Endpoint characterisation modelling for marine eutrophication in LCIA

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Endpoint characterisation modelling for marine eutrophication in LCIA

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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)
To define the **Characterisation Factor (CF)** in (PAF·)[m³·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** [kgO₂/kgN] in receiving ecosystem *j**
- **EF}_j is the **Effect Factor** (PAF·)[m³/kgO₂] in receiving ecosystem *j**
The $FF_{ij}$ [d] is obtained by:

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

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

<table>
<thead>
<tr>
<th>$f_{exp \ i}$</th>
<th>River-N fate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_j$</td>
<td>Marine-N fate</td>
</tr>
</tbody>
</table>
River-N fate modelling
Fate modelling and export to marine coastal waters

\[ f_{\text{exp}i} = (\text{LCI}_N \text{ to air}) * f_{\text{dep to sea}} * f_{\text{dep to mw}} + (\text{LCI}_N \text{ to air}) * f_{\text{to inland}} * f_{\text{dep to ns}} * f_{\text{leach from ns}} * \text{Denitr in sfw} + (\text{LCI}_N \text{ to air}) * f_{\text{to inland}} * f_{\text{dep to as}} * f_{\text{leach from as}} * \text{Denitr in sfw} + (\text{LCI}_N \text{ to air}) * f_{\text{to inland}} * f_{\text{dep to sfs}} * \text{Denitr in sfw} + (\text{LCI}_N \text{ to gw}) * \text{Denitr in gw} * \text{Denitr in sfw} + (\text{LCI}_N \text{ to sfw}) * \text{Denitr in sfw} \]

ns = natural soil
as = agricultural soil
sfw = surface freshwater
mw = marine waters
Marine-N fate modelling

Nitrogen losses ($\lambda_j$) in the marine compartment may be caused by:

- **Denitrification** $\approx 30\%$ (Van Drecht et al., 2003)
  
  *(microbial mediated reduction of $\text{NO}_3^-$, $\text{NO}_2^-$ and $\text{NO}$ into $\text{N}_2$ in bottom sediments)*

- **Sedimentation** $\approx 5\%$ (Nixon et al., 1996)
  
  *(loss to mineralization of $\text{N}$ into bottom sediments)*

- **Advection** $\approx 1/\tau$
  
  *(transport of nitrogen forms or net flushing)*

To find residence time ($\tau$):

- Search literature
- Build archetypes:
  - High dynamics & exposure to regional currents: $\tau \approx 3\text{ mo}$
  - Medium dynamics & exposure to local currents: $\tau \approx 2\text{ yr}$
  - Low dynamics: $\tau \approx 25\text{ yr}$
  - Very low dynamics or embayment: $\tau \approx 90\text{ yr}$
Marine-N loss rate coefficient ($\lambda_j$)

**Includes the 3 loss routes:**
- Denitrification
- Advection
- Sedimentation

N-loss routes follow first-order kinetics with a constant removal rate ($\lambda_r$)

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

\[ \lambda_{denitr} = -\ln(0.70) \]

\[ \lambda_{sed} = -\ln(0.95) \]

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

From literature or archetypes to find $\tau_j$ 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** = \(\frac{M_{\text{biomass}}}{M_N}\) ≈ 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** = \(\frac{M_{O_2}}{M_{\text{biomass}}}\) ≈ 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: \(\frac{kgO_2 \times (1 - BGE)}{kgOM}\) ≈ 0.92 gO\(_2\)/gOM

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

\[
NIE_j = \frac{EmpN_{\text{consumed}}}{TheorN_{\text{available}}}
\]

\[
EmpN_{\text{consumed}} = \frac{DIN}{\text{DIN content in } N_{\text{tot}}} \times M_N \times A_{LME}
\]

with \(DIN = 10^{(\log PP - 2.332)/0.442}\) (Nixon et al., 1996)

**TheorN_{\text{available}}** = \(PP \times \frac{M_N}{M_C} \times A_{LME}\)

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

\[
VCC = \frac{V_{\text{photic habitat}}}{V_{\text{benthic zone}}} = \frac{30}{0.3} = 100
\]

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

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

where \( HC_{50} = 10^{avg(\log EC_{50})} \)

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

Effect Factor (EF)
Grouping EF into climate zones

Mean annual Sea Surface Temperature (maSST)

Latitudinal distribution

Köppen-Geiger climate classification system

### Large Marine Ecosystems grouped in climate zones

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>LME name</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar</td>
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<td>Polar</td>
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<tr>
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<tr>
<td>Tropical</td>
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<td>Tropical</td>
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<tr>
<td>Global</td>
<td></td>
<td>Global</td>
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</table>

### Calculation: maSST 2005 = b × 2005 + a

<table>
<thead>
<tr>
<th>LME name</th>
<th>Estimate mean annual SST 2005</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Ocean</td>
<td>1.2</td>
<td>Polar</td>
</tr>
<tr>
<td>Beaufort Sea</td>
<td>-1.2</td>
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</tr>
<tr>
<td>Antarctic</td>
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</tr>
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<td>Siberian</td>
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<td>Polar</td>
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<td>Luso</td>
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</tr>
<tr>
<td>Kara</td>
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<td>Polar</td>
</tr>
<tr>
<td>Chukchi</td>
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<td>Polar</td>
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<tr>
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<tr>
<td>East Greenland</td>
<td>1.9</td>
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<td>Barents</td>
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<tr>
<td>West Bering</td>
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<tr>
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<td>Southern California-Baja California</td>
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<tr>
<td>Northeast Australia</td>
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<tr>
<td>East Brazil</td>
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<td>Guinea Current</td>
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<tr>
<td>Red</td>
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<tr>
<td>Australia</td>
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<tr>
<td>Sub-Celados</td>
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</tbody>
</table>

### Endpoint characterisation modelling for marine eutrophication in LCIA

**Endpoint**: Characterisation modelling for marine eutrophication in LCIA

- **LME**: Large Marine Ecosystem
- **ID**: Identification number
- **EF**: Eutrophication factor
- **mg O2/L**: Milligrams of oxygen per liter
- **kg O2/m³**: Kilograms of oxygen per cubic meter
- **PAF.m³/kgO2**: Production and accumulation factor
- **Calculation**: maSST 2005 = b × 2005 + a

Adapted from www.lme.noaa.gov
Spatial differentiation of the model results

Geographical distribution of the countries showing the Top10 (red) and Bottom10 (green) CFs (emissions to surface freshwater). $CF \text{ unit} = \times 10^3 \text{ PAF} \cdot m^3 \cdot d/\text{kgN}$
Sensitivity analysis

Sensitivity Ratios (SR) were calculated by:

\[ SR_X = \frac{(CF_{\text{end}} - CF_{\text{start}}) / CF_{\text{start}}}{(X_{\text{end}} - X_{\text{start}}) / X_{\text{start}}} \]

(Strandesen et al., 2007)

Tested input parameters:
- \( f_{\text{exp}} \) (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\textsubscript{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*

![Diagram showing sensitivity and uncertainty analysis for marine eutrophication in LCIA.](diagram_image)
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
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

References:


