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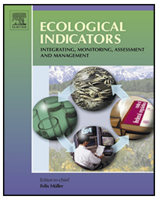

Effect factors for marine eutrophication in LCIA based on species sensitivity to hypoxia

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ABSTRACT

Hypoxia is an important environmental stressor to marine species, especially in benthic coastal waters. Increasing anthropogenic emissions of nutrients and organic matter contribute to the depletion of dissolved oxygen (DO). Biotic sensitivity to low levels of DO is determined by the organisms' ability to use DO as a respiratory gas, a process depending on oxygen partial pressure. A method is proposed to estimate an indicator of the intensity of the effects caused by hypoxia on exposed marine species. Sensitivity thresholds to hypoxia of an exposed ecological community, modelled as lowest-observed-effect-concentrations (LOEC), were compiled from literature for 91 demersal species of fish, crustaceans, molluscs, echinoderms, annelids, and cnidarians, and converted to temperature-specific benthic (100 m depth) LOEC values. Species distribution and LOEC values were combined using a species sensitivity distribution (SSD) methodology to estimate the DO concentration at which the potentially affected fraction (PAF) of the community's species having their LOEC exceeded is 50% ($HC50_{LOEC}$). For the purpose of effect modelling in Life Cycle Impact Assessment (LCIA), effect factors (EF, [(PAF) $m^3\ kgO_2{}^{-1}$]) were derived for five climate zones (CZ) to represent the change in effect due to a variation of the stressor intensity, or $EF = \Delta PAF/\Delta DO = 0.5/HC50_{LOEC}$. Results range from 218 (PAF) $m^3\ kgO_2{}^{-1}$ (polar CZ) to 306 (PAF) $m^3\ kgO_2{}^{-1}$ (tropical CZ). Variation between CZs was modest so a site-generic global EF of 264 (PAF) $m^3\ kgO_2{}^{-1}$ was also estimated and may be used to represent the average impact on a global ecological community of marine species exposed to hypoxia. The EF indicator is not significantly affected by the major sources of uncertainty in the underlying data suggesting valid applicability in characterisation modelling of marine eutrophication in LCIA.

1. Introduction

Hypoxic waters are characterised by low concentration of dissolved oxygen (DO). The threshold for hypoxia is traditionally defined at 2 $mLO_2\ L^{-1}$ (Diaz and Rosenberg, 1995; Gray et al., 2002) after observations of demersal fisheries collapse (Renaud, 1986), at 2 $mgO_2\ L^{-1}$ (Turner et al., 2012; Vaquer-Sunyer and Duarte, 2008), or even at DO concentrations <50% saturation owing to avoidance behaviour and physiological stress (Breitburg, 2002). Regardless of the exact value and unit it represents, hypoxia is used here as the DO threshold beyond which some physiological, behavioural, or other response occurs (Davis, 1975), denoting the degradation of this water quality parameter relative to biotic requirements (Levin et al., 2009; Seibel, 2011).

Hypoxia occurrence can be naturally intensified when vertical density stratification of the water column, due to haloclines and thermoclines, hinders mixing and thus gas transfer to the bottom strata (Conley et al., 2009; Pihl et al., 1992; Rosenberg et al., 1991). The aerobic respiration by heterotrophic bacteria when degrading organic material, may consume the DO down to hypoxic levels. Anthropogenic emissions of organic matter may therefore contribute to hypoxia, as well as nutrient emissions that boost planktonic growth and increase organic matter export to bottom waters, processes covered in a typical impact pathway of marine eutrophication (Nixon, 1995; Rabalais et al., 2009). The global number of anoxia events, or 'dead zones', has increased exponentially in the last decades (Diaz and Rosenberg, 2008). The World Resources Institute (WRI, 2011) compiled 762 sites reporting eutrophication and hypoxia impacts—and eutrophication has been suggested to be the main cause (Diaz and Rosenberg, 2008, 1995; Justić et al., 1993; Rabalais et al., 2010). Severe ecological impacts may occur including habitat loss, water quality degradation, mass

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mortality, and fisheries decline (Diaz and Rosenberg, 1995; Levin et al., 2009; Middelburg and Levin, 2009; Wu, 2002; Zhang et al., 2010). Future global warming conditions may increase the occurrence and prevalence of hypoxia in coastal waters by the effect of e.g. increased temperature and enhanced stratification (Bakun et al., 2015; Kennedy, 1990; Rabalais et al., 2009). Water temperature increase may also intensify the stress on biota and DO demand for respiratory purposes (Harris et al., 2006) while oxygen solubility decreases as temperature rises (Carpenter, 1966).

Biotic sensitivity to hypoxia varies significantly between species, taxonomic group, or even life stage and so no single universal threshold really exists (Davis, 1975; Diaz and Rosenberg, 1995; Ekau et al., 2010; Gray et al., 2002; Miller et al., 2002; Vaquer-Sunyer and Duarte, 2008). In fact, a gradient of responses is observed with decreasing DO availability, depending on the tolerance or resistance of the species (Diaz and Rosenberg, 1995). Under events of DO shortage, benthic species may adopt avoidance strategies, or exhibit altered behaviour (Chapman and McKenzie, 2009; Wu, 2002). Physiologically, low DO concentration constrains the scope for aerobic metabolism and is therefore a limiting factor for growth and reproduction (Brett, 1979; Fry, 1971; Wu et al., 2003) and ultimately survival (Vaquer-Sunyer and Duarte, 2008; Wu, 2002). Oxygen-regulator species maintain a relatively constant O_2 consumption rate (MO_2) over a range of ambient oxygen partial pressure (PO_2), triggering behaviour and physiologic reflexes aimed at maintaining homeostasis, such as ventilatory (Perry et al., 2009) and cardiovascular responses (Gamperl and Driedzic, 2009). Below a critical PO_2 level, MO_2 declines as PO_2 declines (oxygen-conformation) (Richards, 2011). So, under oxygen-conformation, species show a tolerance threshold beyond which mortality is expected. In short, the initial response to hypoxia aims at maintaining oxygen delivery, then at conserving energy expenditure and reducing energy turnover, and last by enhancing energetic efficiency of remaining metabolic processes and deriving energy from anaerobic sources (reviewed by Wu, 2002).

Respiratory gas exchange is governed by the PO_2 gradient between the external and internal media (Seibel, 2011), modulated by the ventilatory, diffusive, and perfusive conductance of oxygen between media (Childress and Seibel, 1998; Herreid, 1980; Piiper, 1982). Local temperature- and salinity-dependent O_2 solubility determines the ambient PO_2. The intensity of the induced environmental stress increases with the decreasing DO concentration (or the corresponding PO_2 or %Sat). Physiologically, the sensitivity threshold to hypoxia corresponds to the critical PO_2 level, or the point of hypoxic stress at which the oxygen consumption of a regulator becomes dependent on environmental PO_2 and conformity onsets (Herreid, 1980; Hofmann et al., 2011; Richards, 2011). The corresponding DO concentration at which the effect is triggered is taken equivalent to a lowest-observed-effect-concentration (LOEC), i.e. the lowest stressor intensity (highest DO concentration) found by experiment or observation to cause an alteration in morphology, functional capacity, growth, development, or life span of target organisms distinguishable from control organisms (Duffus, 2003).

Life Cycle Assessment (LCA) has been used as an environmental analysis tool to evaluate the potential impacts of anthropogenic emissions, such as those of N that cause hypoxia-driven eutrophication (Hauschild, 2005). However, a method for the estimation of the ecological impact of hypoxia in marine coastal waters has not been broadly agreed upon in LCA methodologies. Benchmarking ecosystem effects in distinct geographic locations, using a harmonised global model, is also lacking (Henderson, 2015). Therefore, a scientifically-based and globally applicable method to quantify an indicator of the effects of hypoxia on marine species richness, as a function of their sensitivity, is proposed. The sensitivity to hypoxia and geographic distribution of representative species was addressed to derive an impact potential to the ecological communities in five climate zones. Such indicator is expressed as an effect factor (EF) and its application for impact characterisation in Life Cycle Impact Assessment (LCIA) is discussed.

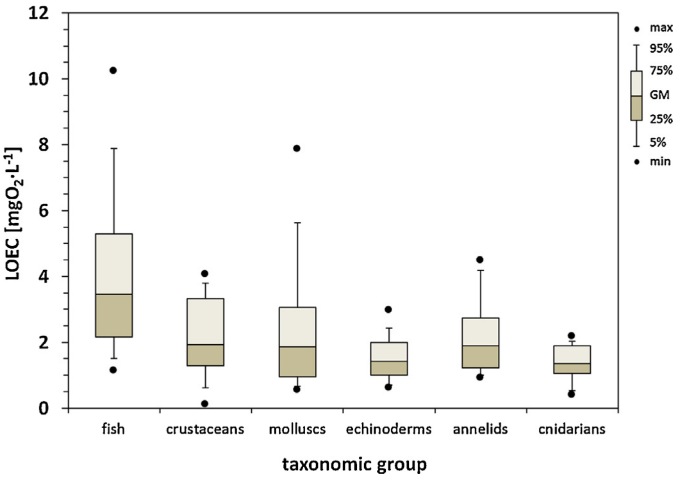

Fig. 1. Distribution of sensitivity thresholds to hypoxia among taxa based on species LOEC (mgO$_2$ L^{-1}).

2. Methodology

The sensitivity to hypoxia of an exposed ecological community may be derived from the sensitivity of the composing individual species. This sensitivity indicator is the basis for an effect factor (EF), as defined and used in LCIA. The EF expresses the ability of the environmental stressor (oxygen depletion) to cause an effect on the exposed marine benthic ecosystem as a potential loss of its species richness. The standard metric, which is also applied for other LCIA indicators addressing ecosystem stress, is the Potentially Affected Fraction (PAF) of species in the ecosystem. The effect estimation is a component of the impact characterisation framework that derives Characterisation Factors (CFs). CFs for emission-related impact categories translate the amount of an emitted substance into a potential impact on the indicator for the chosen category, i.e. marine eutrophication in the present case. Such impact can be caused by anthropogenic air- and waterborne emission of bioavailable nitrogen (N) forms, and organic matter, and CFs can be derived for those emissions. The CF estimation follows the generic framework for emission-based indicators by further modelling a fate factor (FF) and an exposure factor (XF) (Udo de Haes et al., 2002). The FF expresses the persistence of N in the euphotic zone of marine waters, as the product of the fraction of the original emission and its residence time in the compartment (Cosme et al., 2016; Henderson et al., 2011). The ecosystem XF expresses the incorporation of N into planktonic organic matter that gets exported to bottom strata, where it is aerobically respired by heterotrophic bacteria with DO consumption, as proposed by Cosme et al. (2015). The CF, in (PAF) m^3 yr kgN^{-1}, is then the product of the fate, exposure, and effect factors, as summarised in Eq. (1):

$$\mathrm{CF}_{ij} = \mathrm{FF}_{ij} \times \mathrm{XF}_j \times \mathrm{EF}_j \qquad (1)$$

where FF_{ij} (in yr) is the fate factor for emission i to receiving ecosystem j, XF_j (in kgO$_2$ kgN^{-1}) is the exposure factor and EF_j (in (PAF) m^3 kgO$_2$$^{-1}$) the effect factor in ecosystem j. PAF is in fact dimensionless (fraction) and not an actual unit (Heijungs, 2005), so it is shown here in association with the EF's proper unit (m^3 kgO$_2$$^{-1}$) merely for informative purposes.

The proposed methodology to estimate EFs based on species sensitivity to hypoxia requires the identification of relevant target