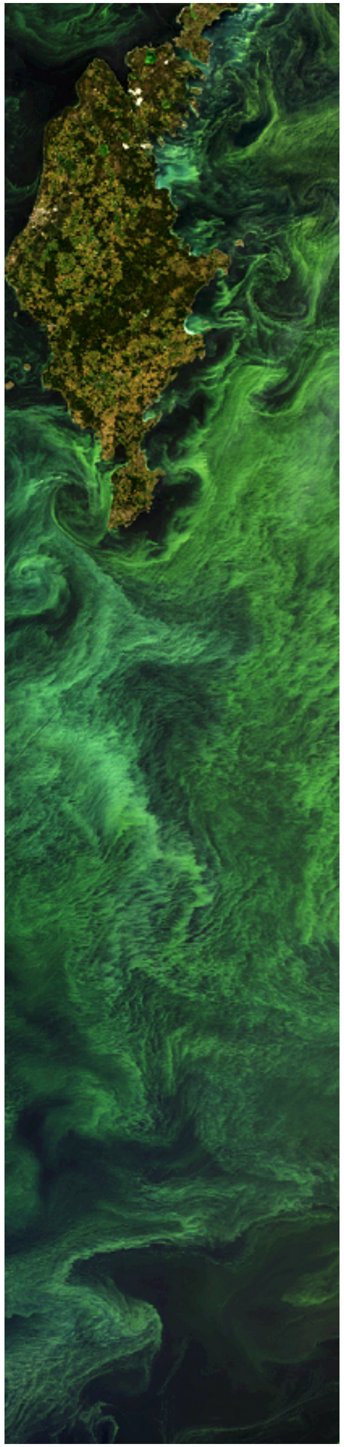

Healthy Baltic Sea
with no hypoxia
Present day
hypoxic Baltic Sea
O_2
oxic
O_2
oxic
60 - 80 m
Redoxcline
O_2
oxic
hypoxic
Potential for
denitrification
100 m to bottom
Chemocline
anoxic/sulfidic
H_2S
Denitrification occurs
in the sediments
No denitrification
in the sediments



The response of the Baltic Sea to *nutrient reductions* will take time



From Conley (2012) – redrawn from Meier et al. (2011)



ge·o·en·gi·neer·ing (ecotechnological approaches)
/jēōenjəˈni(ə)riNG/

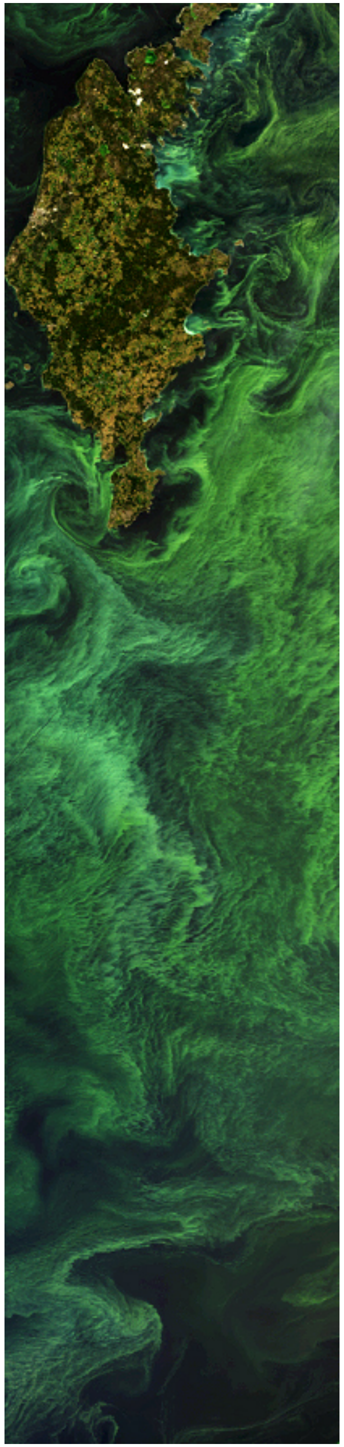
Noun

1. the deliberate large-scale manipulation of an environmental process that affects the earth's climate, in an attempt to counteract the effects of global warming.

Key Reports:

The Royal Society (2009) Geoengineering the climate: science, governance and uncertainty

National Academy of Sciences (2013) Geoengineering climate: Technical evaluation and discussion of impacts



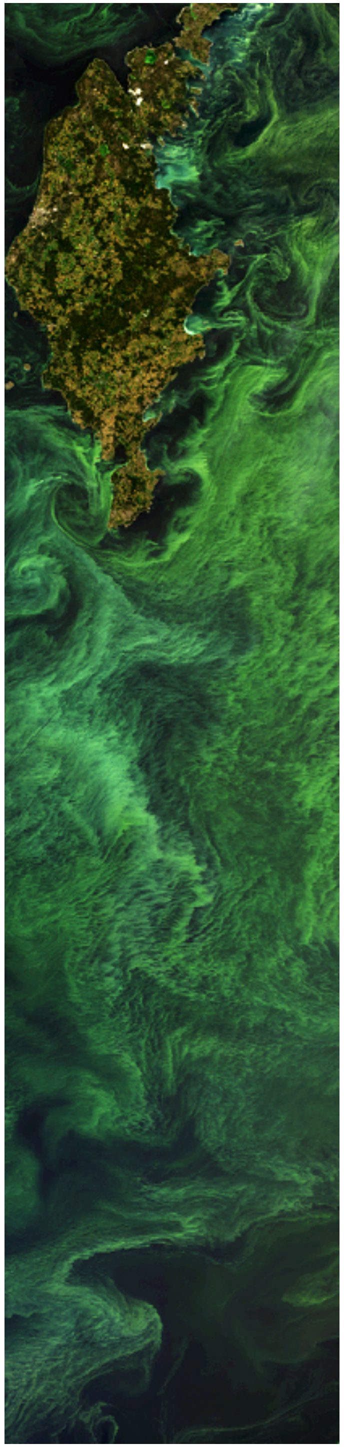
Question

Is “geoengineering” an acceptable solution for

Baltic Sea eutrophication?

What are we going to geoengineer?

Baltic Sea eutrophication



But why?

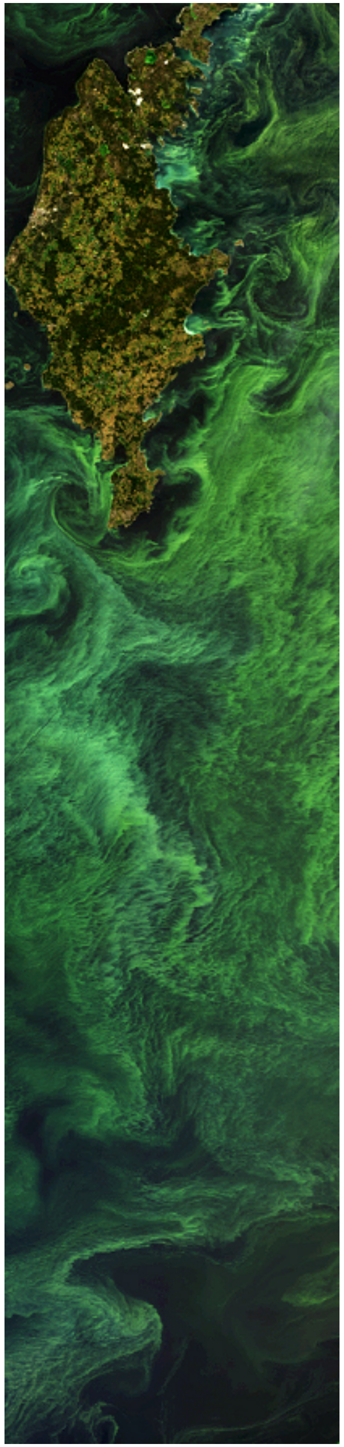
Time scale of improvement is long (decades)
- Geoengineering provides rapid improvements

Costs of nutrient reductions to society are enormous
- Geoengineering is a cheaper alternative

Popular in the media and politically attractive

Ethical Implications

What values should guide us in our relationship to nature?
Man over nature
A source of our existence and part of our being



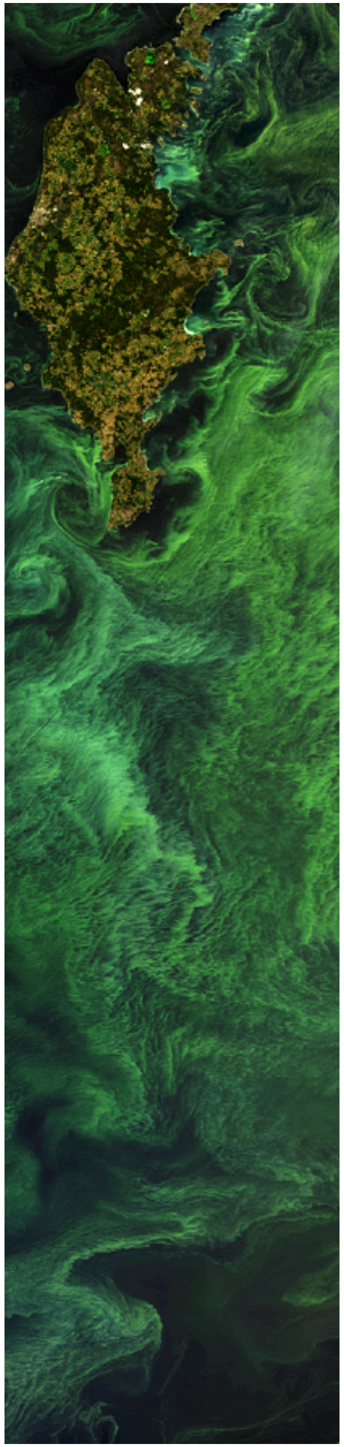
Can we add oxygen to the Baltic?

(Conley et al. 2009, *ES&T*)

The hypoxic area (oxygen < 2 mg/l) averages 49,000 km^2

Would require 2-6 million tons oxygen to be added each year

20,000-60,000 railway cars of liquid oxygen each year to keep bottom waters oxic



Model experiments

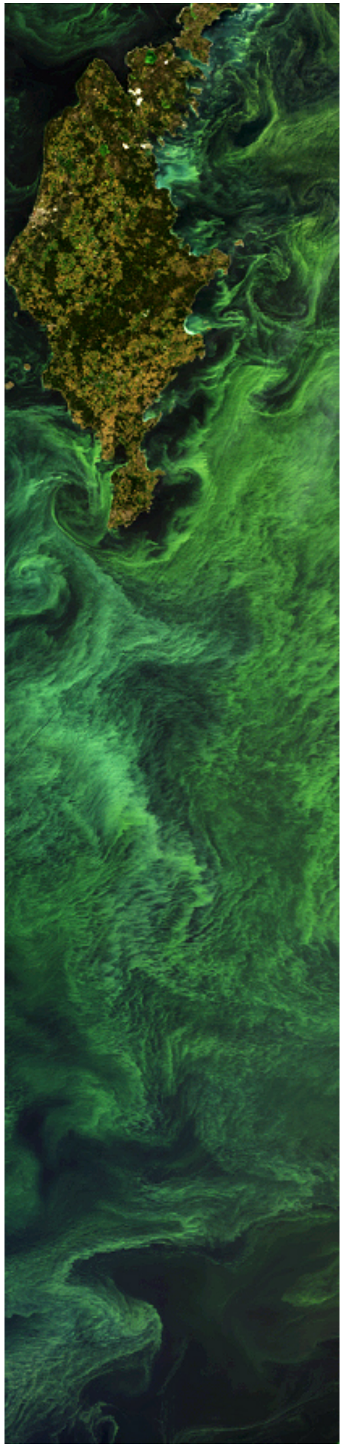
Generalized "engineering" solutions considered:

1) Increase exchange across the Drogden Sill
   More saltwater inflow creates more stratification and more hypoxia.

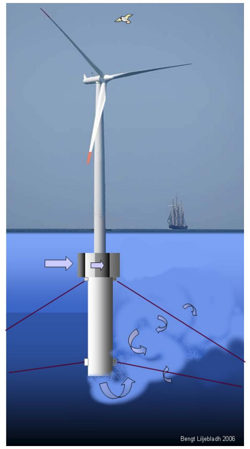
2) Closing the Drogden Sill
   Short term increase in hypoxia (10-15 years), but improved oxygen conditions after 30 years.

3) Halocline ventilation by mid-water mixing (80 m to 125 m)
   The only engineering solution that improves conditions, but has potentially serious ecological effects.

Conley et al. 2009, *ES&T*



Baltic Deepwater Oxygen (BOX)



Mechanically pump oxygenated water below the halocline to oxygenate deep water.

The Box Project and models (Stigebrandt and Kalen 2013) showed a reduction in vertical stratification and increase in inflows from the adjacent basin.

PROPPEN Project

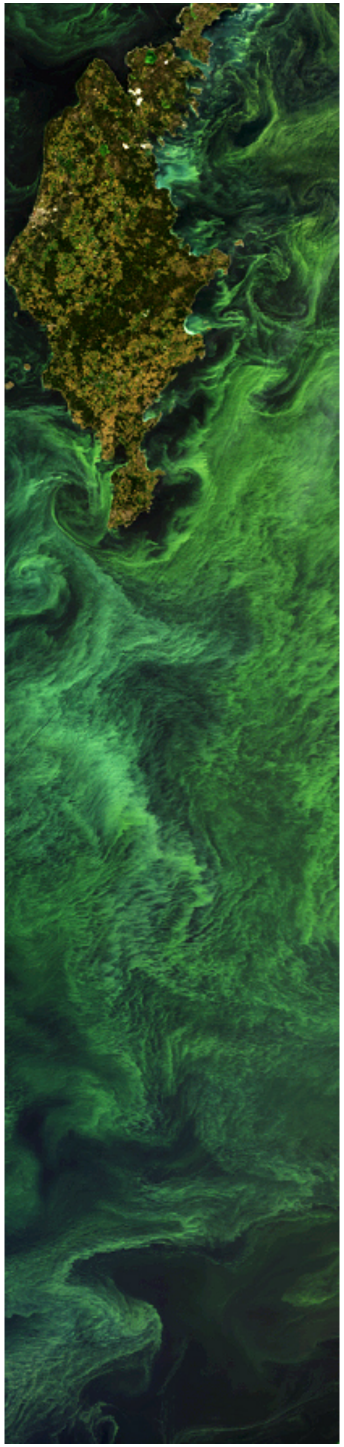
At Sandöfjärden, Finland pumping proved insufficient to keep keep the area oxygenated.

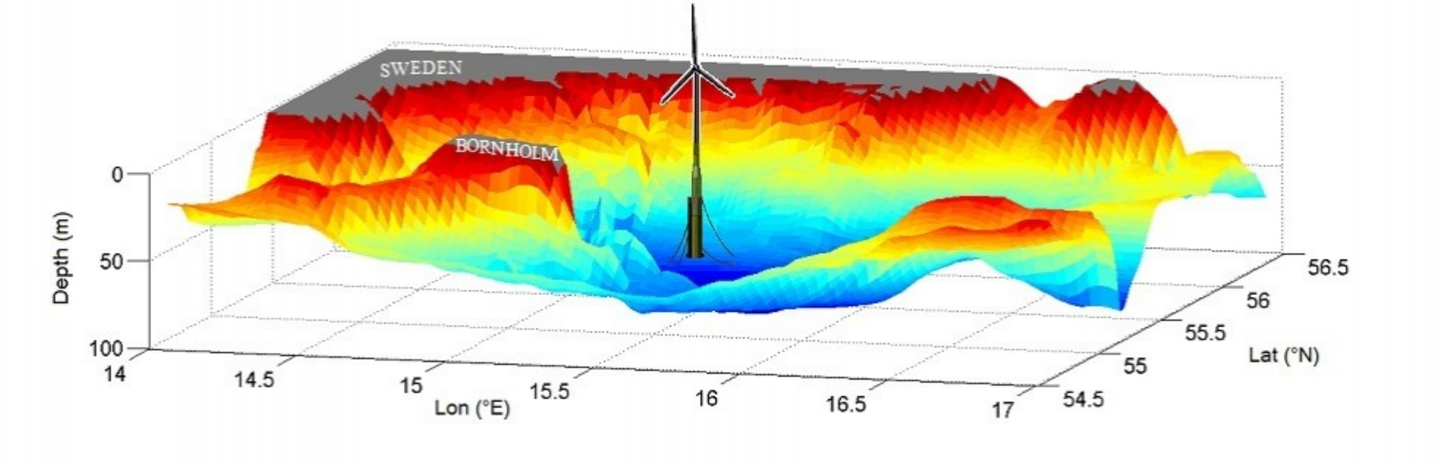
At Lännerstasundet, Sweden pumping caused higher density water to flow in from the adjacent basin.

But, mixing warmed bottom waters increased bottom water oxygen demand!

BOX-WIN (http://BOX-WIN.se)

Baltic Sea oxygenation and floating windpower demonstrator

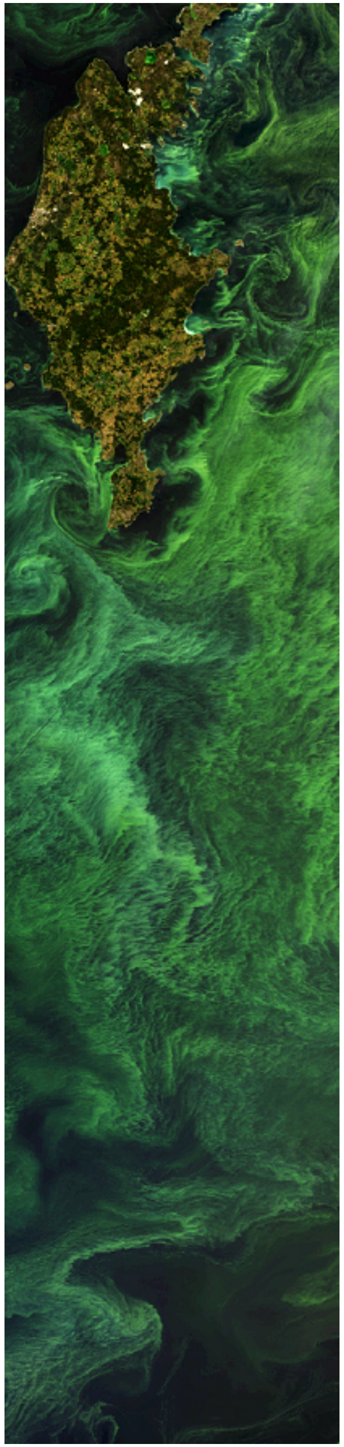




Who decides?

Espoo (EIA) Convention
and the "one-stop-shop" principle
(Danish Energy Agency)

HELCOM has said NO – Sept 2014
but a seminar in Stockholm in
February 2015



Scientific questions:

How much would phosphorus or nitrogen be reduced?

How would the Baltic react to more inflow events?

Would destabilization of the water column allow winter mixing to break through the halocline?

What would happen to phytoplankton, zooplankton and larve?

Consumer questions:

Cost are enormous to set up the system; installation and maintenance costs should also be included.

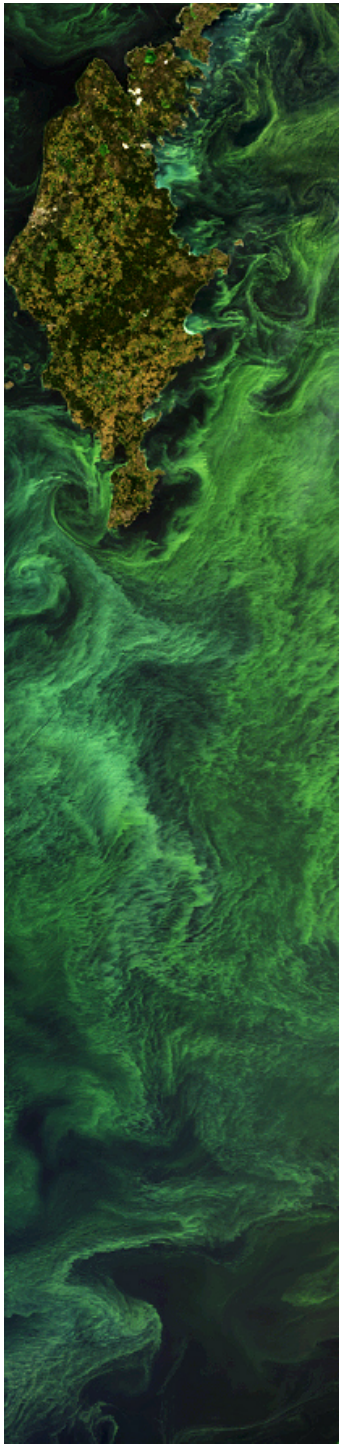
Effect on shipping lanes?

Management concerns:

Would this reduce efforts and money for nutrient reductions?

Phosphorus Sequestration

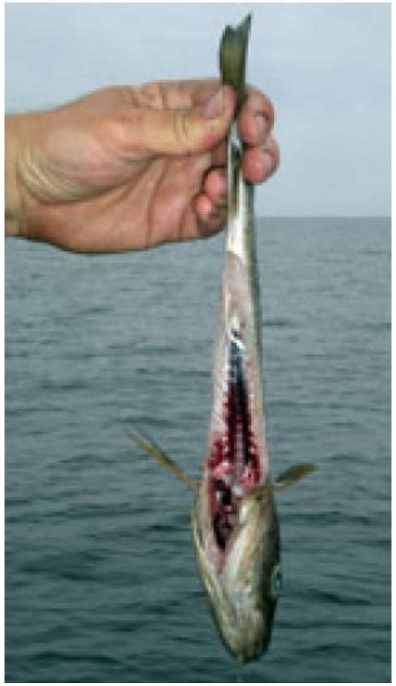
Enhance the permanent burial of
phosphorus in sediments by precipitation
with aluminum or other compounds



Change trophic interactions

Let's fish out the intermediate predators (sprat)
in the Baltic Sea (PLANFISH)

Oops, the cod are starving…



Science News

Recovering Baltic Cod Is Lacking Food

Aug. 20, 2012 — The eastern Baltic cod stock has recently started to recover, after two decades of severe depletion, however with unexpected side-effects.

Pathway to a healthier marine ecosystem based on

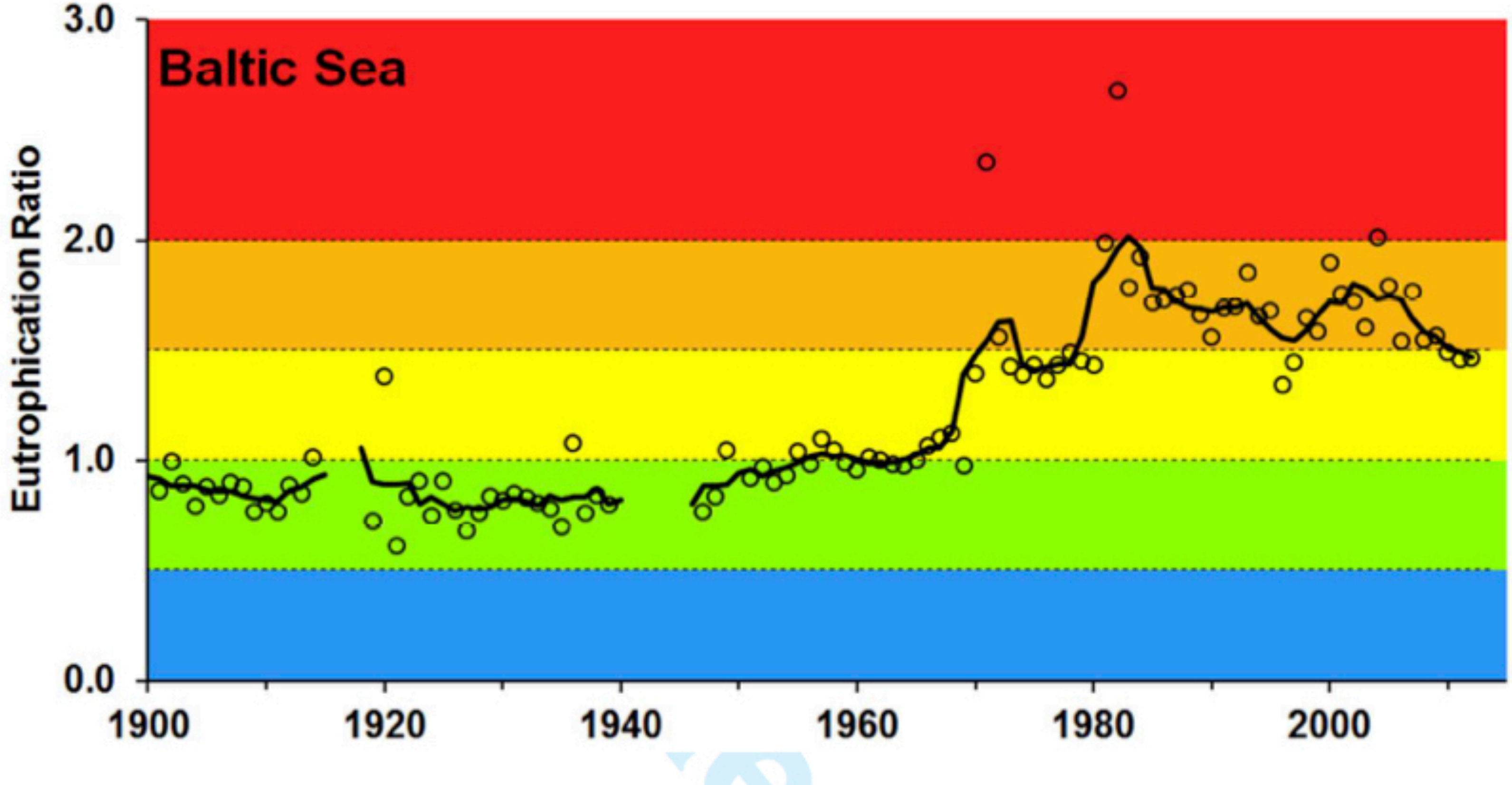
- Basic knowledge
- Monitoring & Assessment
- Governance & Management
- Action

