Spatially-explicit LCIA endpoint model for marine eutrophication and application to future climatic-driven pressures

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Spatially-explicit LCIA endpoint model for marine eutrophication and application to future climatic-driven pressures

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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.
Life Cycle Assessment (LCA)
- Environmental assessment tool
- Evaluates the environmental exchanges (technosphere-ecosphere)
- Potential environmental impacts of a product or service throughout the entire life cycle (resources extraction, processing, manufacturing, assembly, packaging, transport, use, reuse, recycling, and disposal stages)

Life Cycle Impact Assessment (LCIA)
- Characterisation of emissions with Characterisation Factors (CF)
- CFs are substance-specific and represent the substance potency
- CFs translate emissions into potential impacts
- Regional and global impacts
Future scenarios
*Increase in food demand*

Climatic-driven pressures
*Increase in crops productivity*

Projected development of cereal production, global population, fertilizer use and arable land (FAO 2003)
Drivers and goals

Research question

- Understand the **fate processes** affecting nitrogen loadings to coastal waters
- Include ecosystems’ sensitivity to obtain a damage dimension (loss of biodiversity)
- Estimate factors for the impact characterisation (**CFs**)
- Introducing **spatial differentiation** at a suitable scale
- Produce an endpoint damage model to support decision-making processes

How to define CFs for marine eutrophication in a spatially differentiated LCIA endpoint model?
To define the **Characterisation Factor (CF)** in (PAF·)[m³·d/kg]:

\[
\text{CF}_{ij} = \text{FF}_{ij} \cdot \text{XF}_j \cdot \text{EF}_j
\]

Where:

- \(\text{FF}_{ij}\) is the **Fate Factor** [d] for emission route \(i\) to receiving ecosystem \(j\)
- \(\text{XF}_j\) is the **Exposure Factor** [kgO₂/kgN] in receiving ecosystem \(j\)
- \(\text{EF}_j\) 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>
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<tr>
<td>$\lambda_{j}$</td>
<td>Marine-N fate</td>
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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 +
- \((\text{LCI}_N \text{ to air})\) * \(f\) to inland * \(f_{\text{dep}}\) to ns * \(f_{\text{leach}}\) from ns * Denitr in sfw +
- \((\text{LCI}_N \text{ to air})\) * \(f\) to inland * \(f_{\text{dep}}\) to as * \(f_{\text{leach}}\) from as * Denitr in sfw +
- \((\text{LCI}_N \text{ to air})\) * \(f\) to inland * \(f_{\text{dep}}\) to sfs * Denitr in sfw

\( f_{\text{exp } i} = \)

- \((\text{LCI}_N \text{ to ns})\) * Denitr in gw * Denitr in sfw
- \((\text{LCI}_N \text{ to sfw})\) * Denitr in sfw

\( \text{ns} = \text{natural soil} \quad \text{as} = \text{agricultural soil} \quad \text{sfw} = \text{surface freshwater} \quad \text{mw} = \text{marine waters} \)

Spatially-explicit LCIA endpoint model for marine eutrophication
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 $\text{NO}$ into $\text{N}_2$ in bottom sediments)

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

- **Advection ≈ 1/τ**
  (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

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

**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 \(j\)

\[
\lambda_{\text{adv}} = \frac{1}{\tau_j}
\]
**Exposure Factor (XF)**

The $X F_j$ (unit: $kgO_2/kgN$) is estimated by:

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

**Bacterial Growth Efficiency** is the amount of new bacterial biomass produced per unit organic C substrate assimilated after (photosynthesis)

**Nitrogen Incorporation Efficiency** expresses the environmental factors affecting PP rates (ecosystem response) with (Nixon et al., 1996)

**Exposure Factor (XF)** then: after (respiration)

(del Giorgio & Cole, 1998)
**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 \( HC_{50} = 10^{\text{avg}(\log EC_{50})} \)

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)
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 = $\times 10^3 \text{ PAF-m}^3\cdot \text{d/kgN}$
**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\textsubscript{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
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:


