The Challenge of Restoring the Baltic Sea:
Learning From the Past to Find Solutions for the Future

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Baltic Sea

Area = 420 000 km^2
Mean depth = 50 m
Max depth = 459 m

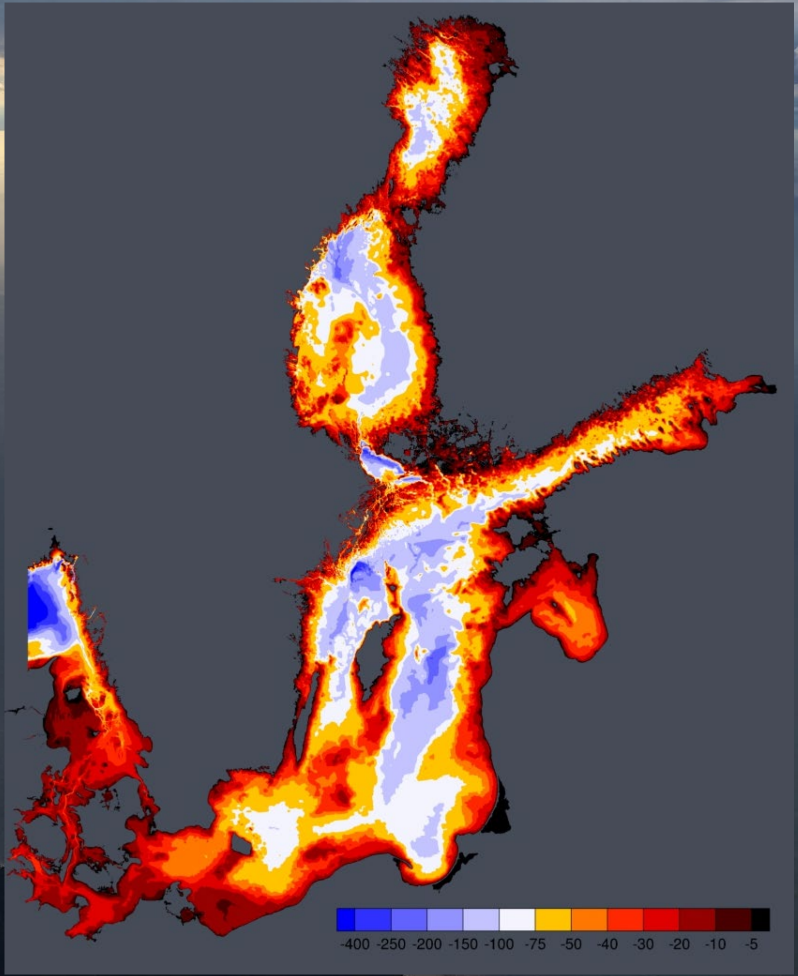
Relatively large shallow entrance area with two shallow sills

Permanent haline stratification

Freshwater supply = 500 km^3 yr^{-1}
Residence time 33 yrs

No tides

Strong seasonality – ice in winter to up to 20 °C in summer



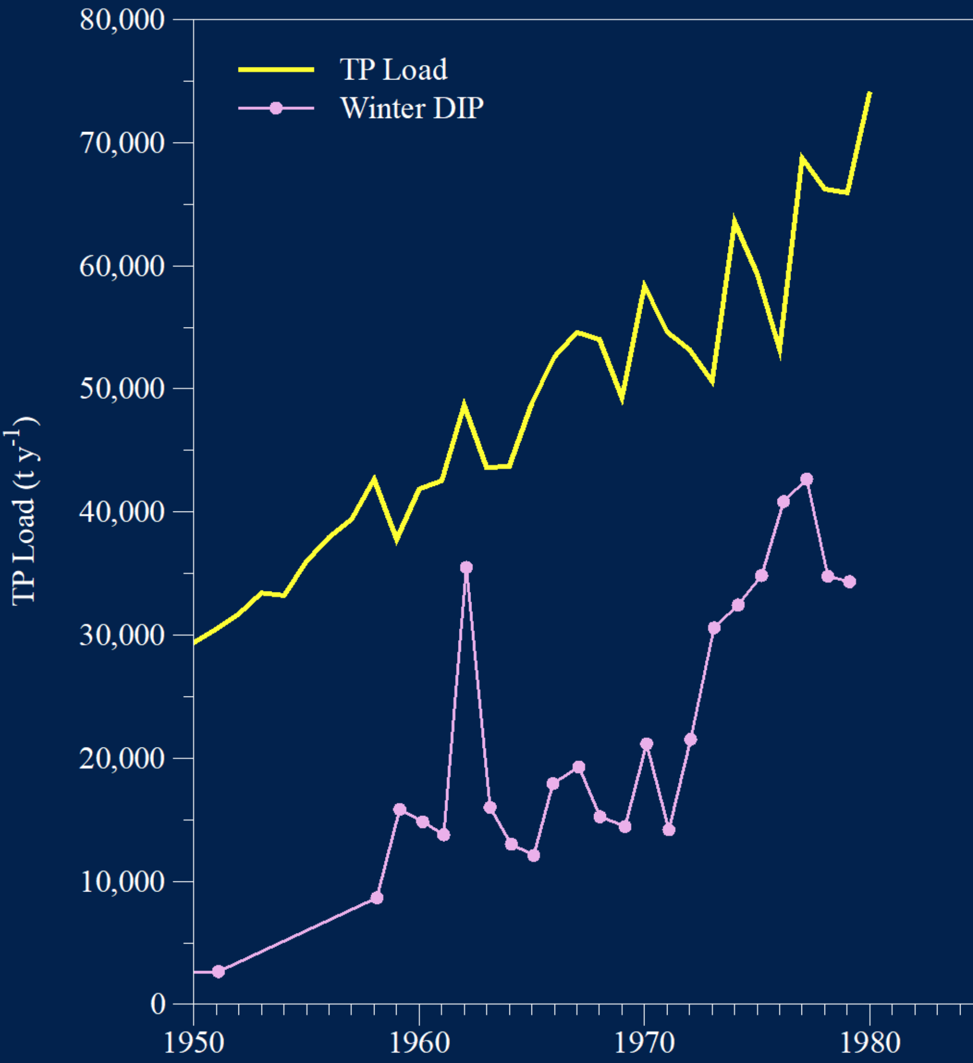
Baltic Sea

Watershed area = 1 730 000 km^2
Proportion forest = 53%
Proportion cultivated = 22%

Population = 84 000 000

Coastal countries = 9
Additional in watershed = 5

People and Agriculture are focused in the South



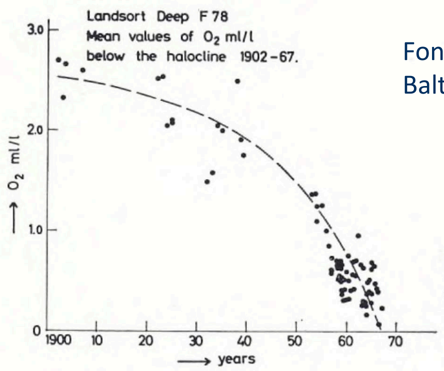
1950s-1970s:

- Population increase (60 – 85 million)
- Urbanisation (30 –> 60%)
- Mechanisation of agriculture
- Fertilizer consumption (at least 3 times increase)

