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Endpoint characterisation modelling for marine eutrophication in LCIA

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Endpoint characterisation modelling for marine eutrophication in LCIA

Session track: Life cycle analysis (LCA) and sustainability
Session LCAS02 – Increasing robustness in LCIA I
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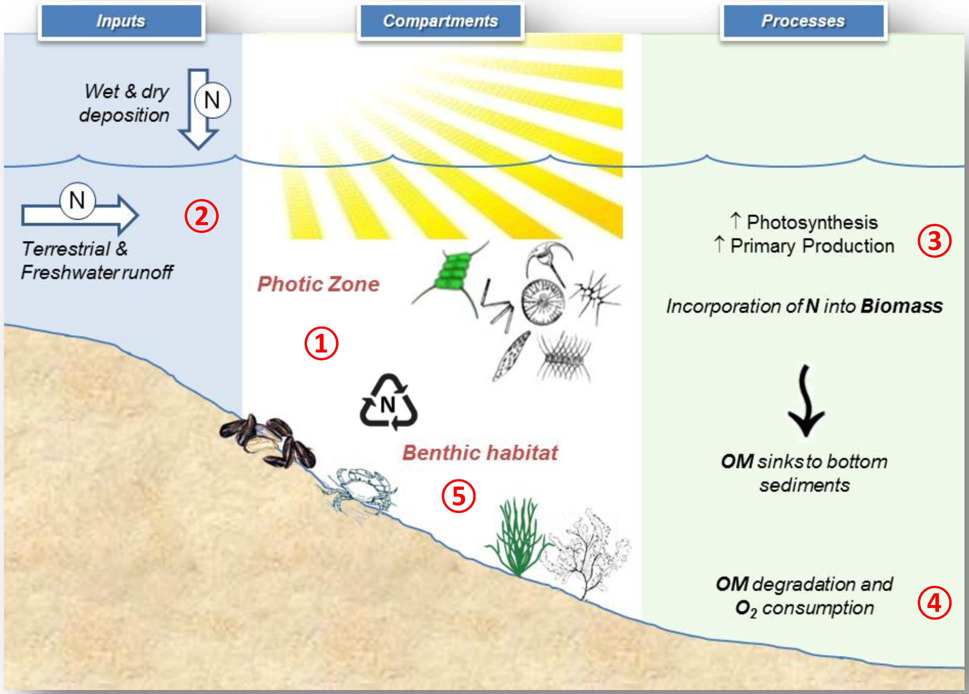
Marine Eutrophication

Ecosystem response to the availability of plant nutrients



① PP sustained by **nutrients** released from microbial and animal metabolism

② **Balance disrupted** by anthropogenic fertilization. **Sources**: run-off from agriculture, atmospheric deposition, and sewage waters

③ Nutrients enrichment promotes **excessive growth** of phytoplankton and macroalgae

④ Bacterial degradation of biomass **consumes dissolved oxygen.** Excessive oxygen depletion may originate hypoxic to anoxic bottom waters

⑤ Sublethal and lethal **effects** on resident biota are expected

Research question

Drivers and goals

Considering that:

- ME impacts depend on the **fate processes** and on the **sensitivity** of the receiving ecosystems
- LCIA still **lacks endpoint characterisation modelling**
- **Spatial differentiation** is essential

Goals:

- Understand the **fate processes** affecting nitrogen loadings to coastal waters
- Estimate factors for the impact characterisation (**CFs**)
- Introducing **spatial differentiation** at a suitable scale

How can CFs for marine eutrophication be defined in a spatially differentiated LCIA endpoint model?

The proposed method

Relates:

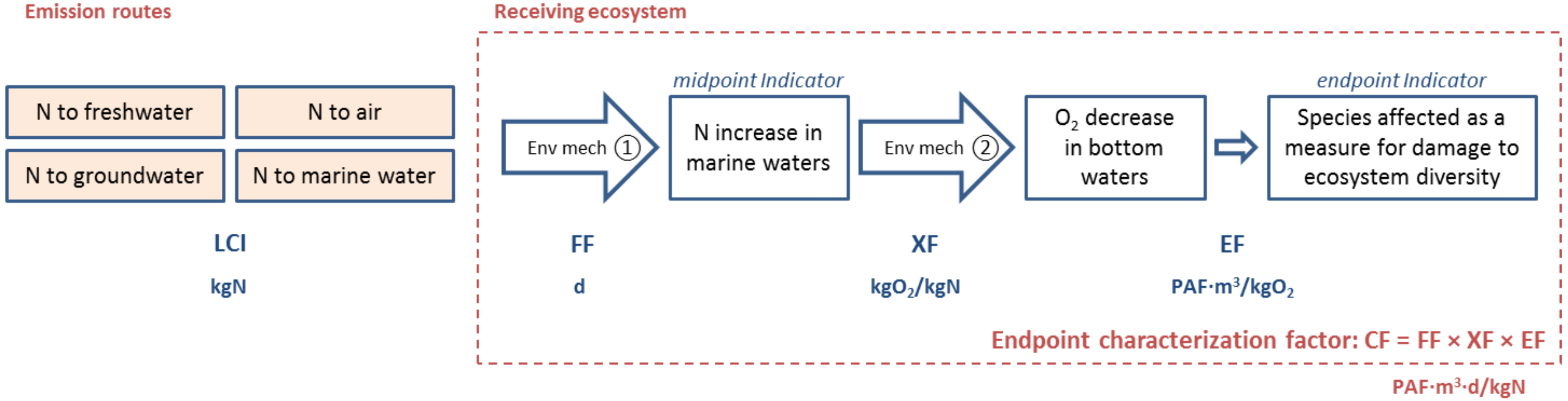
- *Nitrogen loadings*
- *Phytoplankton biomass*
- *Biological response*

Components of the model framework:

- **Fate** modelling:
  - River-N fate models (i.e. from anthropogenic emission sources to export to marine waters)
  - Marine-N fate modelling (i.e. fate of nitrogen in the marine compartment)
- **Exposure** modelling
  (intermediate link from fate to effects, relating photic zone processes with bottom layer processes)
- **Effect** modelling
  (includes the processes leading to impacts on biota)

Model framework

From environmental mechanisms to factors



To define the **Characterisation Factor (CF)** in (PAF·)[m^3·d/kg]:

$$CF_{ij} = FF_{ij} \cdot XF_j \cdot EF_j$$

Where:

- FF_{ij} is the **Fate Factor** [d] for emission route i to receiving ecosystem j
- XF_j is the **Exposure Factor** [kgO_2/kgN] in receiving ecosystem j
- EF_j is the **Effect Factor** (PAF·)[m^3/kgO_2] in receiving ecosystem j

Fate Factor

The FF_{ij} [d] is obtained by:

$$FF_{ij} = \frac{f_{exp\ i}}{\lambda_j}$$

Where:

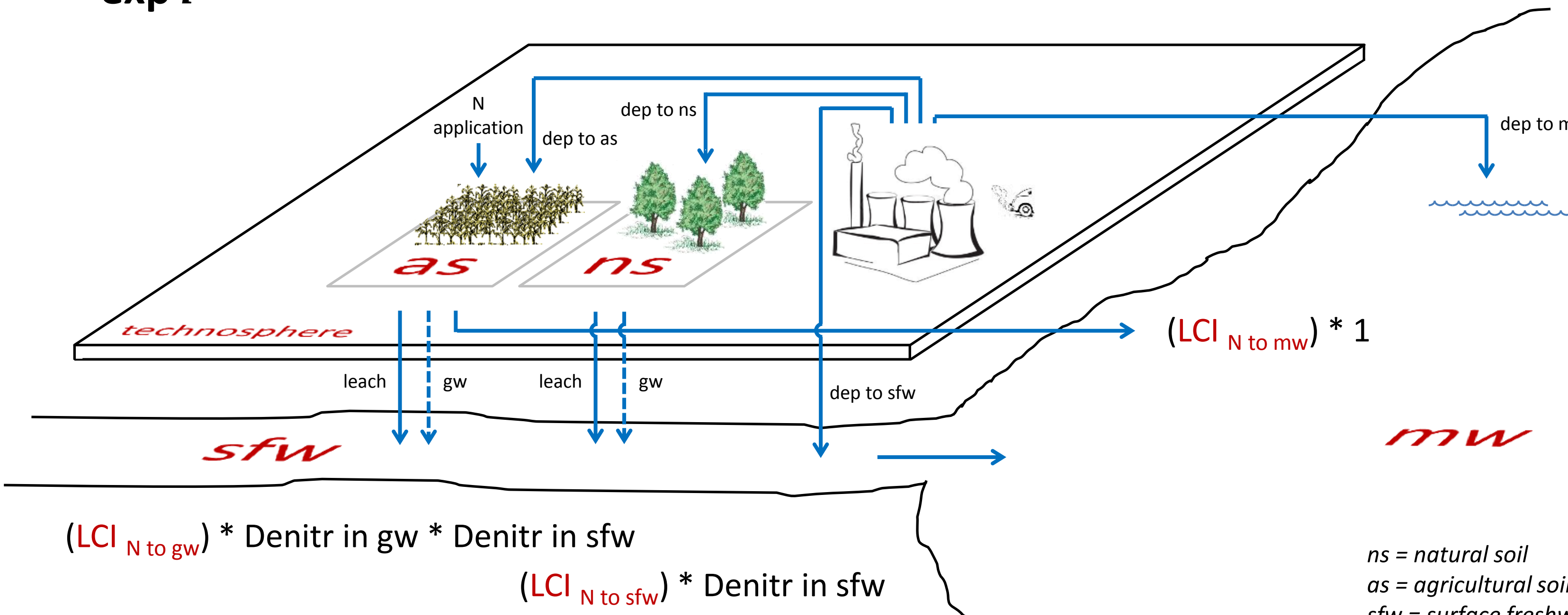
- $f_{\text{exp}\ i}$ [dimensionless] is the fraction of the emitted N that reaches coastal marine waters (exported) calculated for each emission route i
- λ_j [d^{-1}] is the N-loss rate coefficient in receiving ecosystem j

$f_{exp\ i}$	***River-N fate***
λ_j	***Marine-N fate***

River-N fate modelling

Fate modelling and export to marine coastal waters

$$f_{\exp\, i} = \begin{array}{l} (LCI_{\text{N to air}}) * f_{dep} \text{ to sea} * f_{dep} \text{ to mw} + \\ (LCI_{\text{N to air}}) * f \text{ to inland} * f_{dep} \text{ to ns} * f_{leach} \text{ from ns} * \text{Denitr in sfw} + \\ (LCI_{\text{N to air}}) * f \text{ to inland} * f_{dep} \text{ to as} * f_{leach} \text{ from as} * \text{Denitr in sfw} + \\ (LCI_{\text{N to air}}) * f \text{ to inland} * f_{dep} \text{ to sfs} * \text{Denitr in sfw} \end{array}$$



$(LCI_{\text{N to mw}}) * 1$

$(LCI_{\text{N to gw}}) * \text{Denitr in gw} * \text{Denitr in sfw}$

$(LCI_{\text{N to sfw}}) * \text{Denitr in sfw}$

ns = natural soil
as = agricultural soil
sfw = surface freshwater
mw = marine waters

Marine-N fate modelling

Nitrogen losses (λ_j) in the marine compartment may be caused by:

- Denitrification ≈ 30% (Van Drecht et al., 2003)
  (microbial mediated reduction of NO_3^-, NO_2^- and NO into N_2 in bottom sediments)
- Sedimentation ≈ 5% (Nixon et al., 1996)
  (loss to mineralization of N into bottom sediments)
- Advection ≈ 1/τ
  (transport of nitrogen forms or net flushing)

To find residence time (τ):

- Search literature
- Build archetypes:
  - High dynamics & exposure to regional currents: **τ ≈ 3 mo**
  - Medium dynamics & exposure to local currents: **τ ≈ 2 yr**
  - Low dynamics: **τ ≈ 25 yr**
  - Very low dynamics or embayment: **τ ≈ 90 yr**

Marine-N loss rate coefficient (λ_j)

Includes the 3 loss routes:

- *Denitrification*
- *Advection*
- *Sedimentation*

$$\lambda_j = \lambda_{denitr} + \frac{1}{\tau_j} + \lambda_{sed}$$

N-loss routes follow first-order kinetics with a constant removal rate (λ_r)

$$N_t = N_0 \cdot e^{-\lambda_r t}$$

$$\lambda_{denitr} = -\ln(\mathbf{0.70})$$

$$\lambda_{sed} = -\ln(\mathbf{0.95})$$

From literature or archetypes to find τ_j for LME *j*

$$\lambda_{adv} = \frac{1}{\tau_j}$$

Exposure Factor (XF)

The XF_j (unit: kgO_2/kgN) is estimated by:

$$XF_j = \frac{kgOM}{kgN} \times \frac{kgO_2 \times (1-BGE)}{kgOM} \times NIE_j \times VCC$$

$$OM{:}N\ ratio = \frac{M_{biomass}}{M_N} \approx 15.86\ gOM/gN$$

after $106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O \Rightarrow C_{106}H_{263}O_{110}N_{16}P + 138\ O_2$ *(photosynthesis)*

$$O_2{:}OM\ ratio = \frac{M_{O_2}}{M_{biomass}} \approx 1.24\ gO_2/gOM$$

after $(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138\ O_2 \Rightarrow 106\ CO_2 + 122\ H_2O + 16\ HNO_3 + H_3PO_4$ *(respiration)*

$BGE = 0.26$ (del Giorgio & Cole, 1998) then: $\frac{kgO_2 \times (1-BGE)}{kgOM} \approx 0.92\ gO_2/gOM$

BGE is the amount of new bacterial biomass produced per unit organic C substrate assimilated

$$NIE_j = \frac{EmpN_{consumed}}{TheorN_{available}}$$

$EmpN_{consumed} = \frac{DIN}{DIN\ content\ in\ N_{tot}} \times M_N \times A_{LME}$ with $DIN = 10^{(\log PP - 2.332)/0.442}$ (Nixon et al., 1996)

$TheorN_{available} = PP \times M_N / M_C \times A_{LME}$

Nitrogen Incorporation Efficiency expresses the environmental factors affecting PP rates (ecosystem response)

$$VCC = \frac{V_{photic\ habitat}}{V_{benthic\ zone}} = \frac{30}{0.3} = 100$$

Volume Correction Coefficient normalises different volume of photic zone above and benthic habitat at the bottom

Effect Factor (EF)

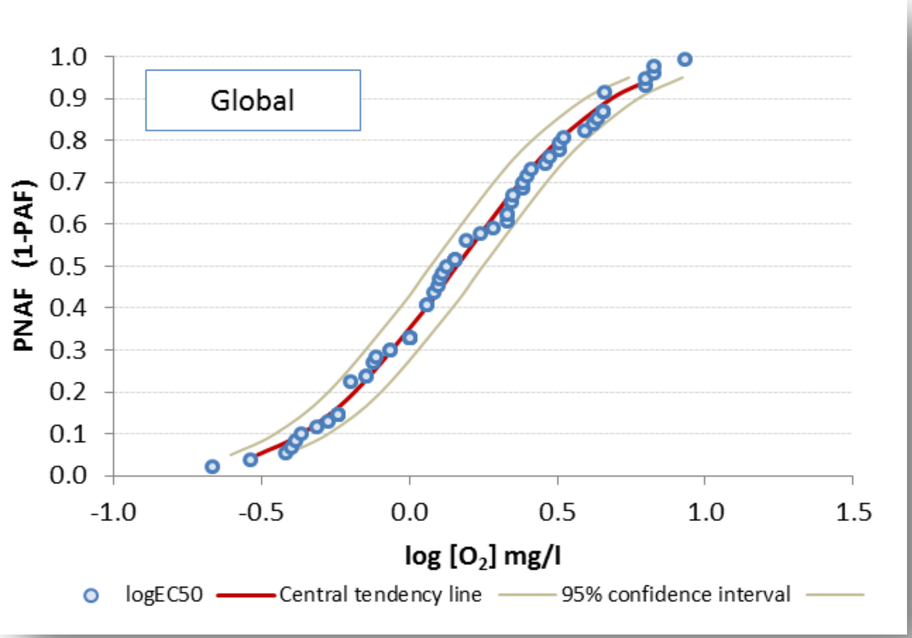
The EF_j (unit: $PAF \cdot m^3/kgO_2$ is estimated by the average gradient method (Pennington et al., 2004)*:*

$$EF = \frac{\Delta PAF}{\Delta [O_2]} = \frac{0.5}{HC_{50}}$$

where $HC_{50} = 10^{avg(logEC_{50})}$

Species sensitivity to hypoxia (EC_{50}) from Vaquer-Sunyer & Duarte (2008)

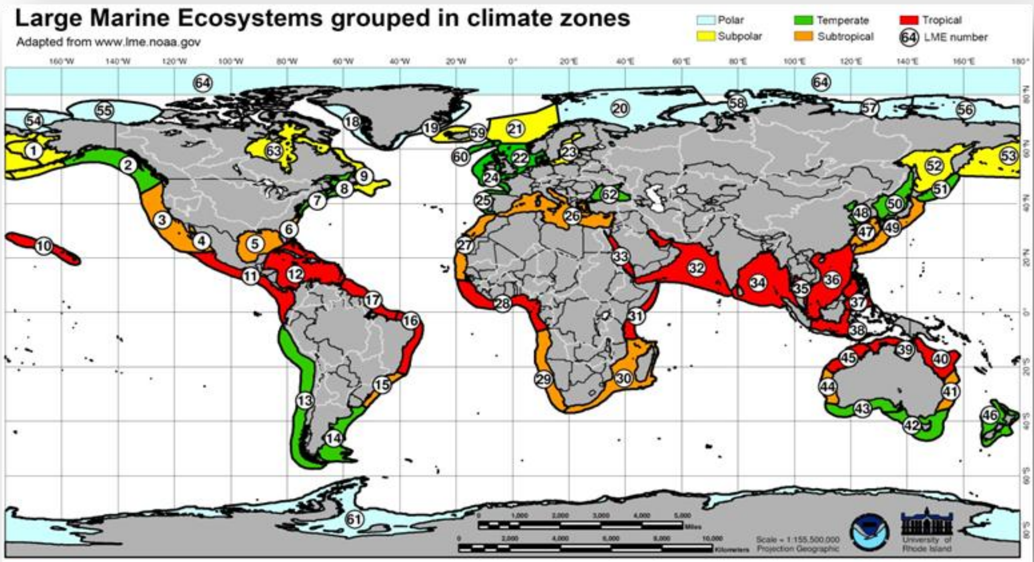
- The Potentially Affected Fraction of species (PAF) is a measure of the loss of biodiversity in the receiving ecosystem
- From Species Sensitivity Distribution (SSD) curves for 5 climate zones + global
- *Probabilistic model that estimates the variability of the sensitivity of individual species to an environmental stressor* (Posthuma et al. 2002)



Grouping EF into climate zones

- *Mean annual Sea Surface Temperature (maSST)*
- *Latitudinal distribution*
- *Köppen-Geiger climate classification system*

Climate zone	LME	taxa	n	α	β	Slope	Inters.	R^2	HC50 (mgO_2/L)	mg/L (kgO_2/m^3)	EF ($PAF.m^3/kgO_2$)
Polar	11	20	20	0.220	0.344	2.632	4.371	0.924	**1.661**	1.66E-03	**3.01E+02**
Subpolar	7	33	33	0.207	0.541	2.408	4.460	0.954	**1.611**	1.61E-03	**3.10E+02**
Temperate	16	55	55	0.133	0.723	2.361	4.659	0.981	**1.357**	1.36E-03	**3.68E+02**
Subtropical	13	41	41	0.228	0.554	2.492	4.414	0.981	**1.691**	1.69E-03	**2.96E+02**
Tropical	17	19	19	0.165	0.247	2.932	4.495	0.914	**1.461**	1.46E-03	**3.42E+02**
Global	64	65	65	0.149	0.735	2.443	4.612	0.984	**1.409**	1.41E-03	**3.55E+02**

