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 \( j \)
Fate Factor

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 $j$

River-N fate

Marine-N fate
River-N fate modelling
Fate modelling and export to marine coastal waters

\[ f_{\text{exp}} = \]

\[
\begin{align*}
(\text{LCI N to air}) & \times f_{\text{dep}} \text{ to sea} \times f_{\text{dep}} \text{ to mw} + \\
(\text{LCI N to air}) & \times f \text{ to inland} \times f_{\text{dep}} \text{ to ns} \times f_{\text{leach}} \text{ from ns} \times \text{Denitr in sfw} + \\
(\text{LCI N to air}) & \times f \text{ to inland} \times f_{\text{dep}} \text{ to as} \times f_{\text{leach}} \text{ from as} \times \text{Denitr in sfw} + \\
(\text{LCI N to air}) & \times f \text{ to inland} \times f_{\text{dep}} \text{ to sfs} \times \text{Denitr in sfw} + \\
(\text{LCI N to air}) & \times f \text{ to inland} \times f_{\text{exp}} \text{ i} \times 1
\end{align*}
\]

\( ns = \text{natural soil} \)
\( as = \text{agricultural soil} \)
\( sfw = \text{surface freshwater} \)
\( mw = \text{marine waters} \)
Nitrogen losses ($\lambda_j$) 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** ≈ $1/\tau$
  *(transport of nitrogen forms or net flushing)*

To find residence time ($\tau$):

- Search literature
- Build archetypes:
  - High dynamics & exposure to regional currents: $\tau \approx 3$ mo
  - Medium dynamics & exposure to local currents: $\tau \approx 2$ yr
  - Low dynamics: $\tau \approx 25$ yr
  - Very low dynamics or embayment: $\tau \approx 90$ 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 ($\lambda_r$)

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

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

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

From literature or archetypes to find $\tau_j$ for LME $j$

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

$$\lambda_j = \lambda_{\text{denitr}} + \frac{1}{\tau_j} + \lambda_{\text{sed}}$$
**OM: N ratio** = \( \frac{M_{\text{biomass}}}{M_N} \approx 15.86 \, \text{gOM/gN} \)

after \( 106 \, \text{CO}_2 + 16 \, \text{HNO}_3 + \text{H}_3\text{PO}_4 + 122 \, \text{H}_2\text{O} \Rightarrow C_{106}H_{263}O_{110}N_{16}P + 138 \, \text{O}_2 \) (photosynthesis)

**O}_2: \text{OM ratio} = \frac{M_{O_2}}{M_{\text{biomass}}} \approx 1.24 \, \text{gO}_2/\text{gOM} \)

after \((\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 138 \, \text{O}_2 \Rightarrow 106 \, \text{CO}_2 + 122 \, \text{H}_2\text{O} + 16 \, \text{HNO}_3 + \text{H}_3\text{PO}_4 \) (respiration)

**BGE = 0.26** (del Giorgio & Cole, 1998) then: \( \frac{\text{kgO}_2 \times (1 - \text{BGE})}{\text{kgOM}} \approx 0.92 \, \text{gO}_2/\text{gOM} \)

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

\[ NIE_j = \frac{\text{EmpN}_{\text{consumed}}}{\text{TheorN}_{\text{available}}} \]

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

\[ \text{TheorN}_{\text{available}} = PP \times M_N/M_c \times A_{\text{LME}} \]

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

**Endpoint characterisation modelling for marine eutrophication in LCIA**
Effect Factor (EF)

The EF, (unit: PAF·m³/kgO₂) is estimated by the average gradient method (Pennington et al., 2004):

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

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

Species sensitivity to hypoxia (EC₅₀) 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**

### Large Marine Ecosystems grouped in climate zones

- **Climate zone**: Polar, Subpolar, Subtropical, Tropical
- **LME name**: Various global and regional LMEs
- **taxa**: Number of species
- **n**: Number of LMEs
- **α**: Estimation mean annual SST 2005
- **β**: Regression coeff. maSST 1957-2005
- **Slope**: Regression coefficient of maSST 1957-2005
- **Inters.**: Interception of regression of maSST 1957-2005
- **r²**: Coefficient of determination of regression of maSST 1957-2005
- **HC50**: 50th percentile of EF
- **mgO₂/L**: Concentration of oxygen in mg/L
- **kgO₂/m³**: Concentration of oxygen in kg/m³
- **PAF.m³/kgO₂**: Partitioning of EF

### Calculation

\[
\text{maSST}_{1957-2005} = b \times 2005 + a
\]

### Global Summary

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>Polar</th>
<th>Subpolar</th>
<th>Subtropical</th>
<th>Tropical</th>
<th>Global</th>
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</thead>
<tbody>
<tr>
<td>LME name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>taxa</td>
<td>64</td>
<td>65</td>
<td>65</td>
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</tr>
<tr>
<td>n</td>
<td>11</td>
<td>7</td>
<td>13</td>
<td>17</td>
<td>64</td>
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<tr>
<td>α</td>
<td>0.220</td>
<td>0.207</td>
<td>0.133</td>
<td>0.165</td>
<td>0.149</td>
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<tr>
<td>β</td>
<td>0.344</td>
<td>0.541</td>
<td>0.723</td>
<td>0.247</td>
<td>0.735</td>
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<tr>
<td>Slope</td>
<td>2.632</td>
<td>2.408</td>
<td>2.361</td>
<td>2.492</td>
<td>2.443</td>
</tr>
<tr>
<td>Inters.</td>
<td>4.371</td>
<td>4.460</td>
<td>4.659</td>
<td>4.414</td>
<td>4.612</td>
</tr>
<tr>
<td>r²</td>
<td>0.924</td>
<td>0.954</td>
<td>0.981</td>
<td>0.914</td>
<td>0.984</td>
</tr>
<tr>
<td>HC50 mg/L</td>
<td>1.661</td>
<td>1.611</td>
<td>1.357</td>
<td>1.691</td>
<td>1.409</td>
</tr>
<tr>
<td>EF</td>
<td>3.01E+02</td>
<td>3.10E+02</td>
<td>3.68E+02</td>
<td>2.96E+02</td>
<td>3.55E+02</td>
</tr>
</tbody>
</table>

### LME Specifics

- **South China Sea**: 26.7 C, 15.5 C, 15.5 C, 15.5 C
- **Bering Sea**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **East China Sea**: 23.0 C, 23.0 C, 23.0 C, 23.0 C
- **Sea of Japan**: 23.0 C, 23.0 C, 23.0 C, 23.0 C
- **East Siberian Sea**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **Sea of Okhotsk**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **Sea of Japan**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **East China Sea**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **Sea of Japan**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **East Siberian Sea**: 22.4 C, 22.4 C, 22.4 C, 22.4 C
- **Sea of Okhotsk**: 22.4 C, 22.4 C, 22.4 C, 22.4 C

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Adapted from www.lme.noaa.gov

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**DTU**

**LC-IMPACT**
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 = \times10^3 \text{PAF} \cdot \text{m}^3 \cdot \text{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

- $f_{\text{exp}}$ 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

![Graph showing sensitivity and uncertainty for marine eutrophication with key issues identified.]
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
- $f_{\text{exp}}$ (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

References:


