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Spatial differentiation of marine eutrophication damage indicators based on species density

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ABSTRACT

Marine eutrophication refers to an ecosystem response to the loading of nutrients, typically nitrogen (N), to coastal waters where several impacts may occur. The increase of planktonic growth due to N-enrichment fuels the organic carbon cycles and may lead to excessive oxygen depletion in benthic waters. Such hypoxic conditions may cause severe effects on exposed ecological communities. The biologic processes that determine production, sink, and aerobic respiration of organic material, as a function of available N, are coupled with the sensitivity of demersal species to hypoxia to derive an indicator of the Ecosystem Response (ER) to N-uptake. The loss of species richness expressed by the ER is further modelled to a marine eutrophication Ecosystem Damage (meED) indicator, as an absolute metric of time integrated number of species disappeared (species yr), by applying a newly-proposed and spatially-explicit factor based on species density (SD). The meED indicator is calculated for 66 Large Marine Ecosystems and ranges from 1.6×10^{-12} species kgN^{-1} in the Central Arctic Ocean, to 4.8×10^{-8} species kgN^{-1} in the Northeast U.S. Continental Shelf. The spatially explicit SDs contribute to the environmental relevance of meED scores and to the harmonisation of marine eutrophication impacts with other ecosystem-damage Life Cycle Impact Assessment (LCIA) indicators. The novel features improve current methodologies and support the adoption of the meED indicator in LCIA for the characterization of anthropogenic-N emissions and thus contributing to the sustainability assessment of human activities.

1. Introduction

Marine eutrophication is an ecosystem response to an increased availability of a growth-limiting nutrient in the euphotic zone of coastal waters (Gray et al., 2002; Rabalais, 2002; Smith et al., 1999) and its consequences are among the most severe and widespread disturbances to marine environments (Diaz and Rosenberg, 2008; GESAMP, 2001). Nitrogen (N) is assumed to be the limiting nutrient in marine coastal waters (Howarth and Marino, 2006; Vitousek et al., 2002), acknowledging that spatial and seasonal limitation by phosphorus (P) or silicon (Si) and cases of co-limitation may occur (see e.g. Arrigo, 2005; Elser et al., 2007; Turner et al., 1998). The N-enrichment of coastal waters boosts planktonic growth, or primary production (PP) – the photosynthetic reduction of inorganic carbon into energy-rich organic carbon involving the assimilation of inorganic dissolved plant nutrients and the utilization of light energy by primary producers, mainly phytoplankton, in the well-lit upper layers of the ocean (euphotic zone) (Chavez et al., 2011; Falkowski and Raven, 2007). The eventual aerobic respiration of this newly produced organic matter may result in oxygen depletion in bottom waters (Cosme et al., 2015; Graf et al., 1982; Ploug et al., 1999) and even in the occurrence of 'dead zones' (Diaz, 2001; Diaz and Rosenberg, 2008). Effects on exposed demersal species (e.g. fish, crustaceans, or bivalves) may then be expected as a function of their sensitivity to hypoxia (Cosme and Hauschild, 2016; Davis, 1975; Diaz and Rosenberg, 1995; Gray et al., 2002; Vaquer-Sunyer and Duarte, 2008) and promote other impacts that may include habitat loss, water quality degradation, mass mortality, and fisheries decline (Diaz and Rosenberg, 1995; Levin et al., 2009; Middelburg and Levin, 2009; Wu, 2002; Zhang et al., 2010a).

Abbreviations: AoP, area of protection; EF, effect factor; ER$_{PAF}$, ecosystem response (estimated from PAF-based effect factors); ER$_{PDF}$, ecosystem response (estimated from PDF-based effect factors); LCIA, life cycle impact assessment; LME, large marine ecosystem; meDF, marine eutrophication damage factor; meED, marine eutrophication ecosystem damage; PAF, potentially affected fraction of species; PDF, potentially disappeared fraction of species; SD, species density; SDM, species distribution model; SR, species richness; SSD, species sensitivity distribution; XF, exposure factor.

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Globally, environmental N-emissions from human activities have increased more than 10-fold in the last 150 years in large part due to the growing demand for reactive nitrogen in agriculture use and for energy production (Galloway et al., 2008). Considering the N emissions throughout the entire life cycle of products and services in the economy, Life Cycle Assessment (LCA) can be used as an environmental analysis tool designed to quantify the resulting potential impacts (Hauschild, 2005). Indicators of marine eutrophication impacts are estimated in the Life Cycle Impact Assessment (LCIA) phase of LCA, typically at the midpoint between emission and damage (endpoint) in the cascade of N-enrichment effects in the marine compartment (Rabalais et al., 2009). This fact is reflected in widespread LCIA methods, like ReCiPe (Goedkoop et al., 2012), EDIP 2003 (Hauschild and Potting, 2005), IMPACT 2002+ (Jolliet et al., 2003), and CML 2002 (Guinée et al., 2002). Recent reviews of the state-of-the-art and research needs regarding marine eutrophication impacts modelling revealed the lack of a consistent link between existing midpoints and damage level (Hauschild et al., 2013; Henderson, 2015). While the midpoint indicator models nutrients fate in the environment, the endpoint indicator further requires exposure and effects modelling for consistency with the generic LCIA framework (Udo de Haes et al., 2002). Recent work has developed explicit ecosystem exposure factors (XF) (Cosme et al., 2015) and effect factors (EF) (Cosme and Hauschild, 2016). An XF × EF coupled indicator represents the ecosystem response to N-uptake by primary producers in coastal waters. Additional fate modelling may deliver the marine eutrophication impact potential of a unit mass of N emitted from anthropogenic sources.

