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Publication date:
2015

Document Version
Peer reviewed version

Coupling ecosystems exposure to nitrogen and species sensitivity to hypoxia: modelling marine eutrophication in LCIA

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Summary
Characterisation modelling in Life Cycle Impact Assessment (LCIA) quantifies impacts of anthropogenic emissions by applying substance-specific impact potentials, or Characterisation Factors (CF), to the amount of substances emitted. Nitrogen (N) emissions from human activities enrich coastal marine ecosystems and promote planktonic growth that may lead to marine eutrophication impacts. Excessive algal biomass and dissolved oxygen (DO) depletion typify the ecosystem response to the nutrient input. The present novel method couples a mechanistic model of coastal biological processes that determines the ecosystem response (exposure) to anthropogenic N enrichment (eXposure Factor, XF [$kgO_2 \cdot kgN^{-1}$]) with the sensitivity of species exposed to oxygen-depleted waters (Effect Factor, EF [$(PAF) \cdot m^3 \cdot kgO_2^{-1}$], expressed as a Potentially Affected Fraction (PAF) of species). Thus, the coupled indicator (XF*EF, [$(PAF) \cdot m^3 \cdot kgN^{-1}$]) represents the potential impact on benthic and demersal marine species caused by N inputs. Preliminary results range from 2 $(PAF) \cdot m^3 \cdot kgN^{-1}$ (Central Arctic Ocean) to 94 $(PAF) \cdot m^3 \cdot kgN^{-1}$ (Baltic Sea). Comparative contributions per country or watersheds can also be obtained. Further adding environmental fate modelling of N emissions completes the CF for eutrophying emissions making it a useful contribution for sustainability assessment of human activities, as applied in Life Cycle Assessment (LCA).

Introduction
In Life Cycle Impact Assessment (LCIA) substance-specific factors (Characterisation Factors, CF) are multiplied by the amount of substances emitted from human activities to the environment in order to estimate their potential impact. LCIA modelling frameworks typically encompass environmental fate of the emissions, exposure of the receiving ecosystems, and effects on the exposed biota. Nitrogen (N) emissions from anthropogenic sources, mainly agriculture and combustion processes, enrich coastal marine ecosystems where they promote the growth of planktonic biomass. Ecosystem responses involve excessive algal growth and dissolved oxygen (DO) depletion in bottom waters after degradation of sinking organic matter. The DO depletion pathway was addressed in combination with the potential effects on exposed species. The loss of species diversity is the damage dimension ultimately assessed as a function of N emitted.

The present study aims at integrating the processes that describe the ecosystem exposure to nutrient enrichment and the resulting effect on the exposed species. Together these characterise the marine eutrophication phenomenon, which is seen as a syndrome of ecosystem responses to the increased availability of the limiting nutrient in the photic zone (Cloern 2013; Cosme et al. submitted).

Material and Methods
This novel method estimates the ecosystem response to anthropogenic N inputs and their effects on exposed species. It couples (i) a mechanistic model of relevant marine biological processes that determines the ecosystems exposure to N inputs (delivering an eXposure Factor, XF), with (ii) an effect estimation model based on species sensitivity to hypoxia (delivering an Effect Factor, EF).

The XF [$kgO_2 \cdot kgN^{-1}$] quantifies the nitrogen-to-oxygen 'conversion' potential. It is based on the carbon pump concept (Ducklow et al. 2001) of production, sinking, and degradation of organic carbon that leads to benthic

DO consumption after aerobic respiration by heterotrophic bacteria, with site-dependent parameterisation. The Large Marine Ecosystems (LME) biogeographical classification system (Sherman and Alexander 1986) was adopted to address the spatial variation of some of the modelled parameters and the XF results. The method is fully described by Cosme et al. (submitted) (see also poster R:24 by Cosme et al., this volume).

The EF [(PAF)$\cdot m^3 \cdot kgO_2^{-1}$] builds on a probabilistic Species Sensitivity Distribution (SSD) methodology. It quantifies potential losses of species richness caused by an environmental stressor (DO depletion) expressed as a Potentially Affected Fraction (PAF) of species (Posthuma et al. 2002). The EFs were estimated at a spatial resolution of five climate zones (polar, subpolar, temperate, subtropical, and tropical) and then assigned to the corresponding 66 LMEs (see also poster R:26 by Cosme and Hauschild, this volume).

The coupled indicator (XF*EF, [(PAF)$\cdot m^3 \cdot kgN^{-1}$]) represents the potential impact on benthic and demersal marine species caused by N-enrichment, modulated by the specific biological response. The oxygen depletion and sensitivity to it in each affected spatial unit is quantified at a LME resolution.

Results and Discussion

Preliminary results of the coupled indicator range from 2 (PAF)$\cdot m^3 \cdot kgN^{-1}$ in the Central Arctic Ocean to 94 (PAF)$\cdot m^3 \cdot kgN^{-1}$ in the Baltic Sea, i.e. spatial variation of a factor ≈42 among LMEs. The damage dimension of the impacts can be converted into [species$\cdot kgN^{-1}$] by applying global or site-dependent species densities [species$\cdot m^{-3}$] if available.

The XFs obtained show spatial differentiation in agreement with the current understanding of the biological and oceanographic processes, and is consistent with primary productivity patterns and hotspots (Behrenfeld and Falkowski 1997; Chassot et al. 2010). The coupled indicator is an essential component of CFs modelling in LCIA for marine eutrophication impacts and may also be useful for ecosystems health management. Further adding a fate model of the anthropogenic N emissions (Azevedo et al. 2013) will deliver comparative contributions from distinct countries or watersheds, thus being useful to the assessment of the sustainability of human activities with eutrofying emissions, as applied in Life Cycle Assessment (LCA) of product systems.

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