Increased hypoxia in open Baltic observed already late 1960s

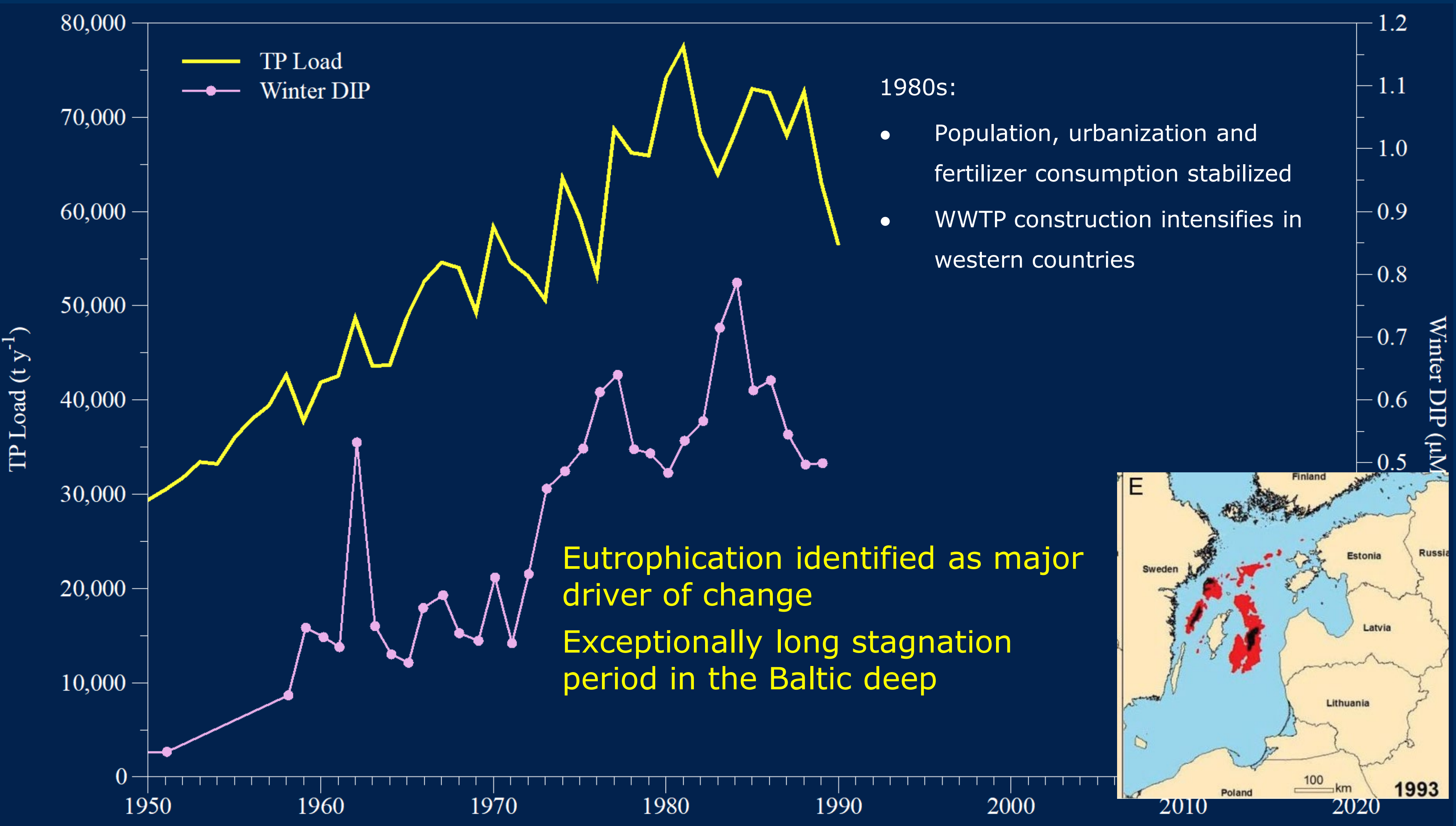
Eutrophication in lakes identified

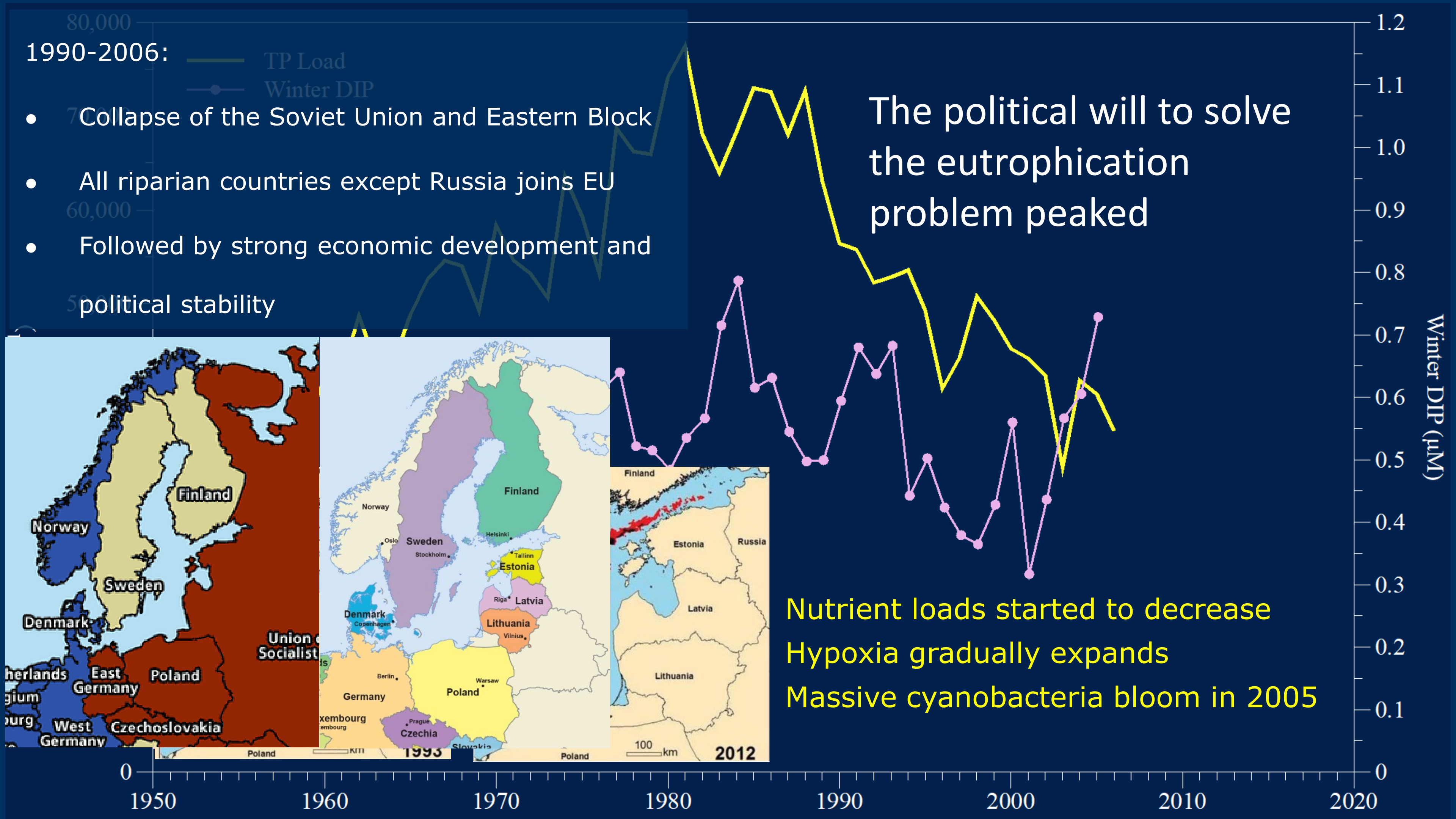
Initial WWTP construction in western countries



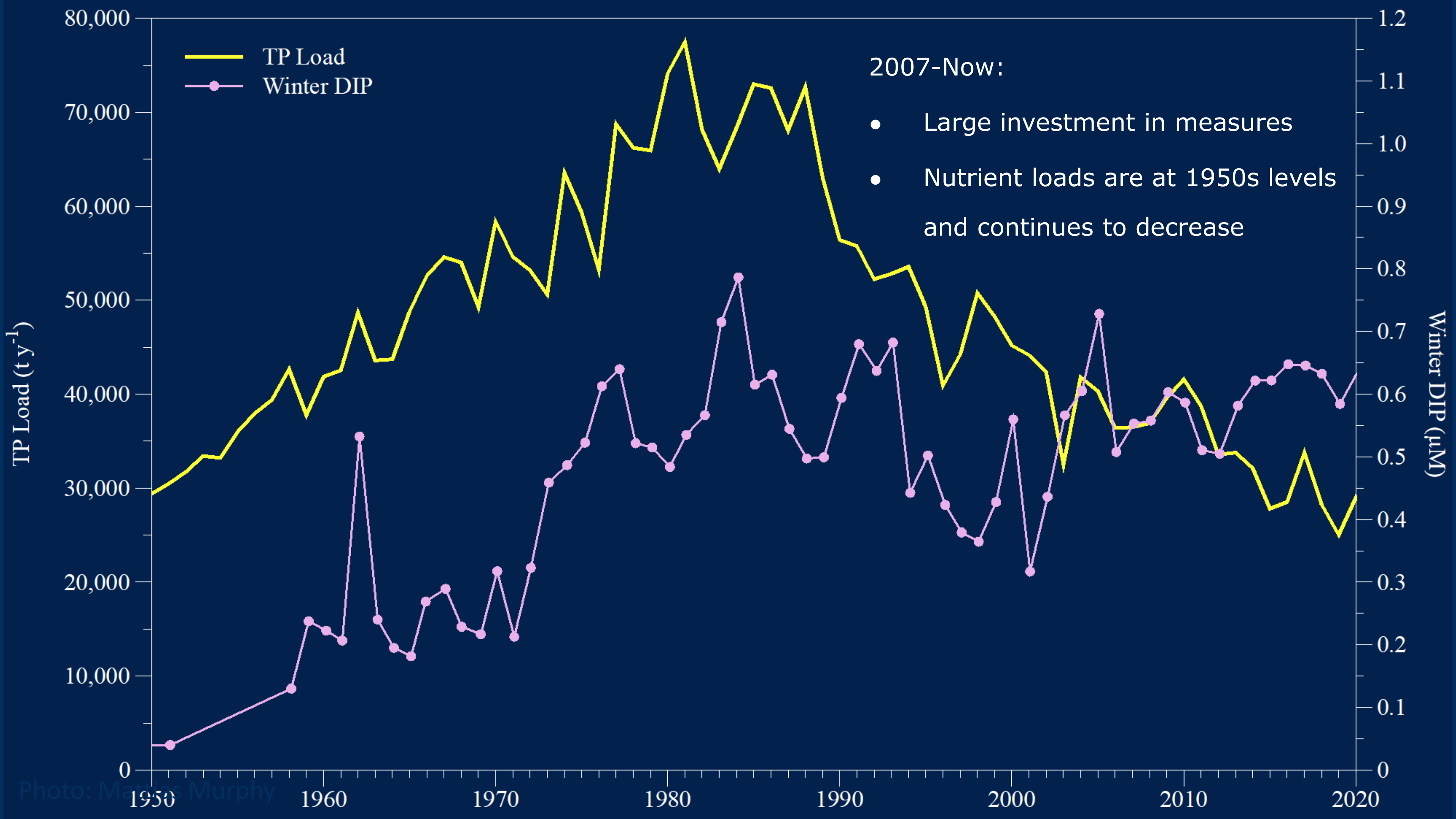
Fonselius, S. H. 1969. Hydrography of the Baltic deep basins III.

Fig. 23. Mean values of dissolved oxygen in ml/l below the halocline at station F 78 (Landsort Deep) from 1900 to 1967.


TP Load
Winter DIP
TP Load (t y-1)
Winter DIP (µM)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
1950
1960
1970
1980
1990
2000
2010
2020
1980s:
• Population, urbanization and fertilizer consumption stabilized
• WWTP construction intensifies in western countries
Eutrophication identified as major driver of change
Exceptionally long stagnation period in the Baltic deep
E
Finland
Sweden
Estonia
Russia
Latvia
Lithuania
Poland
100 km
1993



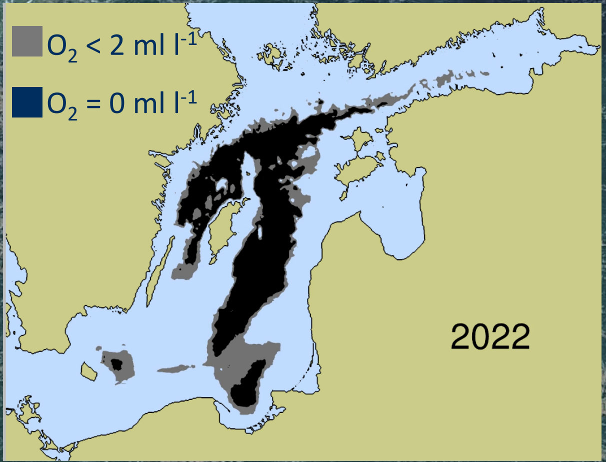
1990-2006:
• Collapse of the Soviet Union and Eastern Block
• All riparian countries except Russia joins EU
• Followed by strong economic development and political stability
The political will to solve the eutrophication problem peaked
Nutrient loads started to decrease
Hypoxia gradually expands
Massive cyanobacteria bloom in 2005
TP Load
Winter DIP
80,000
60,000
0
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Winter DIP (μM)
1950
1960
1970
1980
1990
2000
2010
2020
Norway
Finland
Sweden
Denmark
East Germany
Poland
West Germany
Czechoslovakia
Union of Socialist
Norway
Oslo
Sweden
Stockholm
Finland
Helsinki
Tallinn
Estonia
Riga
Latvia
Lithuania
Vilnius
Denmark
Copenhagen
Berlin
Germany
Warsaw
Poland
Prague
Czechia
Slovakia
1993
Finland
Estonia
Russia
Latvia
Lithuania
Poland
100 km
2012


TP Load
Winter DIP
2007-Now:
Large investment in measures
Nutrient loads are at 1950s levels and continues to decrease
TP Load (t y-1)
Winter DIP (µM)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1950
1960
1970
1980
1990
2000
2010
2020
Photo: Mattias Murphy

Hypoxia worse than ever
Cyanobacteria blooms worse than ever

Frustration and despair!

Science-based advice is more important than ever



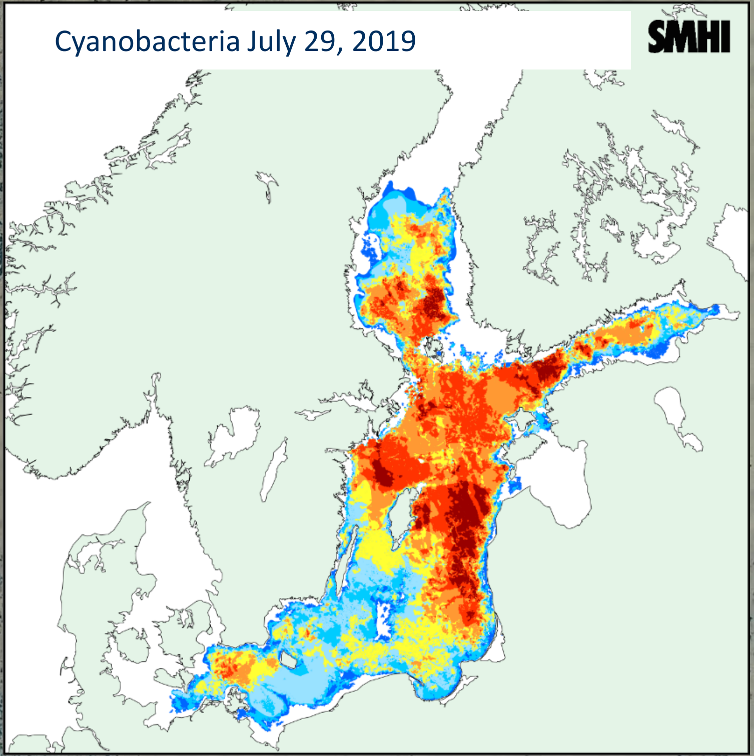
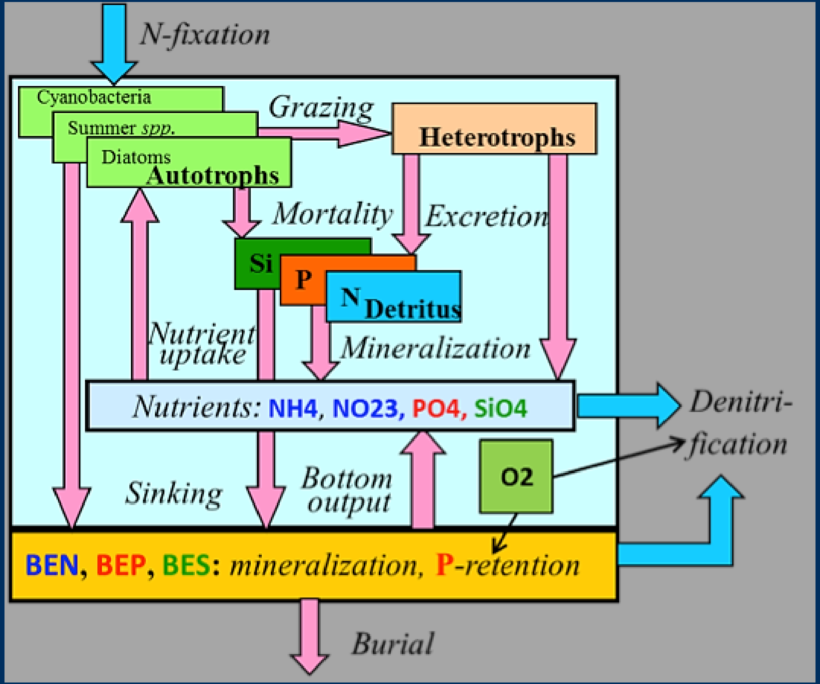


Photo: Mattias Murphy

Model tools are available to help us understand

BALTSEM

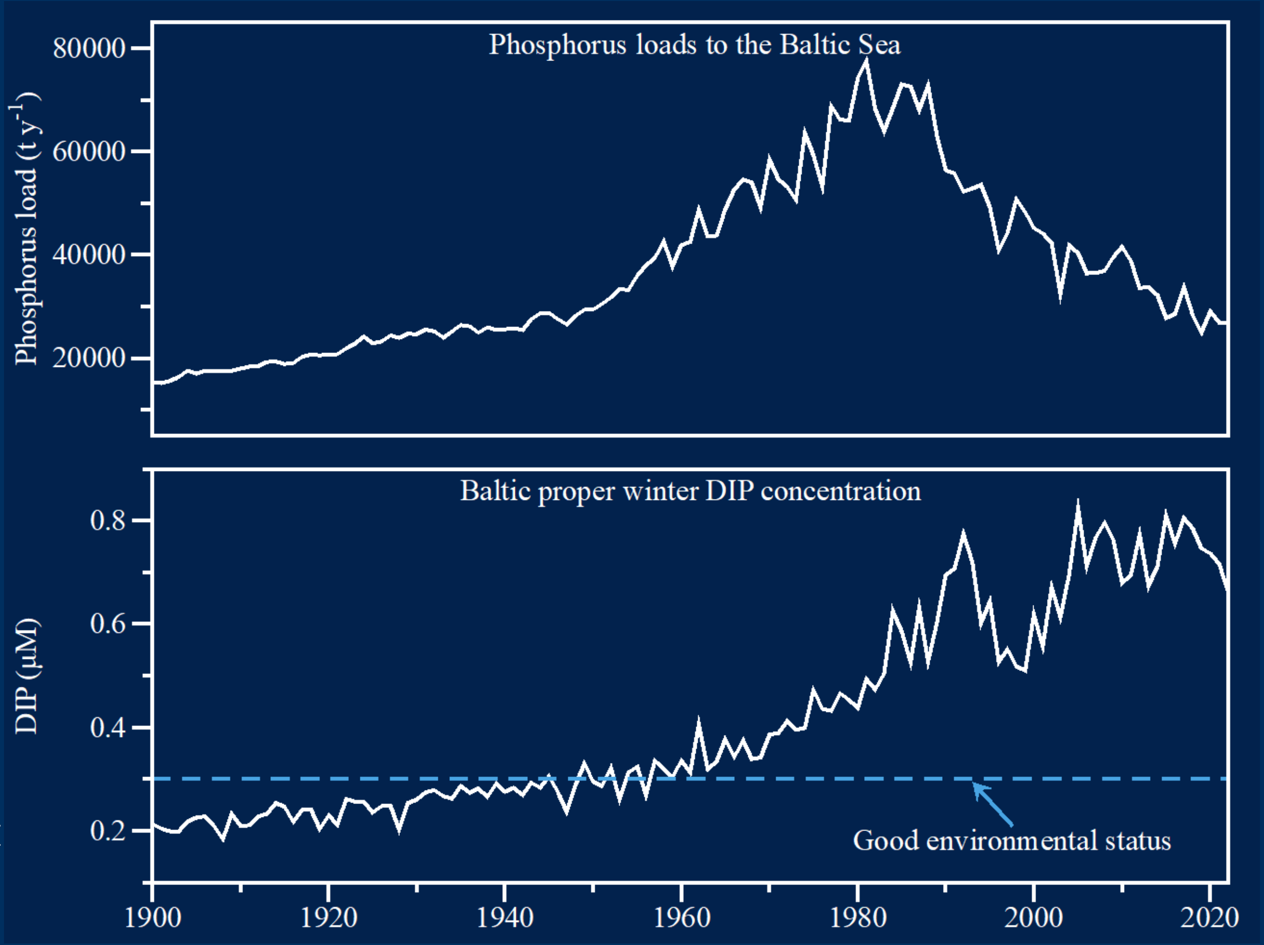
- Coupled physical-biogeochemical model
- Forced by weather, river runoff and North Sea boundary; and nutrient loads
- Hindcast simulation 1970-2021



Background to the present state

Loads are close to the level of the 1950s

Good status is close to the concentrations of the 1950s



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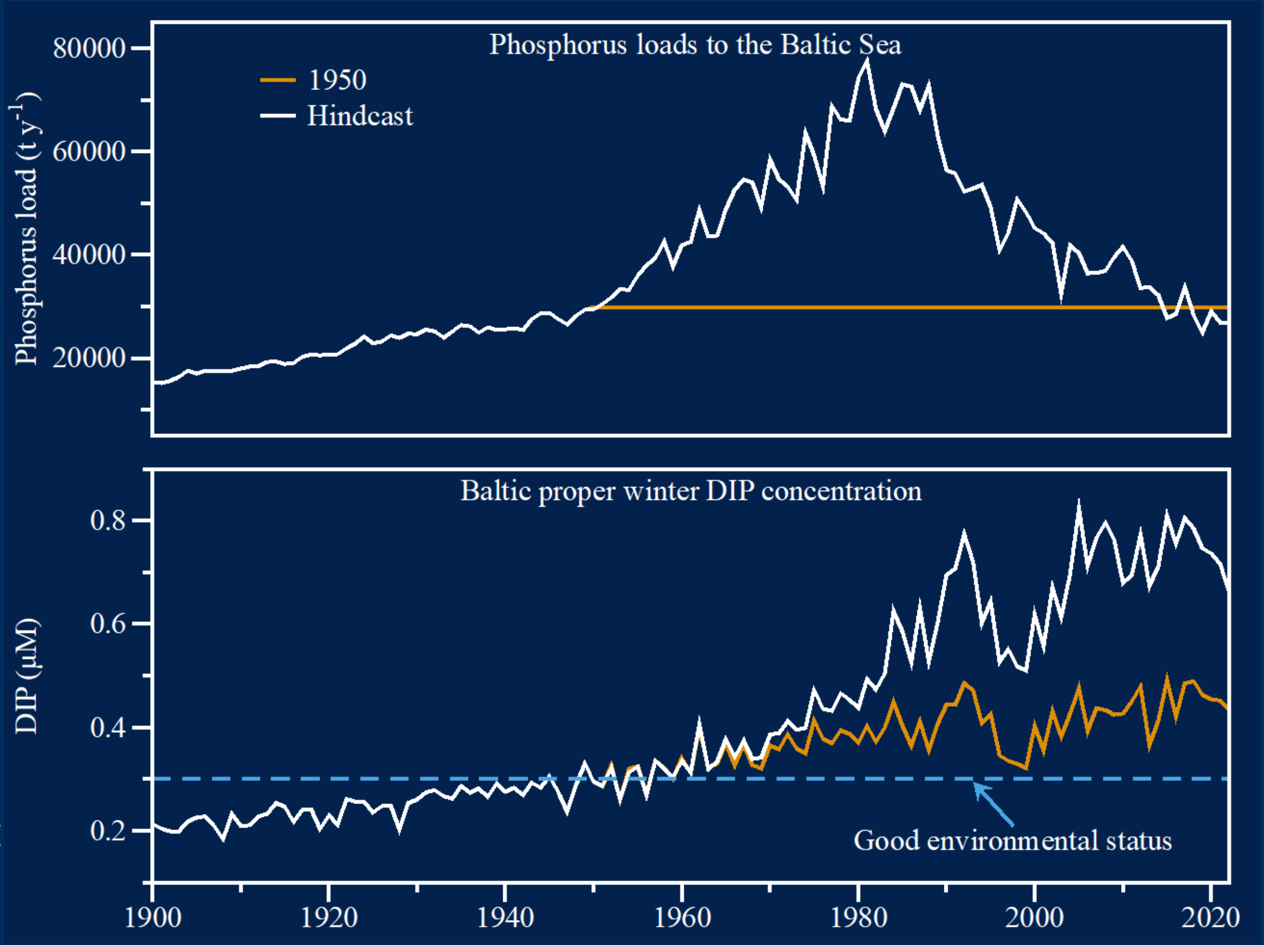
Delayed response in the sea

Simulation with loads maintained at 1950 level



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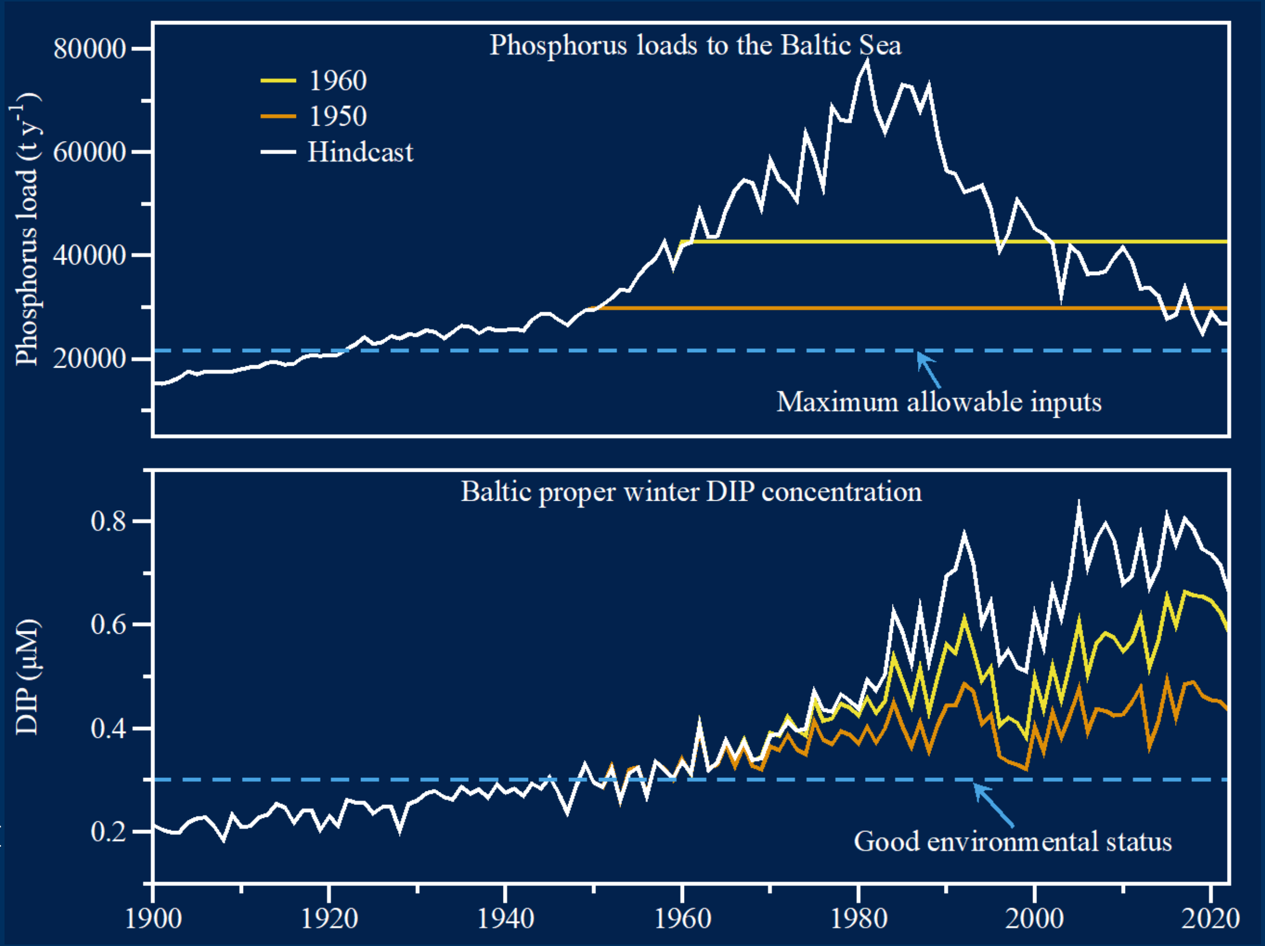
Delayed response in the sea

1960 loads would have led to substantial eutrophication



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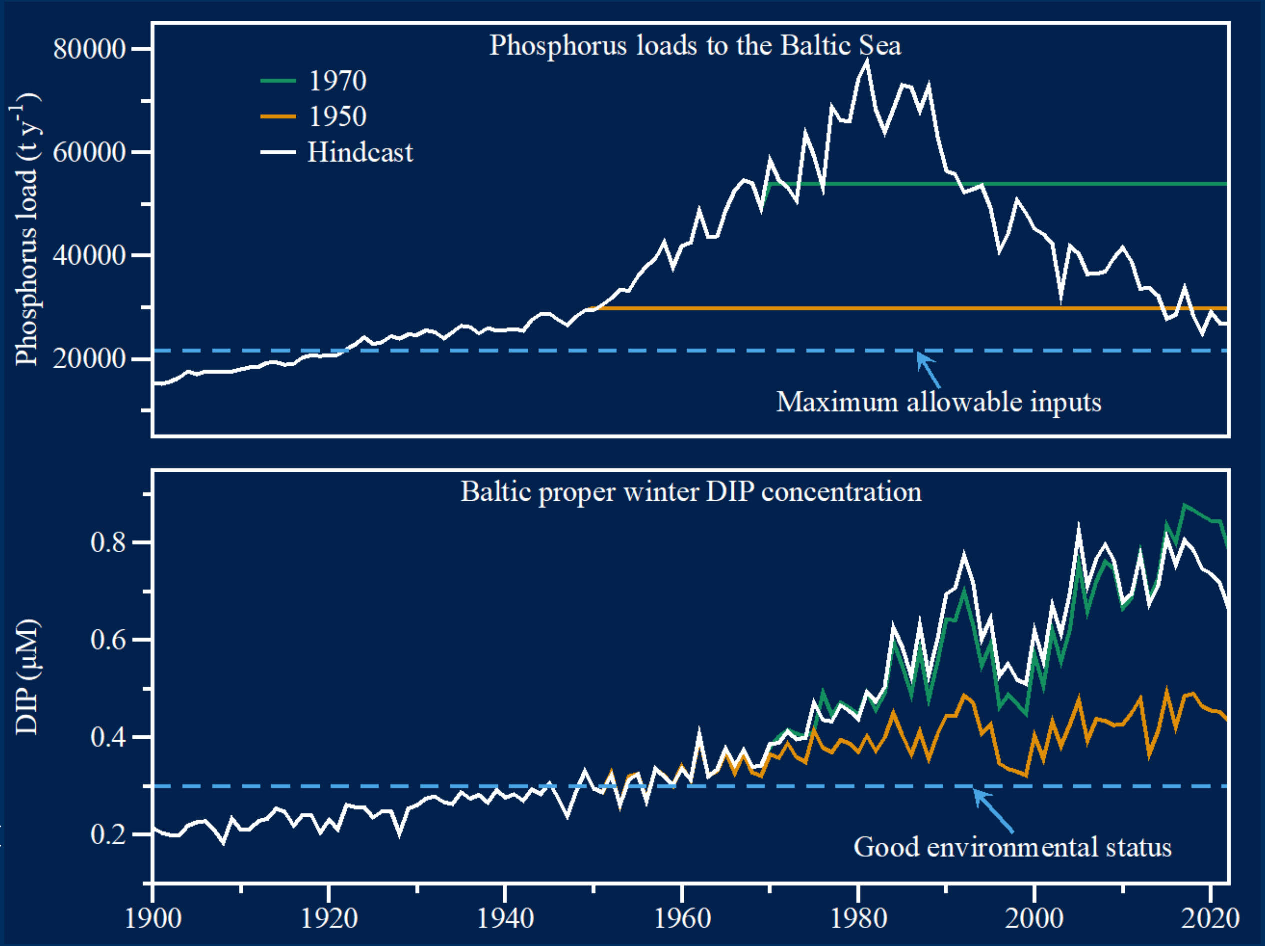
Delayed response in the sea



And 1970 loads to conditions worse than observed today

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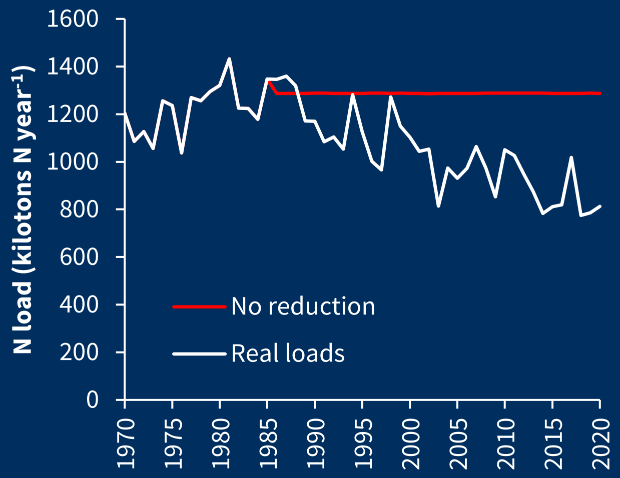
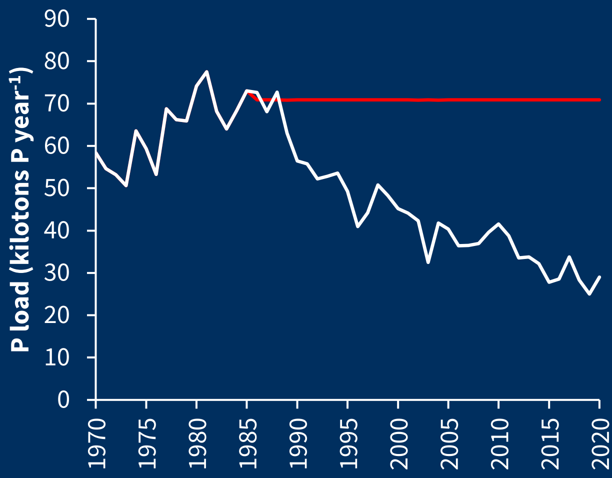
Have measures had an effect?

Two scenarios: one with observed loads one without reduction since mid-1980s





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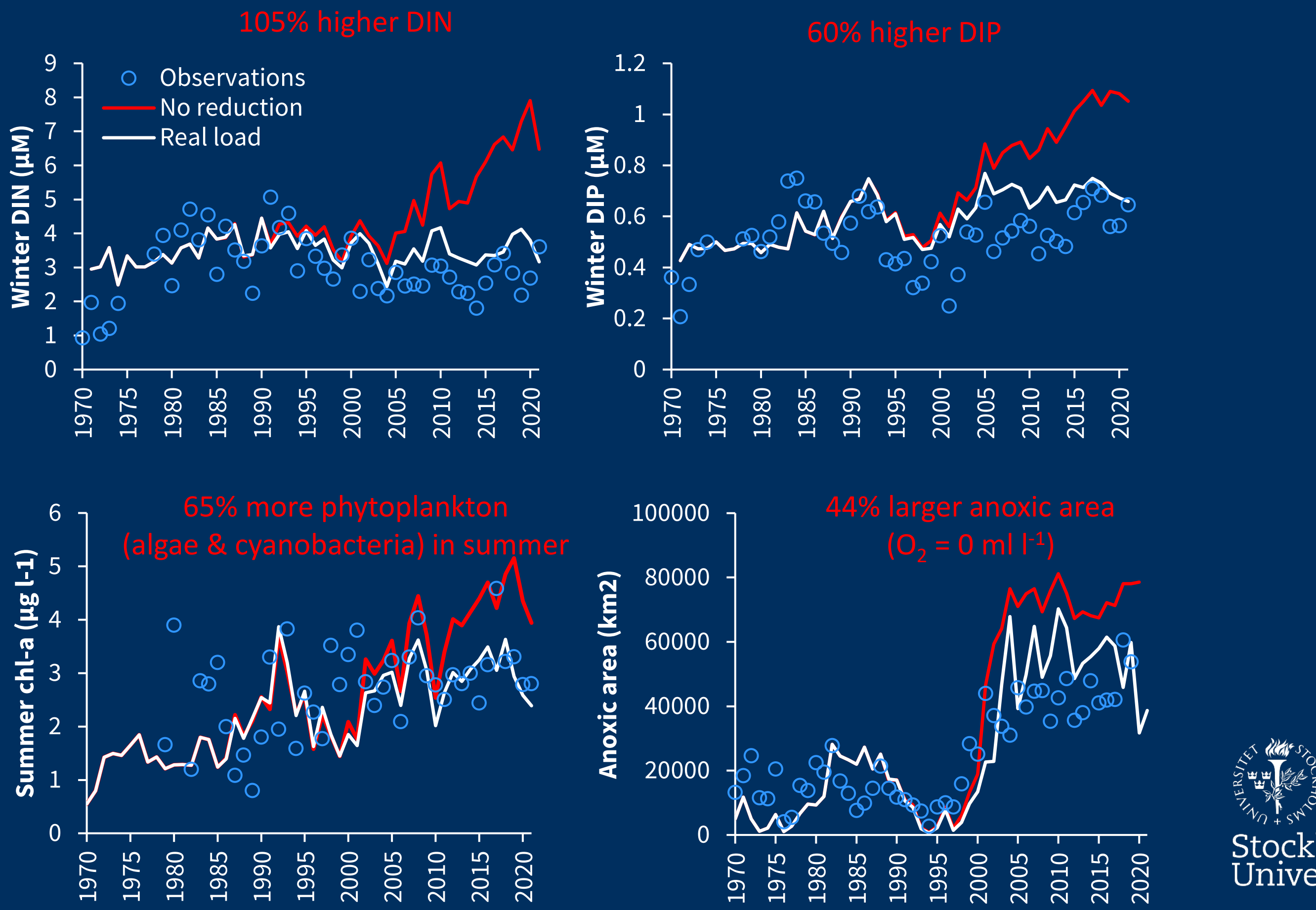
It would have been much worse without the effort made!



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Eutrophication goal

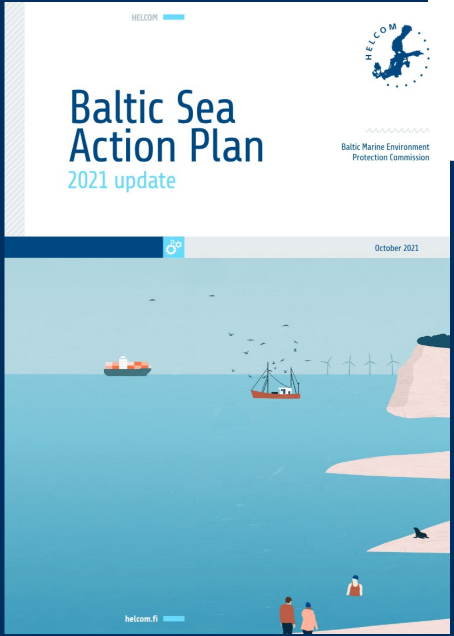
“Baltic Sea unaffected by eutrophication”

Ecological objectives

- *Concentrations of nutrients close to natural levels*
- *Clear waters*
- *Natural level of algal blooms*
- *Natural distribution and occurrence of plants and animals*
- *Natural oxygen levels*

Management objective

- *Minimize inputs of nutrients from human activities*



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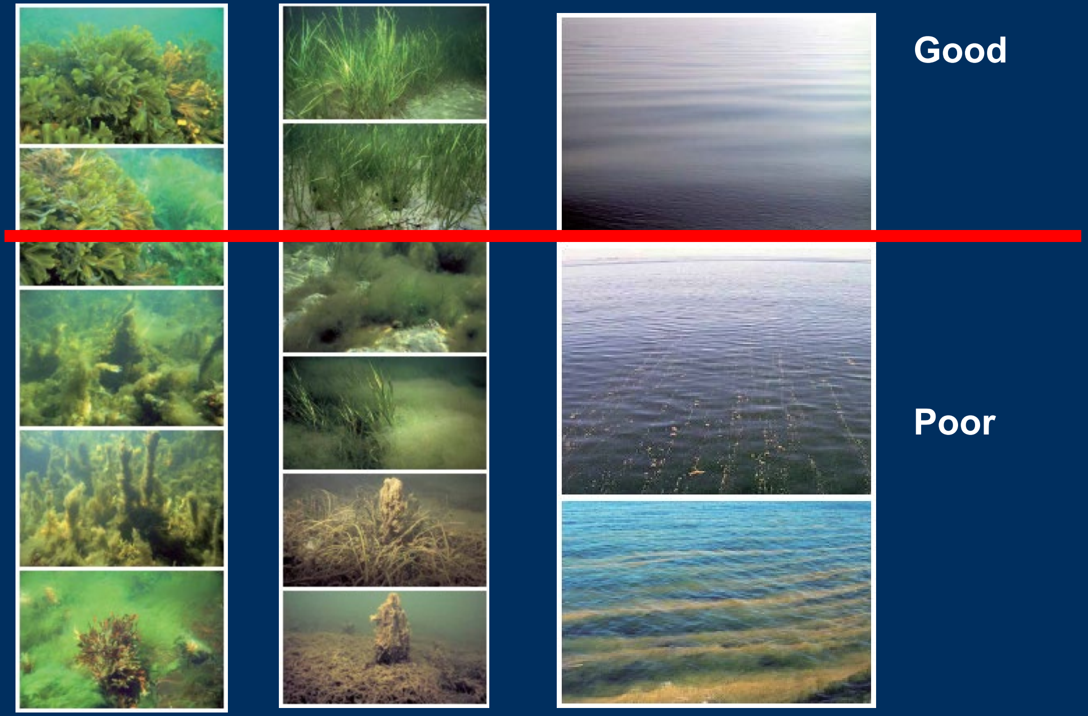
Indicators and thresholds

Quantify objectives using measurable indicators and define thresholds of these



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Method to determine Maximum Allowable Inputs

Question to be answered is:

What combination of loads to the basins satisfies both targets and provides the maximal loads? ->

optimization problem

1. Determine relationships between loads and indicator response from a large amount (1000nds) of cleverly chosen model simulations

2. Find the solution to the optimization problem from the data base of relationships

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Table 1. Maximum allowable inputs (MAI) of nitrogen (TN) and phosphorus (TP) to the Baltic Sea sub-basins (in tonnes/year)

	Maximum allowable inputs (MAI)	
Baltic Sea sub-basin	**Total nitrogen (TN)** tonnes/year	**Total phosphorous (TP)** tonnes/year
Kattegat	74,000	1,687
Danish Straits	65,998	1,601
Baltic Proper	325,000	7,360
Bothnian Sea	79,372	2,773
Bothnian Bay	57,622	2,675
Gulf of Riga	88,417	2,020
Gulf of Finland	101,800	3,600
Baltic Sea	**792,209**	**21,716**

Nutrient input ceilings

Eutrophication goal

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- *Clear waters*
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- *Natural distribution and occurrence of plants and animals*
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Management objective

- *Minimize inputs of nutrients from human activities*

Table 2a. Net nutrient input ceilings (NIC) of nitrogen for the HELCOM countries, non-HELCOM countries in the Baltic Sea catchment area, other countries with airborne input, Baltic Sea shipping and North Sea shipping (in tonnes/year).

	Bothnian Bay	Bothnian Sea	Baltic Proper	Gulf of Finland	Gulf of Riga	Danish Straits	Kattegat
Germany	947	3,920	34,077	1,645	1,747	23,647	4,661
Denmark	280	1,148	9,025	421	462	28,067	28,538
Estonia	113	404	1,478	11,334	13,099	22	24
Finland	35,087	28,700	1,827	20,457	295	76	89
Lithuania	108	495	25,878	305	8,820	66	80
Latvia	73	330	6,457	246	43,074	31	34
Poland	668	3,125	151,997	1,407	1,596	1,480	1,443
Russia	839	1,993	10,317	61,503	3,296	238	245
Sweden	17,718	32,633	30,690	626	525	6,056	32,799
Other countries with airborne input	1,375	5,008	26,947	2,986	2,188	4,933	4,502
Belarus	-	-	13,456	-	12,820	-	-
Czech Republic	-	-	3,551	-	-	-	-
Ukraine	-	-	1,693	-	-	-	-
Baltic Sea shipping	284	1,141	5,180	675	345	651	701
North Sea shipping	131	475	2,427	196	150	729	884

Table 2b. Net nutrient input ceilings (NIC) of phosphorus for the HELCOM countries, non-HELCOM countries in the Baltic Sea catchment area (in tonnes/year).

	Bothnian Bay	Bothnian Sea	Baltic Proper	Gulf of Finland	Gulf of Riga	Danish Straits	Kattegat
Germany	-	-	109	-	-	401	-
Denmark	-	-	21	-	-	979	815
Estonia	-	-	9	225	185	-	-
Finland	1,683	1,246	-	315	-	-	-
Lithuania	-	-	703	-	175	-	-
Latvia	-	-	167	-	1,061	-	-
Poland	-	-	4,291	-	-	-	-
Russia	-	-	242	2,909	99	-	-
Sweden	811	1,133	318	-	-	116	753
Belarus	-	-	349	-	407	-	-
Czech Republic	-	-	57	-	-	-	-
Ukraine	-	-	47	-	-	-	-

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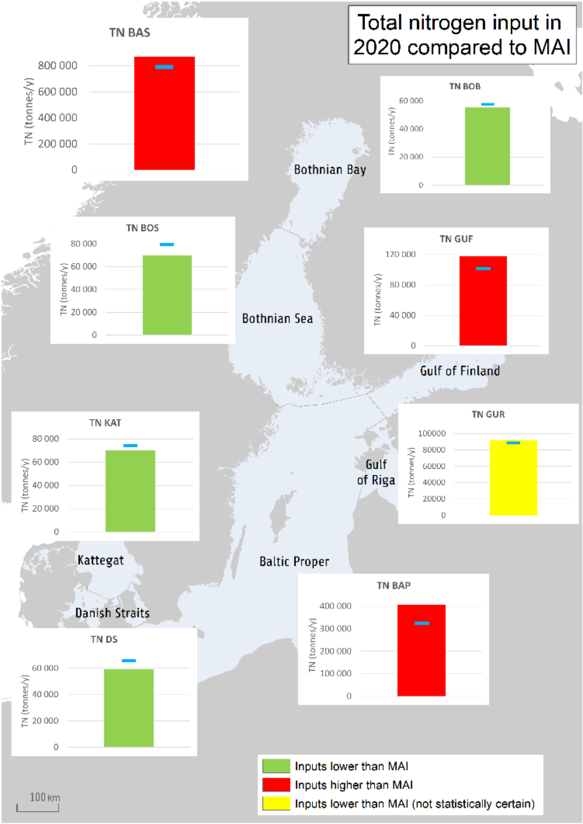
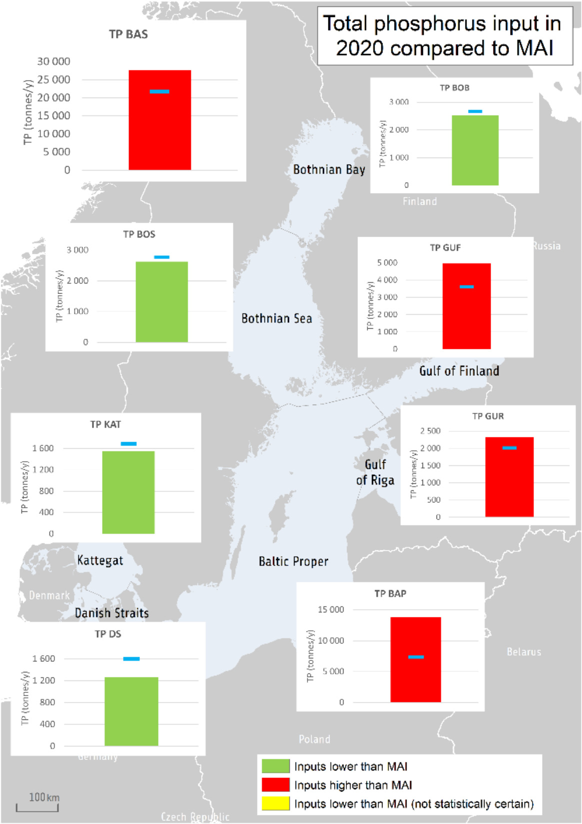
Nutrient inputs are still higher than Maximum Allowable Inputs
HELCOM PLC assessment





HELCOM (2023) Inputs of nutrients to the sub-basins (2020). HELCOM core indicator report. https://indicators.helcom.fi/indicator/inputs-of-nutrients/

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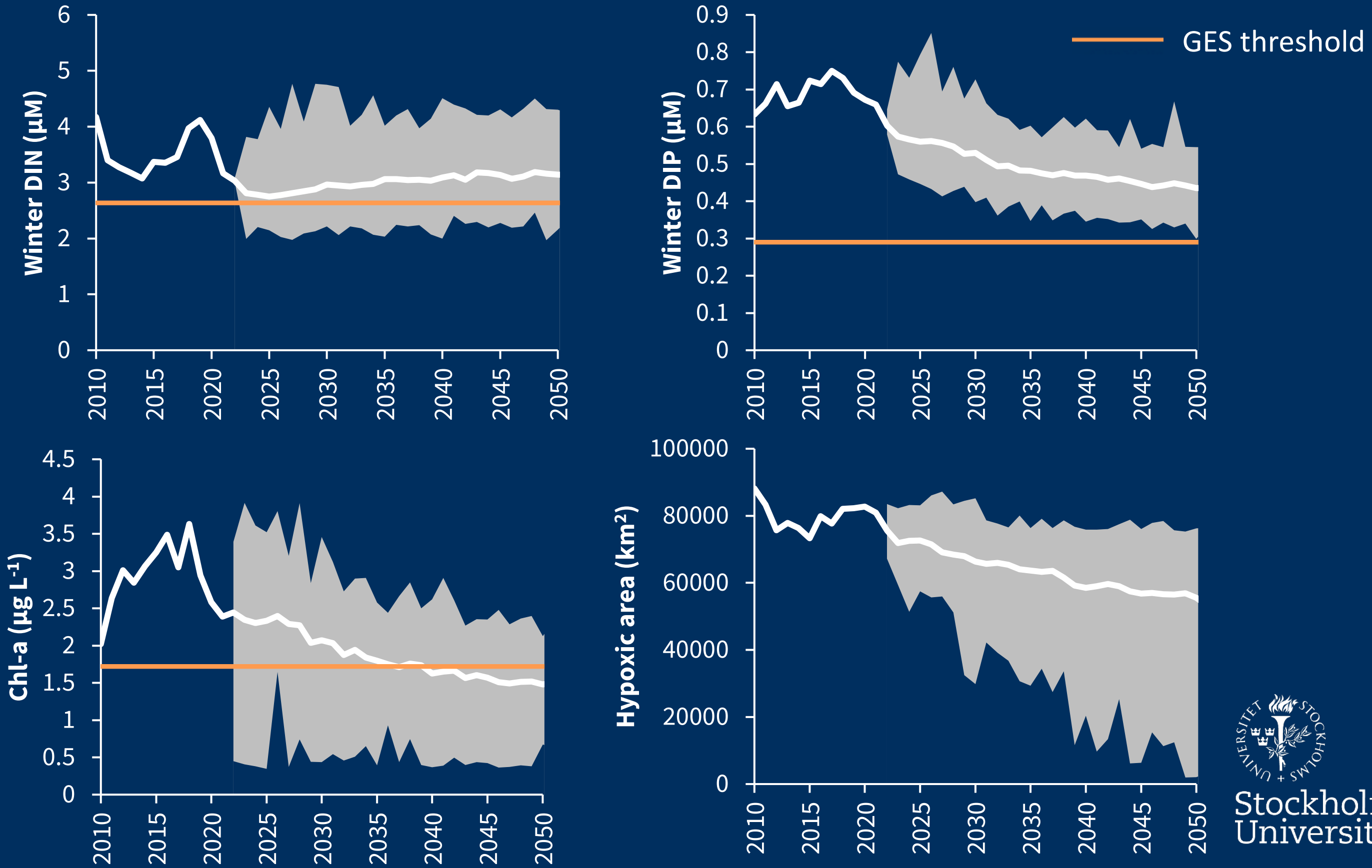
What about the future?

- Scenarios with present day nutrient inputs (2020)
- 100 simulations with randomized meteorogical forcing

We can expect a gradual improvement with current nutrient inputs



Shaded area represent range of "natural" variability

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and several GES thresholds may be reached but only by the end of the century

Simulated eutrophication ratios (ER).
ER < 1 = good environmental status target reached

Eutrophication state indicator	Target value*	Today (2016-2021)	Future 2050	Future 2100
Winter DIN	2.64 µM	1.38	1.19	1.20
Winter DIP	0.29 µM	2.43	1.51	1.33
Total N	16.25 µM	1.30	1.09	0.99
Total P	0.44 µM	1.87	1.22	0.99
O_2 debt	8.66 mg l^{-1}	1.37	1.09	0.99
Chl-a	1.72 µg l^{-1}	1.74	0.86	0.63

**HELCOM core indicator reports 2023*

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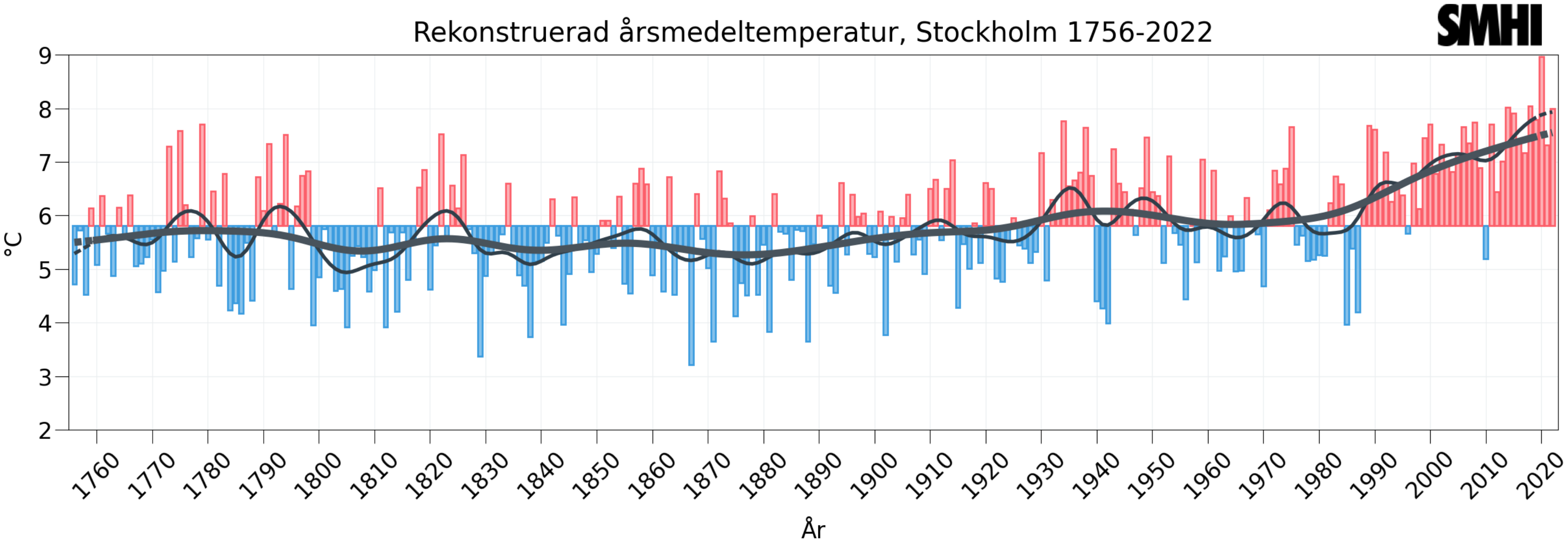
Future challenges – climate change

On-going rapid warming



Staplarna i diagrammet visar rekonstruerad årsmedeltemperatur. Röda staplar visar högre och blå visar lägre temperaturer än medelvärdet för hela serien. Den kraftigaste grå linjen visar ett glidande medelvärde beräknat över ungefär 30 år och den tunnare grå linjen visar ett glidande medelvärde beräknat över ungefär 10 år.

Future challenges – climate change

On-going rapid warming

Heat content of the Baltic Sea
From Baltsem simulation

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Future challenges – climate change

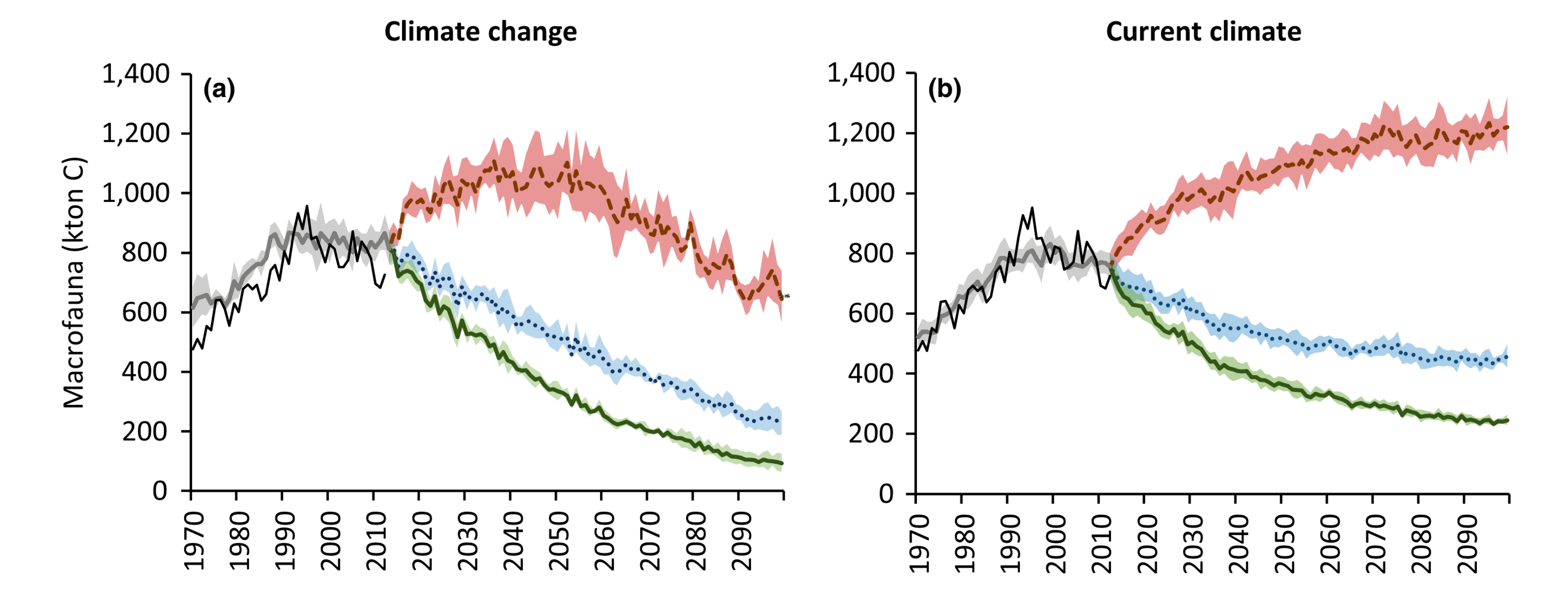
On-going rapid warming

Average temperature in the Gulf of Bothnia
From Baltsem simulation

Future challenges – climate change

Will lead to major and complex changes in the ecosystem

Amounts of benthic biomass for different levels of nutrient loads
From Baltsem simulation (Ehrnsten et al., 2020)



Concluding remarks

- **Numerical modeling tools are necessary and useful for managing the Baltic Sea**
- **Still models are limited to relatively simplistic physical-biogeochemical processes**
- **Changes due to the ecosystem function from large perturbations by climate change may be drastic and difficult to simulate**
- **Novel technology can help!**

Thanks for support from

Swedish Agency for Marine and Water Management

FORMAS

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