In all of the excitement of SEKSEKSEK’s & €€€’s

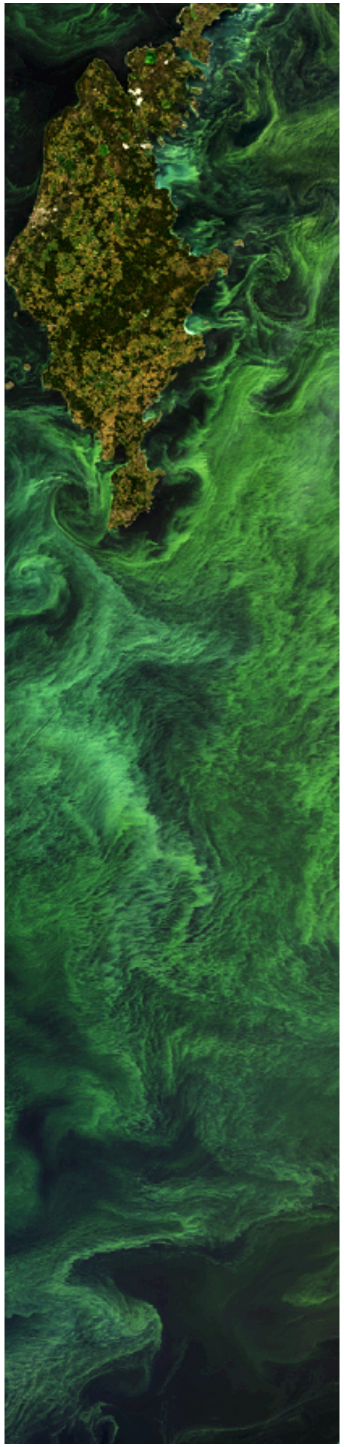
We must reduce nutrients for mitigation to be effective.

The Baltic Sea is getting better!

HELCOM Eutrophication Assessment Tool (HEAT 3.0)
(Based on Chl, DO, benthic biomass, winter DIN/DIP, secchi depth, CDOM)



Andersen et al. 2015



Perspectives

Nutrients inputs have stimulated the growth of algae creating the largest human induced low oxygen zone in the world

AND

“Geoengineering” promises rapid improvements

BUT

The potential ecological effects could be devastating to the Baltic Sea ecosystem

THEREFORE

We must focus on the prescribed nutrient reductions


Thanks for listening!