Methodology-wise, other ecosystem-related LCIA indicators at the endpoint level, e.g. for ecotoxicity or acidification, can be aggregated into damage to the ecosystem, also known as an Area of Protection (AoP) (Udo de Haes et al., 1999), and be expressed as a time-integrated loss of species richness, i.e. species·yr. Such conversions currently adopt a site-generic marine species density (SD) value (Goedkoop et al., 2012) – an inherent model (rough) simplification. Recent work focusing on marine species distribution (Jones and Cheung, 2015) may provide the damage modelling with site-dependent SDs to estimate environmentally relevant damage factors (DF). The present approach derives the ecosystem response (ER) indicator from the cause-effect chain triggered by N-enrichment of coastal waters that leads to impacts on ecological communities affected by oxygen depletion. The spatial differentiation given by the exposure and effect components of the model work is further combined with the natural occurrence of the potentially affected species in coastal waters around the globe (i.e. their density, SD). Given the local to regional character of marine eutrophication and hypoxia events, this impact assessment approach seems useful for comparative purposes.

The goal of this study is to quantify spatially explicit damage potentials for N emissions that fuel primary production in coastal waters and thus contributing to marine eutrophication. This quantification requires (i) the derivation of an ecosystem response indicator, obtained by combining the ecosystem exposure to N and the effects on biota caused by hypoxia, and (ii) an additional conversion of the damage to ecosystem from relative to absolute metrics, based on site-dependent species density. The application of such method is discussed for characterisation modelling of anthropogenic emissions of N with eutrophying impacts in a LCIA framework.

2. Methodology

The approach used here is consistent with the LCIA framework for emission-related impact indicators. It potential impacts to the ecosystem by combining environmental fate of substances emissions, exposure of the receiving ecosystem to these, and the effect caused on exposed species (Pennington et al., 2004b; Udo de Haes et al., 2002) (Section 2.1). The present method proposes an indicator for the loss of species richness caused by hypoxia-based marine eutrophication expressed as a volume-integrated Potentially Affected Fraction (PAF) of species per unit mass of N uptaken (Sections 2.2–2.4). A metrics conversion to Potentially Disappeared Fraction (PDF) of species is proposed for harmonisation with other ecosystem-related endpoint indicators (Section 2.5). An additional conversion to an absolute metric is proposed, based on site-dependent species density obtained from marine species distribution models (Sections 2.5–2.8).

2.1. Framework

The LCIA factor, or Characterisation Factor (*CF*, $(\mathrm{PAF})\,\mathrm{m}^3\,\mathrm{yr\,kgN}^{-1}$), that translates the quantity of an emission into its potential impact on the exposed environmental compartment (coastal marine ecosystem) is derived as summarised in Eq. (1):

$$CF_{ij} = FF_{ij} \times XF_j \times EF_j \tag{1}$$

where FF_{ij} (yr) is the fate factor for emission route *i* (N to air, from soil, to fresh-, or to marine water) to receiving ecosystem *j* (coastal marine), XF_j ($\mathrm{kgO_2\,kgN^{-1}}$) is the exposure factor and EF_j ($(\mathrm{PAF})\,\mathrm{m}^3\,\mathrm{kgO_2}^{-1}$) the effect factor, both in ecosystem *j*. PAF is included for informative reasons as it is not an actual unit but a dimensionless quantity (fraction) (Heijungs, 2005). Acknowledging the meaning and application of CFs in impact assessment, the scope of the present method is limited to the estimation of the ecosystem response to N uptaken by phytoplankton, for which XF and EF are applied (see Fig. 1). Spatial explicit fate modelling can however be adapted for waterborne (Cosme et al., 2016) and airborne N emissions (Dentener et al., 2006; Roy et al., 2012).

2.2. Exposure factors

The XF comprises the assimilation of N that boosts planktonic growth, followed by the export of organic carbon to bottom strata where heterotrophic bacteria consume dissolved oxygen by aerobic respiration. The model work proposed by Cosme et al. (2015) describes the biological processes of N-limited primary production (PP), metazoan consumption, and bacterial degradation, in four distinct organic carbon sinking routes. The resulting XFs, nitrogen-to-oxygen 'conversion' potentials, are available at a recommended spatial resolution of Large Marine Ecosystems (LMEs) (Sherman and Alexander, 1986) and range from 0.45 $\mathrm{kgO_2\,kgN^{-1}}$ in the Central Arctic Ocean to 16 $\mathrm{kgO_2\,kgN^{-1}}$ in the Baltic Sea (Fig. S.1) (Cosme et al., 2015).

2.3. Effect factors

The EF represents the average effect of hypoxia on an exposed demersal community. It is derived from the sensitivity of the composing individual species to hypoxia, with threshold values expressed as lowest-observed-effect-concentrations (LOEC), integrated with a Species Sensitivity Distribution (SSD) methodology (Posthuma and Suter, 2002) to estimate a $\mathrm{HC50_{LOEC}}$ value (Cosme and Hauschild, 2016). This represents the intensity of the stressor, i.e. a dissolved oxygen (DO) level, at which 50% of the species are affected above their individual threshold. The EF [$(\mathrm{PAF})\,\mathrm{m}^3\,\mathrm{kgO_2}^{-1}$] is derived as the average variation of effect (ΔPAF, [dimensionless]) in the ecological community in ecosystem *j* due to a variation of the stressor intensity (ΔDO, [$\mathrm{kgO_2\,m^{-3}}$]) in the same ecosystem