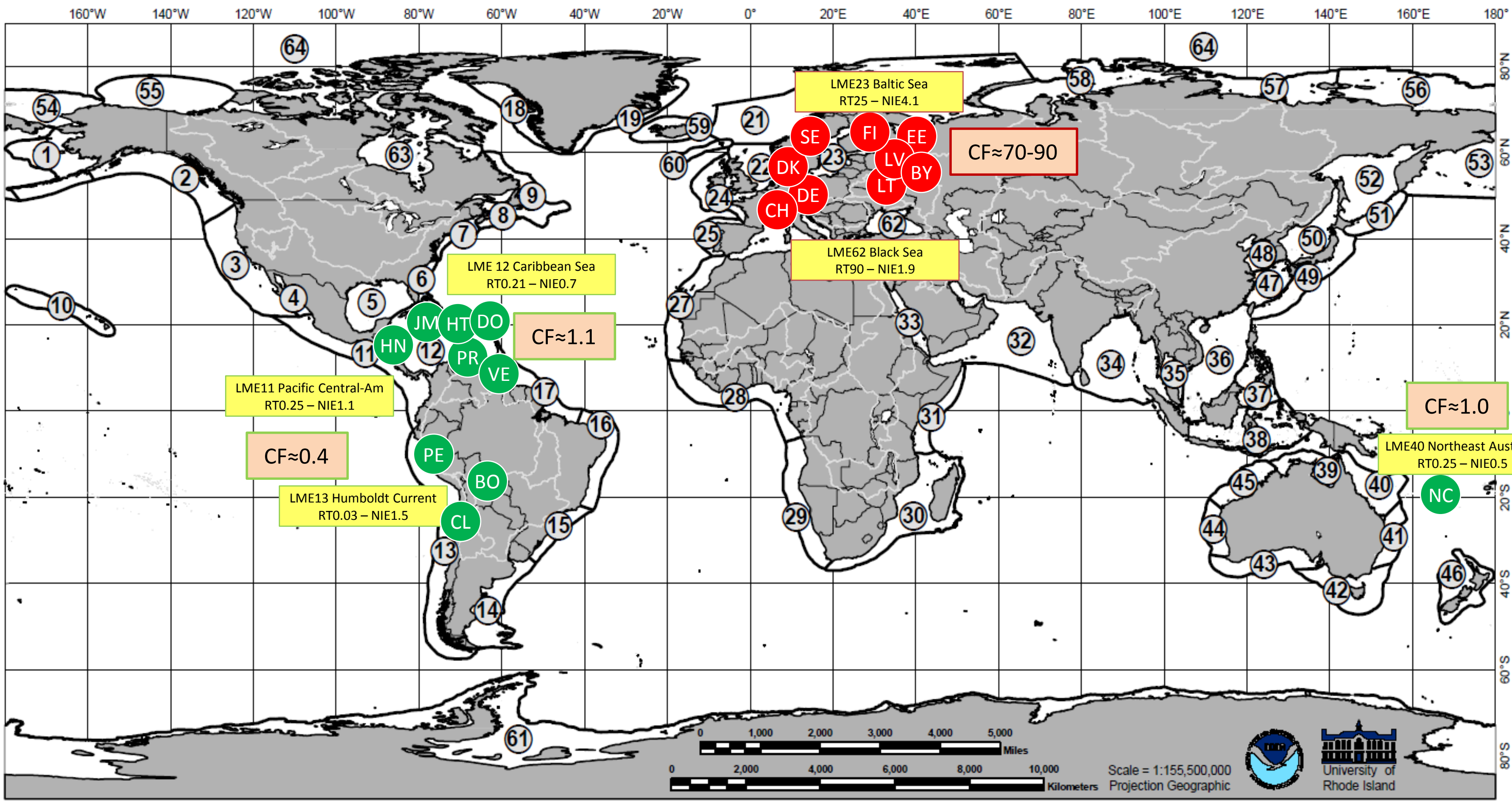


Adapted from www.lme.noaa.gov

ID LME name	maSST 1957-2005 regression coeff. b	 a	Calculation: $maSST_{2005} = b \times 2005 + a$ Estimation mean annual SST 2005	Classification Climate zone
64. Arctic Ocean	*ice covered all year*		***-1.2***	Polar
55. Beaufort Sea	0.0034	-8.1379	**-1.2**	Polar
61. Antarctic	0.0023	-5.7893	**-1.2**	Polar
56. East Siberian Sea	0.0075	-16.1415	**-1.1**	Polar
57. Laptev Sea	0.0065	-13.6953	**-0.8**	Polar
58. Kara Sea	0.0061	-12.8746	**-0.5**	Polar
54. Chukchi Sea	0.0118	-23.6389	**-0.1**	Polar
63. Hudson Bay	0.0120	-23.1076	**1.0**	Polar
18. West Greenland Shelf	0.0086	-16.2938	**1.0**	Polar
19. East Greenland Shelf	0.0104	-18.9583	**1.9**	Polar
20. Barents Sea	-0.0008	4.8359	**3.3**	Polar
52. Sea of Okhotsk	0.0100	-15.4208	**4.6**	Subpolar
1. East Bering Sea	0.0094	-13.6712	**5.1**	Subpolar
53. West Bering Sea	0.0097	-14.3607	**5.2**	Subpolar
9. Newfoundland-Labrador Shelf	0.0157	-25.9772	**5.6**	Subpolar
59. Iceland Shelf	-0.0022	10.3775	**6.0**	Subpolar
23. Baltic Sea	0.0153	-22.3495	**8.3**	Subpolar
21. Norwegian Sea	0.0036	1.2815	**8.6**	Subpolar
51. Oyashio Current	0.0097	-12.4524	**7.0**	Temperate
8. Scotian Shelf	0.0235	-38.7342	**8.4**	Temperate
60. Faroe Plateau	-0.0030	15.5008	**9.6**	Temperate
2. Gulf of Alaska	0.0078	-6.0887	**9.6**	Temperate
22. North Sea	0.0179	-25.3213	**10.5**	Temperate
14. Patagonian Shelf	0.0031	4.6785	**10.8**	Temperate
7. Northeast U.S. Continental Shelf	0.0221	-31.7350	**12.6**	Temperate
24. Celtic-Biscay Shelf	0.0083	-3.5225	**13.1**	Temperate
50. Sea of Japan/East Sea	0.0167	-19.9861	**13.4**	Temperate
62. Black Sea	-0.0017	18.2366	**14.9**	Temperate
42. Southeast Australia	0.0108	-6.8315	**14.9**	Temperate
46. New Zealand Shelf	0.0023	10.8093	**15.4**	Temperate
48. Yellow Sea	0.0197	-24.1103	**15.4**	Temperate
13. Humboldt Current	0.0083	-0.1418	**16.5**	Temperate
25. Iberian Coastal	0.0162	-15.5848	**17.0**	Temperate
43. Southwest Australia	0.0086	0.0699	**17.2**	Temperate
3. California Current	0.0065	4.3347	**17.4**	Subtropical
26. Mediterranean	0.0088	2.2496	**20.0**	Subtropical
29. Benguela Current	0.0054	9.9577	**20.7**	Subtropical
27. Canary Current	0.0098	2.4479	**22.0**	Subtropical
47. East China Sea	0.0317	-41.3278	**22.2**	Subtropical
44. West-Central Australia	0.0167	-11.1084	**22.4**	Subtropical
15. South Brazil Shelf	0.0228	-22.8069	**22.9**	Subtropical
49. Kuroshio Current	0.0132	-3.4566	**23.0**	Subtropical
41. East-Central Australia	0.0115	-0.0330	**23.0**	Subtropical
4. Gulf of California	0.0254	-26.4000	**24.5**	Subtropical
6. Southeast U.S. Continental Shelf	-0.0031	31.0589	**24.8**	Subtropical
30. Agulhas Current	0.0139	-2.4145	**25.5**	Subtropical
5. Gulf of Mexico	0.0038	18.4183	**26.1**	Subtropical
10. Insular Pacific-Hawaiian	0.0006	23.6974	**25.0**	Tropical
40. Northeast Australia	0.0095	7.7313	**26.7**	Tropical
16. East Brazil Shelf	0.0116	3.9558	**27.2**	Tropical
31. Somali Coastal Current	0.0094	8.4143	**27.3**	Tropical
11. Pacific Central-American	0.0060	15.4948	**27.5**	Tropical
28. Guinea Current	0.0118	3.8046	**27.6**	Tropical
32. Arabian Sea	0.0085	10.5733	**27.7**	Tropical
12. Caribbean Sea	0.0005	26.7566	**27.8**	Tropical
45. Northwest Australia	0.0086	10.5848	**27.8**	Tropical
17. North Brazil Shelf	0.0044	19.0068	**27.9**	Tropical
36. South China Sea	0.0163	-4.5643	**28.0**	Tropical
33. Red Sea	0.0060	16.1768	**28.1**	Tropical
39. North Australia	0.0085	11.1456	**28.2**	Tropical
34. Bay of Bengal	0.0102	8.3154	**28.7**	Tropical
38. Indonesian Sea	0.0109	6.9714	**28.7**	Tropical
35. Gulf of Thailand	0.0082	12.3672	**28.9**	Tropical
37. Sulu-Celebes Sea	0.0126	3.6460	**29.0**	Tropical

Spatial differentiation of the model results

Geographical distribution of the countries showing the Top10 (red) and Bottom10 (green) CFs (emissions to surface freshwater). ***CF unit = ×10³ PAF·m³·d/kgN***



Sensitivity analysis

Sensitivity Ratios (SR) were calculated by:

$$SR_X = \frac{(CF_{end} - CF_{start})/CF_{start}}{(X_{end} - X_{start})/X_{start}}$$

(Strandesen et al., 2007)

Tested input parameters:

- f_{exp} (in FF)
- Sedimentation rate (in FF)
- Denitrification rate (in FF)
- Residence time (LME) (in FF)
- BGE (in XF)
- PP rate (in XF)
- VCC (in XF)
- HC_{50} value (in EF)

Independent 10% variation of each input parameter

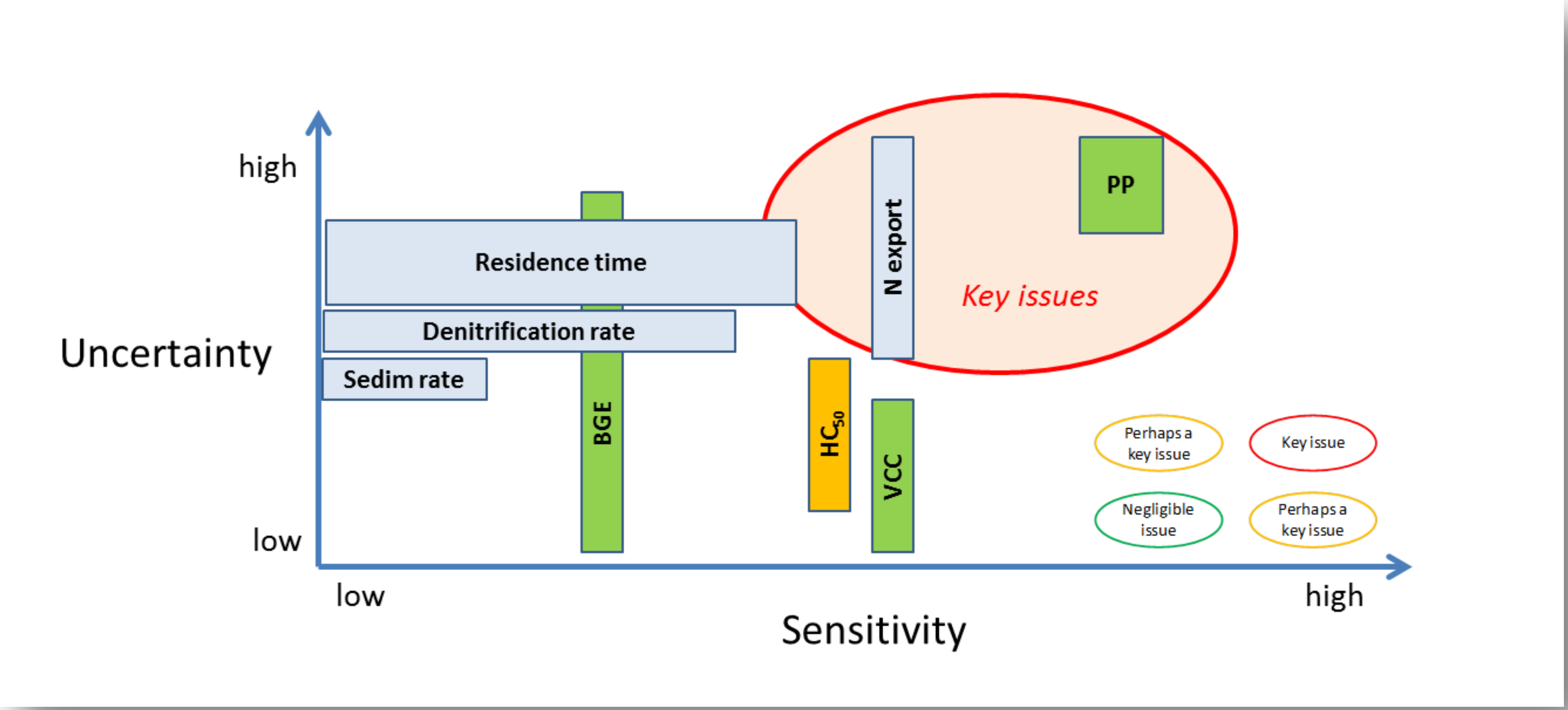
Uncertainty estimation

Extreme values of possible variation range

- f_{exp} for countries exporting to multiple receiving LME: **null to total export**
- Sedimentation rate: **5% to 8%** (Nixon et al., 1996)
- Denitrification rate: **30% to 52.7%** (Van Drecht et al., 2003 and Wollheim et al., 2008)
- Residence time: **lower to upper archetype or -50%/+50% of used value**
- BGE: **0.01 to 0.69** (del Giorgio & Cole, 1998)
- PP rates datasets show discrepancies between different sources: **high uncertainty**
- VCC is a model decision: **low uncertainty**

Key issues

Combining sensitivity and uncertainty



Data quality improvement

Effort investment vs. return analysis

- Sed and Denitr rates – **high** investment and **low** return
- VCC – **high** investment and **medium** return
- BGE – **medium** investment and **low** return
- Expanding the EC_{50} dataset – **high** investment and **medium** return
- RT – **high** investment and **medium** return
- f_{exp} (N-export splitting) – **medium** investment and **high** return
- PP datasets – **low** investment and **high** return

Increasing priority

Weaknesses

- Dependency on third-party models (emissions, deposition)
- Dependency on the LCI model for the spatial aggregation of CF and NFs
- Unknown uncertainty associated with these ‘input’ models
- Low confidence on PP dataset
- No spatial differentiation for marine sedimentation and denitrification rates in the FF

Strengths

- Endpoint modelling
- Transparent and reproducible FFs, XFs, and EFs
- Spatially differentiated CFs
- High geographic applicability
- CFs and NFs for 233 Country-to-LME and 143 countries for 4 N-emission routes
- Global default CF and NF
- Key issues for data quality improvement identified

Thank you for your attention

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