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)
Model framework

*From environmental mechanisms to factors*

To define the **Characterisation Factor** (CF) in \( (\text{PAF} \cdot \text{m}^3/\text{d/kg}) \):

\[
CF_{ij} = FF_{ij} \cdot XF_j \cdot EF_j
\]

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\(\cdot\))[m\(^3\)/kgO\(_2\)] 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 $j$
River-N fate modelling

Fate modelling and export to marine coastal waters

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

\[ (\text{LCI N to air}) * f_{\text{dep}} \text{ to sea} * f_{\text{dep}} \text{ to mw} + \]
\[ (\text{LCI N to air}) * f \text{ to inland} * f_{\text{dep}} \text{ to ns} * f_{\text{leach}} \text{ from ns} * \text{Denitr in sfw} + \]
\[ (\text{LCI N to air}) * f \text{ to inland} * f_{\text{dep}} \text{ to as} * f_{\text{leach}} \text{ from as} * \text{Denitr in sfw} + \]
\[ (\text{LCI N to air}) * f \text{ to inland} * f_{\text{dep}} \text{ to sfs} * \text{Denitr in sfw} \]

\[ (\text{LCI N to gw}) * \text{Denitr in gw} * \text{Denitr in sfw} \]

\[ (\text{LCI N to sfw}) * \text{Denitr in sfw} \]

\[ (\text{LCI N to mw}) * 1 \]

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** ≈ 30% (Van Drecht et al., 2003)  
  (microbial mediated reduction of $\text{NO}_3^-$, $\text{NO}_2^-$ and NO into $\text{N}_2$ 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: $\tau \approx 3 \text{ mo}$
  - 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 ($\lambda_r$)

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

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

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

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

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

$$\lambda_{\text{adv}} = \frac{1}{\tau_j}$$
**OM: N ratio**
\[
\frac{M_{\text{biomass}}}{M_N} \approx 15.86 \text{ gOM/gN}
\]
after \(106 \text{CO}_2 + 16 \text{HNO}_3 + \text{H}_3\text{PO}_4 + 122 \text{H}_2\text{O} \Rightarrow C_{106}\text{H}_{263}\text{O}_{110}\text{N}_16\text{P} + 138 \text{O}_2\) (photosynthesis)

**O\text{2: OM ratio}**
\[
\frac{M_{\text{O}_2}}{M_{\text{biomass}}} \approx 1.24 \text{ gO}_2/\text{gOM}
\]
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 \(_j\)**
\[
\frac{\text{EmpN}_{\text{consumed}}}{\text{TheorN}_{\text{available}}} = \frac{\text{DIN}}{\text{DIN content in } N_{\text{tot}}} \times M_N \times A_{\text{LME}} \quad \text{with } DIN = 10^{(\log PP - 2.332)/0.442} \quad \text{(Nixon et al., 1996)}
\]
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

\[
XF_j = \frac{\text{kgOM}}{\text{kgN}} \times \frac{\text{kgO}_2}{\text{kgOM}} \times (1 - \text{BGE}) \times \text{NIE}_j \times \text{VCC}
\]
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 \( HC_{50} = 10^{avg(logEC_{50})} \)

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

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>LME</th>
<th>taxa</th>
<th>n</th>
<th>α</th>
<th>β</th>
<th>Slope</th>
<th>Inters.</th>
<th>$r^2$</th>
<th>HC50</th>
<th>mg/L</th>
<th>mgO2/L</th>
<th>kgO2/m3</th>
<th>PAF.m3/kgO2</th>
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<tr>
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</table>

Large Marine Ecosystems grouped in climate zones

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 unit = ×10³ PAF·m³·d/kgN**
**Sensitivity analysis**

*Sensitivity Ratios (SR) were calculated by:*

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

(Strandenes et al., 2007)

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**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\(_{50}\) 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

References:


