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Social–Ecological Analysis and Models for Digital Twin Oceans

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Scenario-based cumulative impact assessments for ecosystem-based planning and management

Life REEF Conference
Session 4: Pressure and Impact Analysis
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Ida Maria Bonnevie
idarei@plan.aau.dk
Assistant Professor
Aalborg University Copenhagen

Cumulative pressures affect the seas

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Eutrophication

Overfishing

Hazardous substances

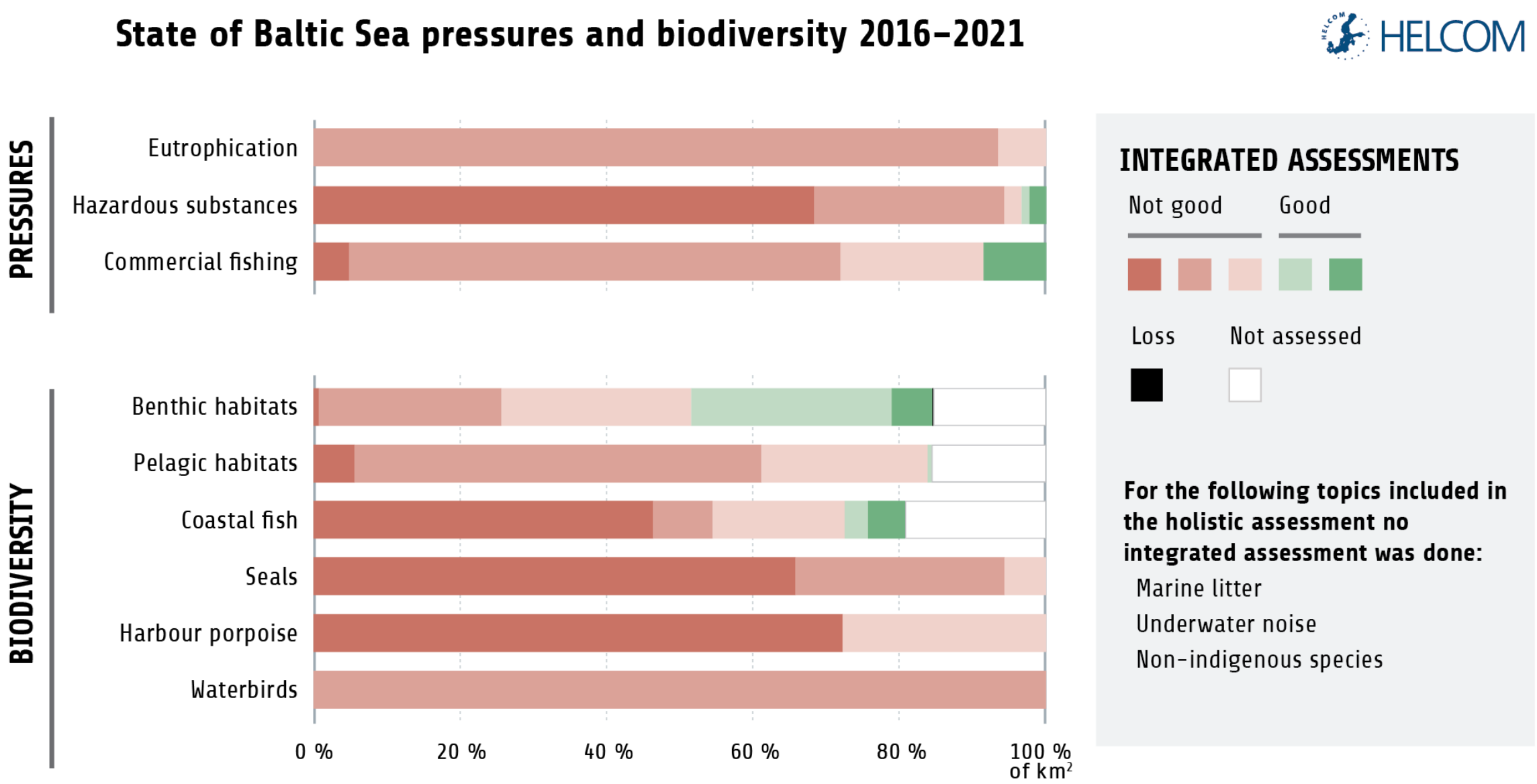
Disturbance

Marine litter

Tourism

etc.

Pressures and biodiversity in the Baltic Sea



HELCOM (2023)

The CIA method by Halpern et al. (2008)

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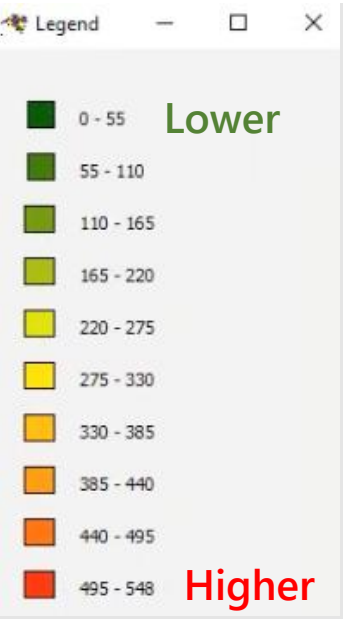
The additive approach $I_{Sum}(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{m} D_i(x,y)e_j(x,y)\mu_{i,j}$

Analysis data from:
HOLAS 2 (HELCOM 2017a)

ID	ECOSYSTEM	P1	P2	P3	P4
1	Productive_surface_waters	14	4	10	15
2	Oxygenated_deep_waters	10	9	7	18
3	Infralittoral_Hard_Bottom	17	18	13	13
4					13
5					13
6	Infralittoral_mixed	15	18	12	13

Sensitivity matrix with weights μ

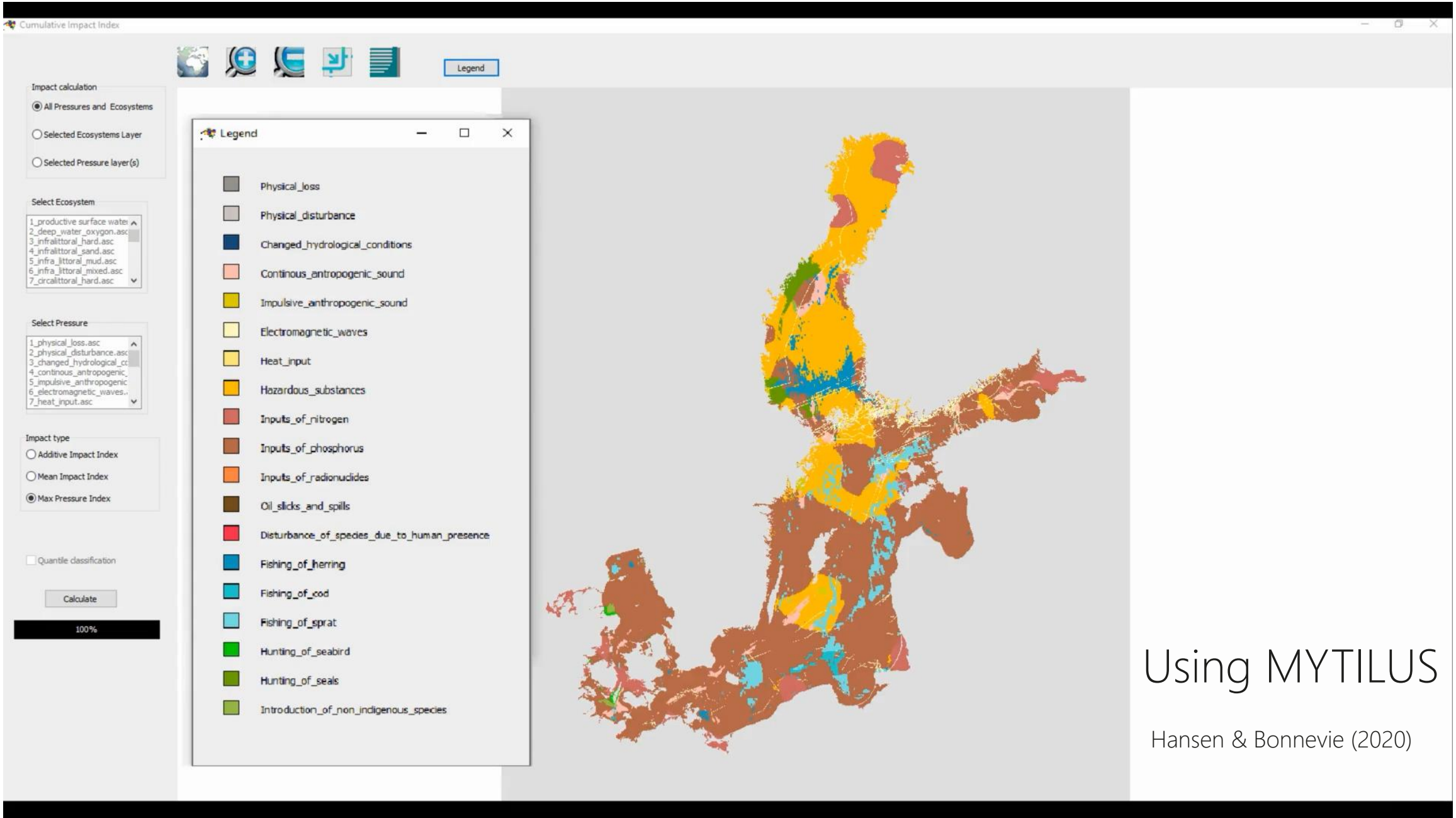


Pressures

Ecosystems

Cumulative impacts

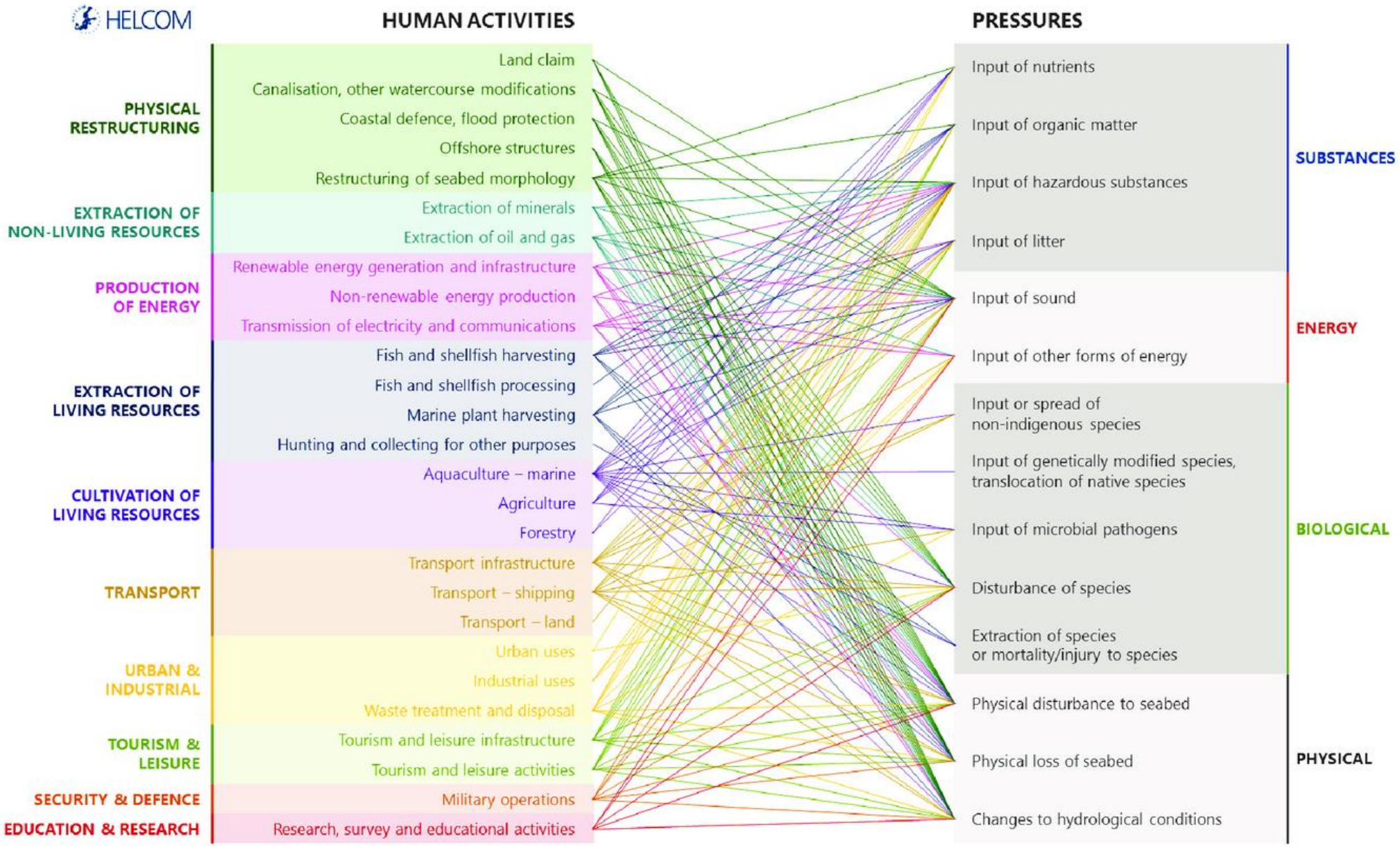
Scenario-based approach to fishing



Using MYTILUS

Hansen & Bonnevie (2020)

Human activities and their pressures



HELCOM (2017b)

What-if scenarios in MSP

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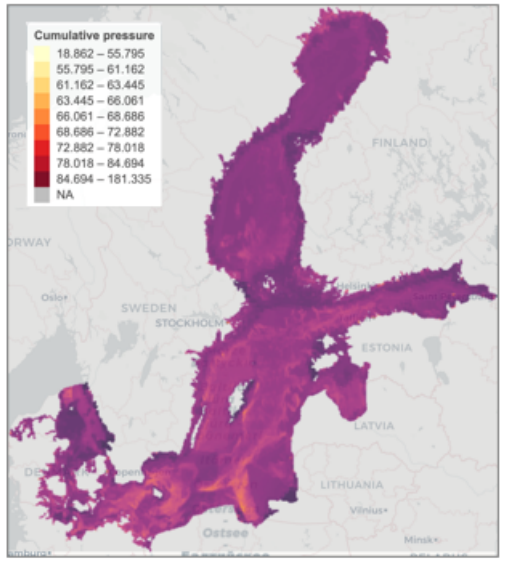


A) Cumulative Pressure Index

Pressures aggregated

Human **A**activities

State of ecosystem components

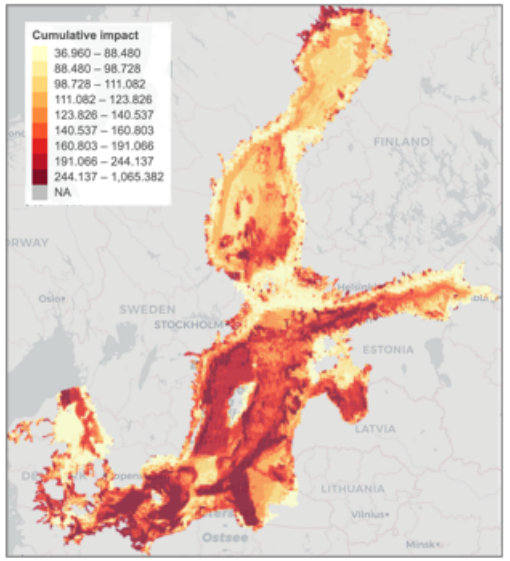
Impact on ecosystem services

B) Cumulative Impact Index

Drivers e.g. population, GDP

Response in MSP

What-if scenarios



A) Cumulative Pressure Index:

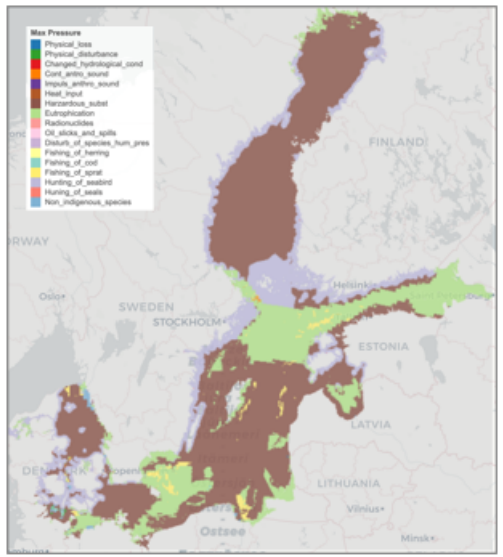
$$BSII(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{m} PLi(x,y) * ECj(x,y) * SSi,j$$

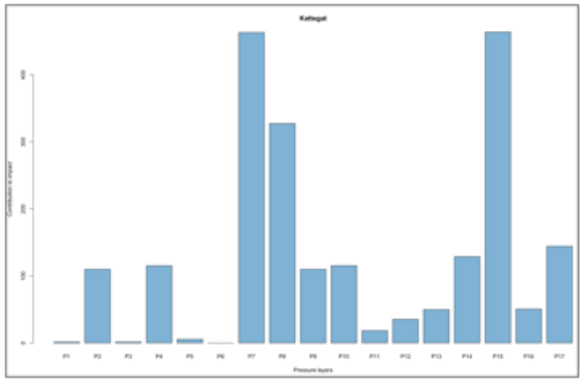
B) Cumulative Impact Index:

$$BSPI(x,y) = \sum_{i=1}^{n}(PLi(x,y)\frac{1}{m}\sum_{j=1}^{m} SSi,j)$$

The MYTILUS-R suite provides several analytical diagnostics to support the identification of adverse impacts on the ecosystem as well as finding appropriate measures to mitigate the impacts and apply a scenario-based approach to compare various options.

Max Pressure





Hansen & Bonnevie (2025) - MPA in MSP conference in Bødø 2025

P7: Hazardous substances
P8: Nutrients concentration (N and P)
P15: Hunting seabirds

Score changes reflect changed conditions

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ECOSYSTEMS VERTICAL / PRESSURES HORISONTAL	Physical loss	Physical disturbance	Changes to hydrological conditions	Inputs of Continuous Sounds	Inputs of impulsive sound	Inputs of Electromagnetic and Seismic Wav	Input of Heat	Inputs of Hazardous substances	Inputs of nitrogen	Inputs of phosphorus	Introduction of radionuclides	Oil slicks and spills	Disturbance of species	Extraction of herring	Extraction of cod	Extraction of sprat	Hunting of Seabirds	Hunting of Seals	introduction of non-indigenous species
Productive surface waters (Chl-a)	4	0	-2	0	4	0	0	0	-3		0	0	4	0	2	0	5	5	0
Deep water habitats not influenced by permanent anoxia	-6	-2	0	0	4		0	0	-1		0	4	0	3	3	3	3	3	0
Infralittoral coarse sediment	-1	0	0	0	0		0	0	0		0	0	0	0	0	3	3	3	0
Infralittoral sand	-1	0	0	0	0		0	0	0		0	0	0	0	0	1	3	3	0
Infralittoral mud	-2	0	0	0	0		0	0	0		0	0	0	0	0	1	3	3	0
Infralittoral mixed sediment	-1	0	0	0	0		0	0	0		0	0	0	0	0	2	3	3	0
Infralittoral mud or Infralittoral sand																			
Infralittoral rock and biogenic reef																			
Circalittoral coarse sediment	-1	0	0	0	0		0	0	0		0	0	0	0	0	4	5	5	0
Offshore circalittoral coarse sediment																			
Circalittoral sand	-1	0	0	0	0		0	0	0		0	0	0	0	0	1	3	3	0
Offshore circalittoral sand																			
Circalittoral mud	-2	0	0	0	0		0	0	0		0	0	0	0	0	3	1	2	0
Offshore circalittoral mud																			
Circalittoral mixed sediment	-1	0	0	0	0		0	0	0		0	0	0	0	0	3	3	3	0
Circalittoral mud or Circalittoral sand																			
Circalittoral rock and biogenic reef																			
Offshore circalittoral mixed sediment																			
Offshore circalittoral mud or Offshore circalittoral sand																			
Offshore circalittoral rock and biogenic reef																			
Furcellaria lumbricalis distribution	-1	0	0	0	1		0	0	0		0	0	2	2	0	4	3	3	0
Zostera marina distribution	-1	0	0	0	0		0	0	0		0	0	6	4	0	5	3	4	0
Charophyte distribution	-1	0	0	-1	0		0	0	0		0	0	3	3	0	5	3	3	0
Mytilus distribution	-1	0	0	0	0		0	0	0		0	0	1	-1	0	2	0	-1	0
Fucus distribution	-1	0	0	1	1		0	0	0		0	0	2	0	0	3	0	0	0
Sandbanks (1110)	-1	5	0	0	0		0	0	0		0	0	3	2	1	5	3	3	0
Estuaries (1130)	-1	0	0	0	0		-3	0	0		0	0	3	3	2	7	2	4	0
Mudflats and sandflats (1140)	-1	0	0	0	0		0	-2	0		0	0	3	8	8	8	2	4	0
Coastal lagoons (1150)	-1	0	0	-2	0		0	0	0		0	0	3	3	4	7	1	3	0
Large shallow inlets and bays (1160)	-1	0	0	-1	0		0	0	0		0	0	2	3	2	7	1	3	0
Reefs (1170)	0	0	-1	-4	-4		0	0	0		0	0	-1	2	1	5	4	4	0
Baltic Esker islands (1610)	-1	0	0	0	0		0	0	0		0	0	1	1	0	5	0	2	0
Submarine structures made by leaking gas (1180)	-2	-2	0	2	0		0	0	3		0	0	3	1	-1	5	7	9	0
Boreal Baltic islets and small islands (1620)	-1	0	0	0	0		0	0	0		0	0	1	1	0	5	0	1	0
Cod abundance	0	0	0	0	0		0	0	0		0	0	0	0	0	0	0	0	0
Potential spawning areas for cod (PBS)	-7	-1	-2	0	0		-2	2	0		2	-3	0	2	-4	2	1	1	0
Herring abundance	0	0	0	0	0		0	0	0		0	0	0	0	0	0	0	0	0
Sprat abundance	0	0	0	0	0		0	0	0		0	0	0	0	0	0	0	0	0
Potential spawning areas for European flounder (PBS)																			
Potential spawning areas for Baltic flounder (PBS)																			
Potential recruitment areas for perch (PBS)	-2	1	1	-2	-1		-1	-1	2		1	-2	4	7	15	9	-1	-1	0
Potential recruitment areas for pikeperch (PBS)	-2	0	1	0	0		0	0	3		2	-2	3	11	18	12	3	3	0
Recruitment areas of roach																			
Wintering areas for birds	-4	-2	0	0	-2		1	0	0		-4	0	0	0	3	0	-2	14	0
Breeding areas for birds	-4	-1	0	-2	-3		1	0	0		-6	0	0	0	2	0	-2	15	0
Migration routes for birds																			
Grey seal distribution	0	-2	-2	0	0		0	0	-1		0	-1	-3	0	0	0	14	-4	0
Harbour seal distribution	0	-2	-2	0	0		0	0	-1		0	0	-1	0	0	0	17	-1	0
Ringed seal distribution	-2	-2	-2	0	0		-5	0	0		1	-1	-2	0	7	0	14	-4	0
Harbour porpoise distribution	0	1	-3	0	0		0	-2	-2		0	0	-2	0	0	0	-2	-1	0

Change in sensitivity scores from

HOLAS 2 (2011-2016[a]) minus

HOLAS 3 (2016-2021[b])

[a]HELCOM 2017a

[b]HELCOM 2023

Negative change: score increase

Positive change: score decrease

Missing data

Score changes reflect changed conditions

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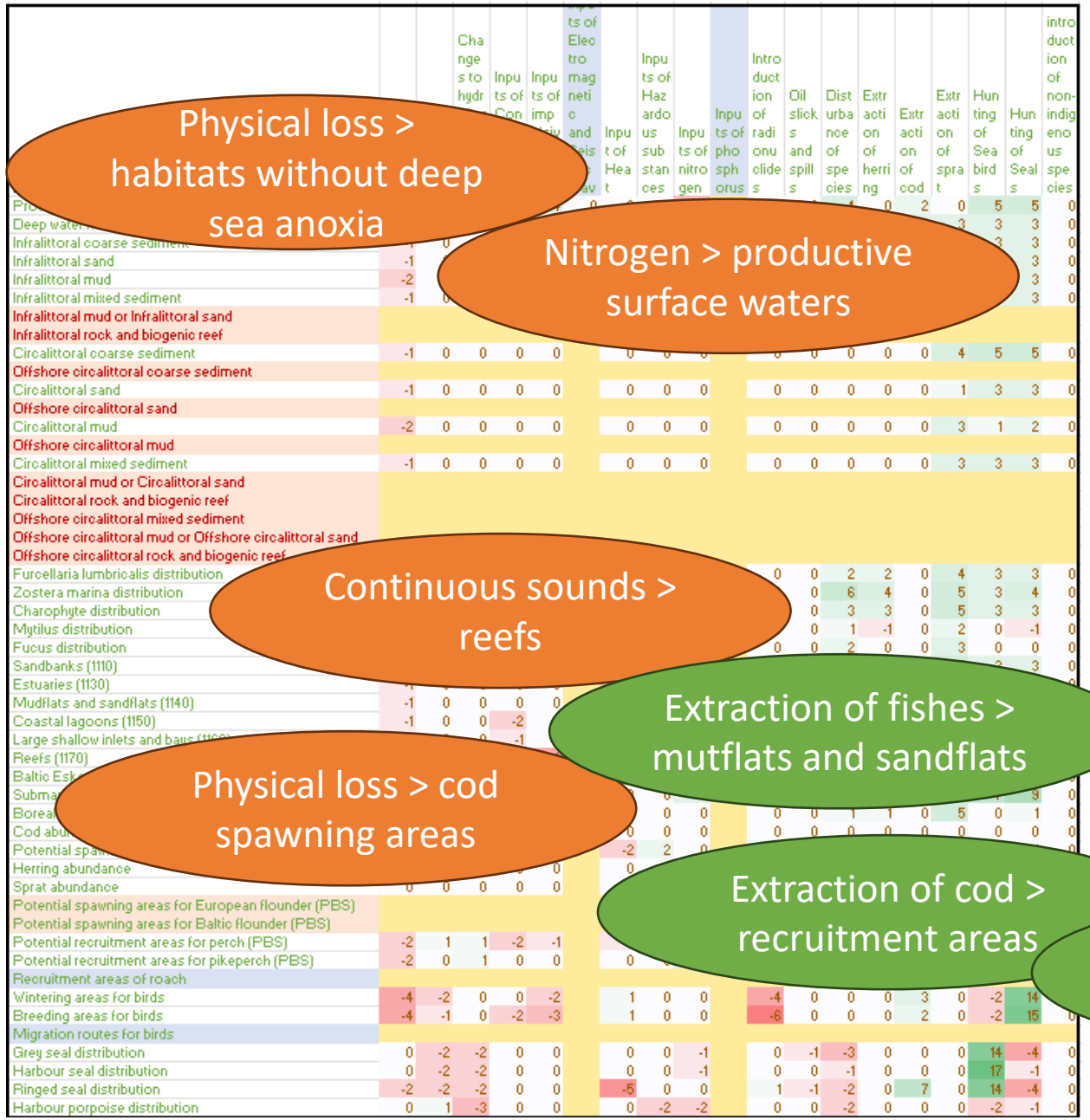

Change in sensitivity scores from

HOLAS 2 (2011-2016[a]) minus

HOLAS 3 (2016-2021[b])

[a]HELCOM 2017a

[b]HELCOM 2023

Negative change: score increase

Positive change: score decrease

Missing data

How to consider climate change?

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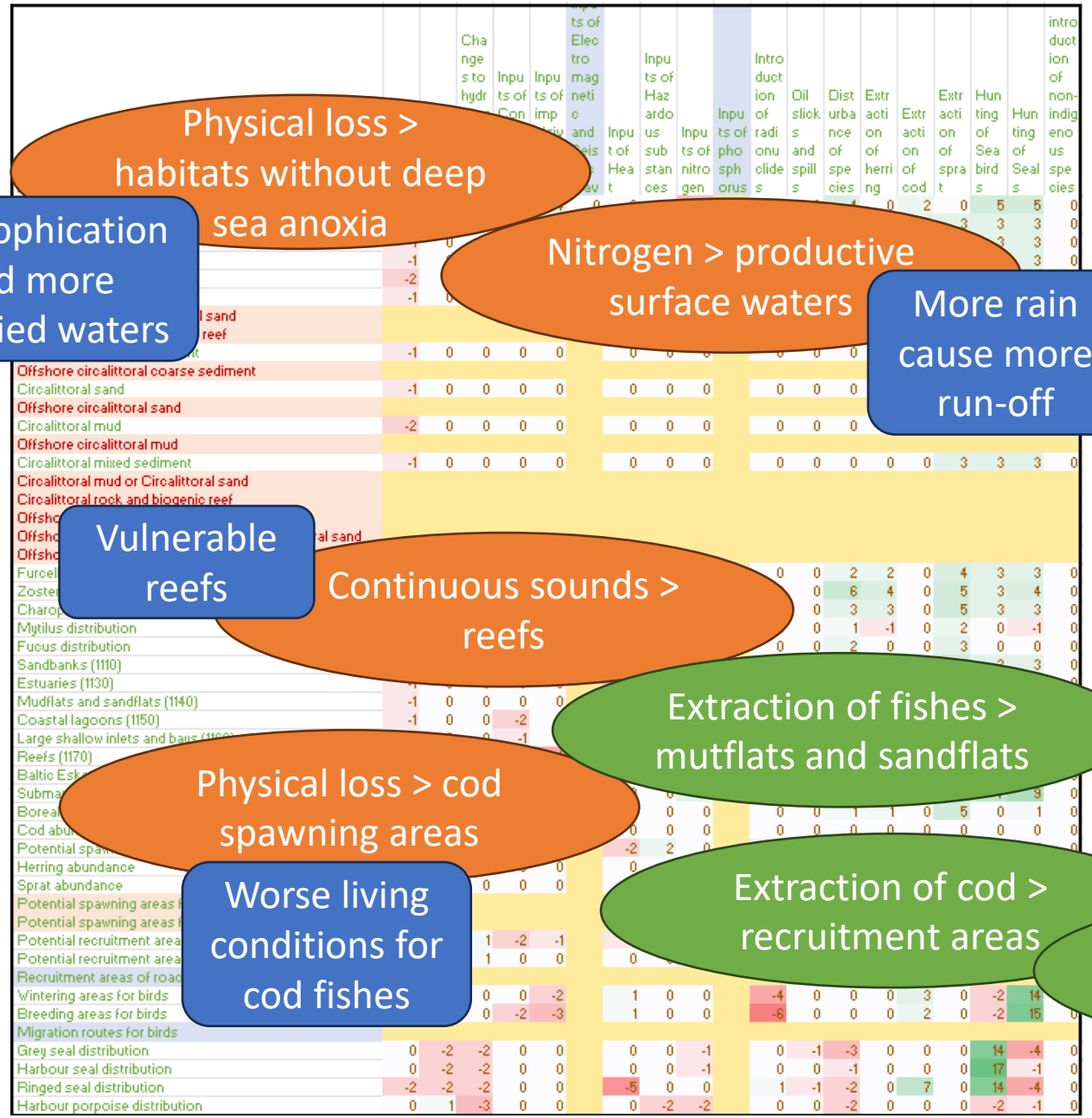


Change in sensitivity scores from

HOLAS 2 (2011-2016[a]) minus

HOLAS 3 (2016-2021[b])

[a]HELCOM 2017a

[b]HELCOM 2023

Negative change: score increase

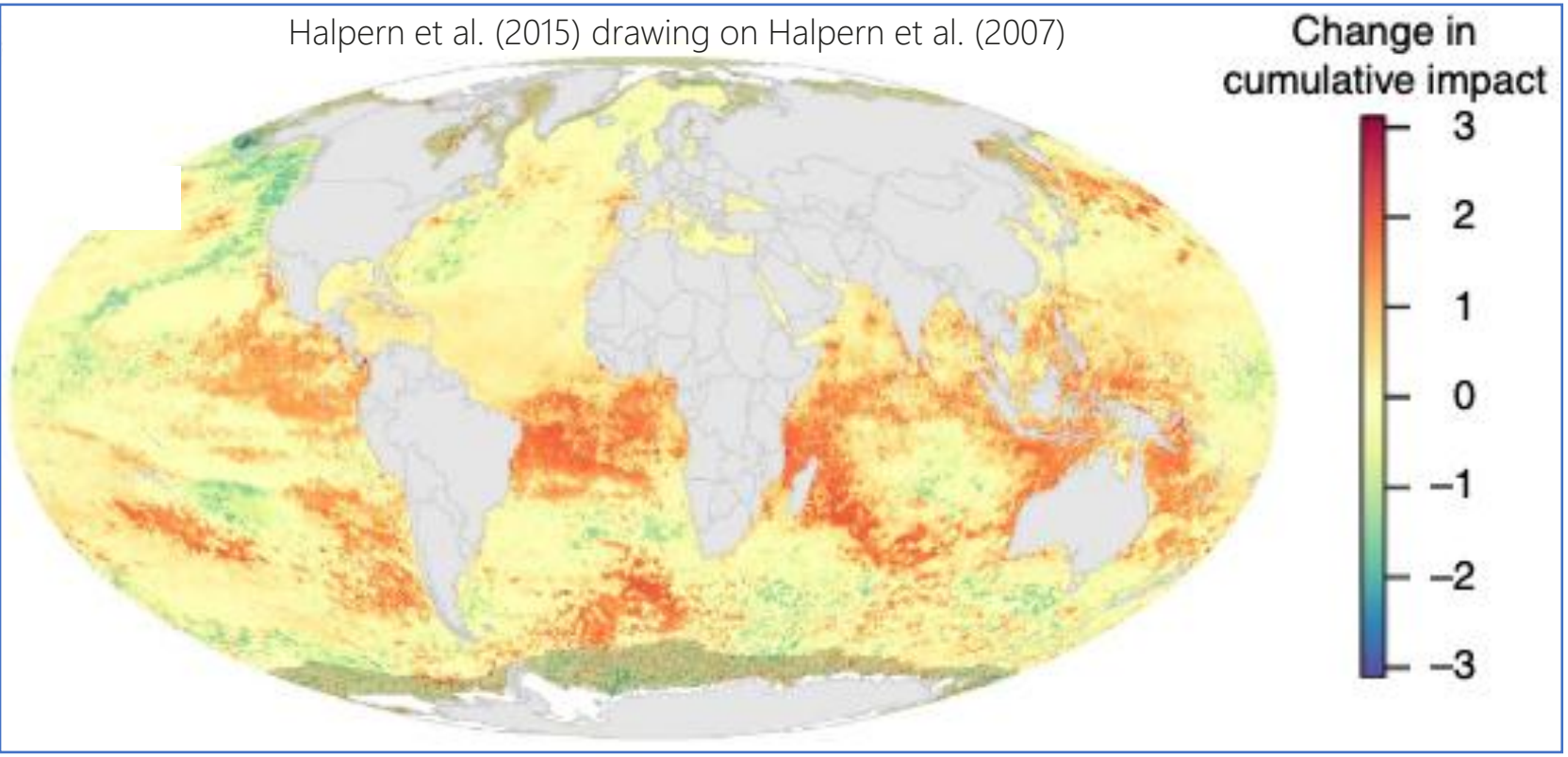
Positive change: score decrease

Missing data

Cumulative impact change over time

Halpern et al. (2007)

Halpern et al. (2015) drawing on Halpern et al. (2007)



Ecosystem-pressure scores in 2008

Intertidal					Coastal				
Rocky intertidal	Intertidal mud	Beds	Mangrove	Salt marsh	Coral reef	Seagrass	Kelp forest	Rocky reef	Suspension/reef feeder reef
1.8	1.1	0.2	1.4	1.4	2.6	2.1	0.0	1.7	0.0
1.3	2.1	0.6	2.1	2.3	1.1	2.0	0.8	1.5	2.8
0.8	0.7	0.0	0.9	1.6	0.9	0.6	0.0	0.5	1.8
2.4	2.1	1.9	2.0	1.5	2.2	1.9	0.8	2.1	2.4
2.2	1.7	0.8	1.1	2.0	1.9	0.4	0.2	1.6	2.4
2.1	2.8	0.1	1.4	1.7	1.2	1.0	1.0	2.2	2.8
2.1	1.6	0.6	0.5	2.0	0.7	0.8	0.0	2.2	2.7

1 stressor. Values are modified from previous values[2]

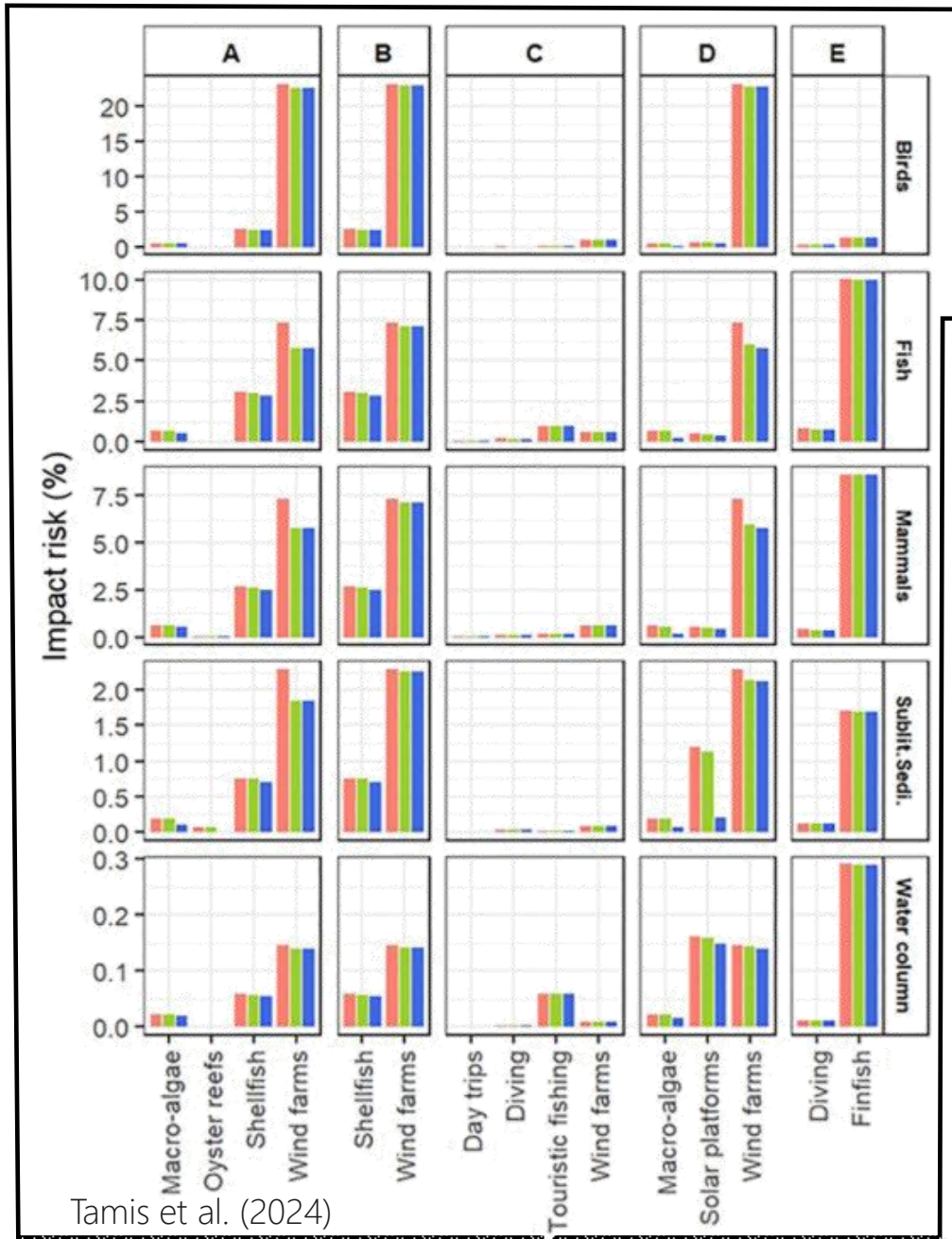
Ecosystem-pressure scores in 2013

Salt Marsh	coral	sea grass	Kelp Fore	rocky reef	Susp.-Fee	shallow	soft shelf	hard shelf	soft slope	hard slope	soft deep	hard deep	seamounts	pelagic	pelagic_deep
.9	1.8	2.1	0.4	1.6	1.4	2.0	1.4	1.7	2.0	0.6	1.3	0.0	0.0	1.2	0.0
.7	1.2	1.0	1.0	2.2	2.8	1.2	1.4	0.0	2.0	0.2	1.7	0.0	0.0	1.9	1.6
.0	0.7	0.8	0.0	2.2	2.7	1.5	2.1	0.2	2.1	0.2	1.8	0.0	0.0	2.3	1.6
.8	1.0	0.5	0.5	0.7	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
.6	2.3	2.5	1.6	2.5	3.0	2.0	1.1	2.9	0.0	0.0	1.6	0.0	0.0	0.9	0.0
.0	1.2	0.2	1.5	2.7	3.1	2.1	3.0	3.1	3.2	2.8	2.3	3.0	3.5	2.1	0.8
.0	1.6	1.1	2.1	2.9	0.7	2.1	2.0	3.2	2.3	2.4	2.0	0.0	0.0	1.6	0.0
dem_nd_lb	0.6	1.4	0.7	0.7	0.8	1.2	0.8	1.6	2.2	0.5	1.6	1.5	2.4	1.8	1.8	1.5	0.0	0.0	1.2	0.0
pel_hb	0.9	0.0	0.1	0.0	0.5	0.5	0.0	0.0	2.6	0.0	0.0	1.1	2.8	0.2	0.0	1.6	0.0	0.0	3.0	2.2
pel_lb	0.0	0.0	0.0	0.0	0.4	0.7	0.0	0.0	2.6	0.0	0.6	0.8	2.8	0.2	0.0	0.5	0.0	0.0	2.2	0.6
artisanal	1.3	0.4	0.7	1.7	0.6	2.3	0.3	0.8	2.2	1.0	0.0	0.9	1.9	0.0	0.4	0.3	0.0	0.9	1.0	0.0
sst	2.8	1.4	0.6	2.4	1.4	2.8	2.1	2.0	1.9	0.8	0.5	2.5	2.9	2.3	0.9	2.5	1.5	1.8	3.3	2.3
uv	0.9	1.3	0.0	0.2	1.1	0.8	0.5	0.1	0.7	0.0	0.3	1.9	1.8	0.0	0.0	1.3	0.0	0.0	1.5	0.0
acid	0.9	1.0	0.0	1.2	1.3	1.1	1.4	0.0	1.1	0.7	0.1	1.7	2.5	2.1	1.6	2.2	2.7	2.7	1.8	0.0
sea level rise	2.5	1.9	2.1	3.0	3.1	2.4	2.6	1.6	1.5	1.8	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
invasives	2.8	2.9	0.9	1.0	2.8	1.5	1.2	1.3	2.5	2.6	2.7	1.6	1.5	0.2	0.5	1.5	0.0	0.0	2.3	0.0
ocean_pollution	1.3	0.8	0.5	1.2	1.2	1.2	0.5	0.1	1.7	0.0	1.1	1.2	0.3	1.4	1.7	2.3	1.2	1.2	1.7	0.4
shipping	0.3	1.9	1.9	2.0	1.4	1.5	1.9	0.0	1.4	0.0	0.3	1.7	0.9	0.1	1.0	0.9	0.0	0.0	1.9	0.0
oil rigs	1.0	0.9	0.8	1.3	0.9	0.5	1.6	0.0	1.7	0.4	0.1	0.5	2.1	1.6	2.2	1.9	1.6	1.4	1.5	0.0

- 12 stressors (a mix of pressures and activities)
- equivalent methods and data sources
- Change in 5 years 2008 to 2013

Halpern et al. (2015)

Decreasing cumulative impacts through multi-use



Tamis et al. (2024)

Single Use

Multi Use 1 = spatial proximity and shared services

Multi Use 2 = integrated infrastructures

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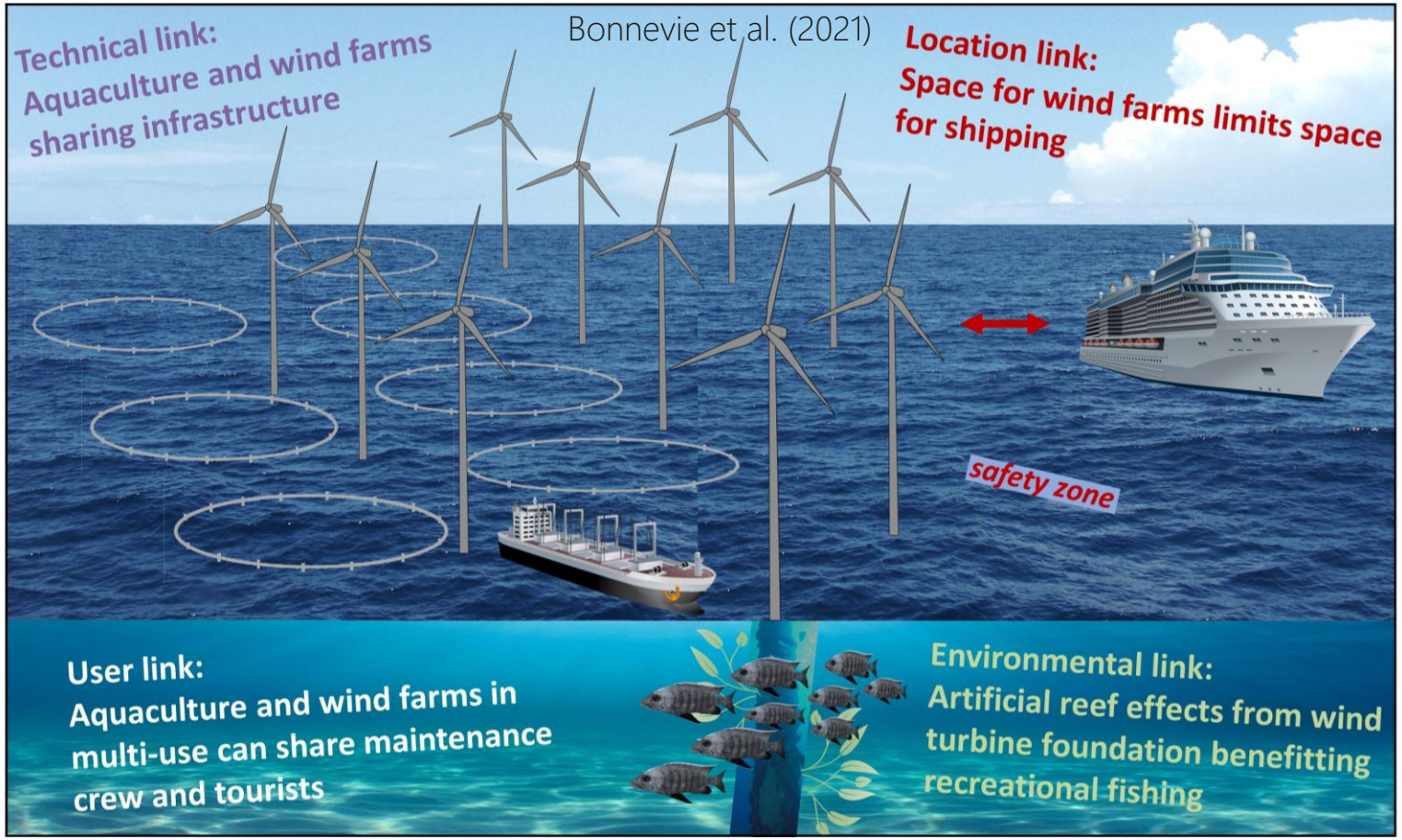

Bonnevie et al. (2021)

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BONUS BASMATI
Baltic Sea Maritime Spatial Planning for Sustainable Ecosystem Services

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Thank you!

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