Environment International 89–90 (2016) 48–61

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review

Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA)

John S. Woods [a,*], Karin Veltman [b], Mark A.J. Huijbregts [c], Francesca Verones [a], Edgar G. Hertwich [d]

[a] Industrial Ecology Programme, Norwegian University of Science and Technology (NTNU), Sem Sælands vei 7, NO-7491 Trondheim, Norway
[b] Department of Environmental Health Sciences (EHS), School of Public Health, University of Michigan, 1415 Washington Heights, Ann Arbor, MI 48109-2029, USA
[c] Radboud University Nijmegen, Institute for Water and Wetland Research, Department of Environmental Science, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands
[d] Yale School of Forestry & Environmental Studies, 195 Prospect Street, New Haven, CT 06511, USA

ARTICLE INFO

Article history:
Received 22 September 2015
Received in revised form 22 December 2015
Accepted 26 December 2015
Available online xxxx

Keywords:
Marine biodiversity
Life cycle assessment
Ecosystem quality
Human interventions
Impact pathways
Pollution

ABSTRACT

Human demands on marine resources and space are currently unprecedented and concerns are rising over observed declines in marine biodiversity. A quantitative understanding of the impact of industrial activities on the marine environment is thus essential. Life cycle assessment (LCA) is a widely applied method for quantifying the environmental impact of products and processes. LCA was originally developed to assess the impacts of land-based industries on mainly terrestrial and freshwater ecosystems. As such, impact indicators for major drivers of marine biodiversity loss are currently lacking. We review quantitative approaches for cause–effect assessment of seven major drivers of marine biodiversity loss: climate change, ocean acidification, eutrophication-induced hypoxia, seabed damage, overexploitation of biotic resources, invasive species and marine plastic debris. Our review shows that impact indicators can be developed for all identified drivers, albeit at different levels of coverage of cause–effect pathways and variable levels of uncertainty and spatial coverage. Modeling approaches to predict the spatial distribution and intensity of human-driven interventions in the marine environment are relatively well-established and can be employed to develop spatially-explicit LCA fate factors. Modeling approaches to quantify the effects of these interventions on marine biodiversity are less well-developed. We highlight specific research challenges to facilitate a coherent incorporation of marine biodiversity loss in LCA, thereby making LCA a more comprehensive and robust environmental impact assessment tool. Research challenges of particular importance include i) incorporation of the non-linear behavior of global circulation models (GCMs) within an LCA framework and ii) improving spatial differentiation, especially the representation of coastal regions in GCMs and ocean-carbon cycle models.

Contents

* Corresponding author.
E-mail address: john.s.woods@ntnu.no (J.S. Woods).

http://dx.doi.org/10.1016/j.envint.2015.12.033

1. Introduction

Human demands on marine resources and space are currently unprecedented and are expected to further increase in the near future (Millennium Ecosystem Assessment, 2005; Foley et al., 2010). Seen by many (e.g. the European Commission, 2012, and the Australian Government, 2015) as the next frontier for economic development, new marine activities, such as renewable energy harvesting, carbon sequestration and gas hydrate mining, are rapidly emerging (Millennium Ecosystem Assessment, 2005). Traditional marine activities remain important as well. Offshore oil and gas production, world sea trade and marine aquaculture are projected to continue growing in importance over the coming decades (OECD, 2010; US Energy Information Administration, 2010; FAO, 2014). Marine capture fisheries have stabilized but remain important, given that fish consumption per capita is increasing (FAO, 2014; Thrane et al., 2009). Additionally, several marine industrial activities have been expanding from coastal, shallow waters into progressively deeper waters (e.g. ultra-deep oil production fields in Brazil and deep-sea fisheries in the Northwest Atlantic) and to previously unexplored areas (e.g. the Arctic lower shelf) (Millennium Ecosystem Assessment, 2005; US Energy Information Administration, 2010; Crowder et al., 2008; Dalsøren et al., 2007; Morato et al., 2006).

Concurrently, observed declines in marine biodiversity have been attributed to human activities (Millennium Ecosystem Assessment, 2005; Foley et al., 2010; Pauly et al., 2002; Costello et al., 2010). Two comprehensive studies, the Millennium Ecosystem Assessment (2005) and CenSus of Marine Life (Census) (Costello et al., 2010), have documented declines in marine biodiversity on a global scale. Together, these studies identified climate change, ocean acidification, eutrophication-induced hypoxia, habitat change (including seabed damage), overexploitation and invasive species as main drivers of marine biodiversity loss (Millennium Ecosystem Assessment, 2005; Costello et al., 2010). Another prominent driver, albeit currently poorly understood, in marine environments arises from plastic debris (Gall and Thompson, 2015). While some drivers, such as climate change and eutrophication-induced hypoxia, can be traced back to both land-based and sea-based activities; other drivers, such as habitat change, invasive species, and overexploitation, are predominantly linked to sea-based activities (Millennium Ecosystem Assessment, 2005; Foley et al., 2010; Costello et al., 2010; Halpern et al., 2008). A quantitative understanding of the environmental impact of these industrial activities on the marine environment would greatly improve the robustness and completeness of life cycle assessment (LCA).

LCA is a standardized method to evaluate the environmental impact of a product or process over its full life cycle. In LCA, life-cycle inventory data, including emissions produced (e.g. kg CO_2) and resources used (e.g. m^3 of water consumed) are converted to impact scores for various environmental categories, such as global warming, human toxicity, and aquatic eutrophication. Potential inventory data for seven major drivers of marine biodiversity loss are included in Table 1. LCA uses stressor-specific and impact-category specific characterization factors (CF) to convert inventory data to potential impacts. These CFs express the fate and effect of a stressor per unit of intervention (emission or used resource). The fate factor models the spatial distribution and intensity of a unit intervention and is generally obtained from environmental fate models (Curran et al., 2011; Huijbregts et al., 2011). The effect factor relates the intensity of an intervention to a quantified effect, such as the potentially disappeared fraction (PDF) of species (Curran et al., 2011).

LCA is particularly well-suited to identify potential trade-offs that occur across impact categories or life-cycle stages and consequently offers the possibility to optimize the overall environmental performance of a product or process. These key advantages have resulted in an increased LCA application to various technologies in the last decade (Guinée et al., 2011), including several sea-based technologies, such as offshore oil and gas production (Veltman et al., 2011), offshore wind turbines (Weinzettel et al., 2009), marine capture fisheries (Avadí and Fréon, 2013; Pelletier et al., 2007; Ziegler and Valentinsson, 2008) and marine aquaculture (Aubin et al., 2009). LCA, however, was originally developed to assess the impact of land-based product systems on mainly terrestrial and freshwater ecosystems and currently lacks a marine impact focus. The standard suite of LCA impact categories contains only two that are relevant for the marine environment, namely marine eutrophication and marine ecotoxicity (ReCiPe, 2009). Relevant impact indicators for other important drivers of marine biodiversity loss, such as climate change, ocean acidification, eutrophication-induced hypoxia, overexploitation of fishery resources, invasive species and habitat change, are yet lacking. For an adequate assessment of the environmental performance of coastal and offshore industrial activities in LCA it is of utmost importance to develop indicators for important drivers of marine biodiversity loss.

Here, we review quantitative approaches for the environmental assessment of seven major drivers of marine biodiversity loss, i.e. climate change, ocean acidification, eutrophication-induced hypoxia, seabed damage, invasive species, overexploitation and marine plastic debris. We also provide recommendations on how to quantitatively incorporate these drivers of marine biodiversity loss in LCA. We focus on quantitative approaches that have been used to assess marine impacts on a global and/or regional scale, as LCA requires cause–effect models that can be consistently applied to various geographic regions, and impact indicators that are comparable across ecosystems. For each driver, we review the state-of-the art of cause–effect modeling in terms of taxonomic and geographic coverage and the termination point of cause–effect modeling, i.e. whether the approach quantifies impacts on biological systems, consistent with LCA effect (endpoint) modeling, or a change in environmental state, consistent with LCA fate (midpoint) modeling. We identify main current (conceptual) limitations and provide recommendations on steps that need to be taken in order to incorporate the studied drivers of marine biodiversity loss in LCA.

2. Climate change

2.1. Cause–effect

"Climate change" encompasses a range of physical and chemical modifications to the ocean, primarily resulting from greenhouse gas (GHG) driven global warming. Well-documented changes include: i) an increase in average sea surface temperature (SST) and in the frequency and intensity of SST anomalies, ii) a rise in average global sea