Journal of Cleaner Production 73 (2014) 63–71

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

New methods for impact assessment of biotic-resource depletion in life cycle assessment of fisheries: theory and application

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A R T I C L E I N F O

Article history:
Received 1 April 2013
Received in revised form
13 January 2014
Accepted 20 January 2014
Available online 7 February 2014

Keywords:
Biotic resource depletion
Fisheries
Net primary production
Maximum sustainable yield

A B S T R A C T

It is difficult to address all of the direct environmental impacts of fisheries using conventional methods of Life Cycle Assessment (LCA). A methodological framework was developed that calculates regionalised characterisation factors for biomass uptake by fishing activities to assess impacts of biotic-resource depletion at both species and ecosystem levels. These two levels were studied to include effects of catch on the collapse of a particular stock of a given species and on total biomass availability in oceans. Characterisation factors were calculated for 127 fish species and 88 marine provinces. The compatibility of this method with other frameworks is discussed, as well as the methodological limitations. The method was applied to two contrasting examples from fisheries (Northern Atlantic albacore tuna and Northern Argentine anchovy). The impacts of one tonne of tuna on biotic natural resources were 4 and 14 times as high as those of anchovy at the ecosystem and species levels, respectively. The application demonstrates that the method is relevant, as it addresses a topic of global interest and fills a gap in LCA impact assessment to contrast impacts of removals of different fish species in terms of biotic natural resource depletion.

1. Introduction

Life Cycle Assessment (LCA) tends to be exhaustive for the range of impacts it can assess, but as mentioned by Pelletier et al. (2007), improvements are necessary to assess the impacts of seafood products. In seafood LCA case studies, most authors have deemed necessary the addition of non-conventional indicators to (1) take into account removal of fish from ecosystems and allow comparisons between terrestrial and aquatic food products, (2) assess depletion of fish stocks and perturbation of ecosystems by unbalanced exploitation of trophic levels, and (3) assess seafloor damage. With these objectives, they used, respectively, (1) indicators of Net Primary Production use (NPP_{use}), which reflects the quantity of C that fishing activities remove from an ecosystem; (2) small-sized catch ratio, discard ratio, by-catch ratio and fishing-in-balance index (FiB); and (3) area of seafloor trawled (review in Avadi and Fréon, 2013). Outside of LCA, two scarcity factors related to productivity have been introduced to assess impacts of fishing activities by Halpern et al. (2008) and Libralato et al. (2008), respectively. To harmonise these proposals, Langlois et al. (2011) suggested creating a new impact category, called "sea use" by analogy with "land use", which could assess transformation and occupation impacts in marine ecosystems. They suggested keeping the most consensual framework of terrestrial land use (Milà i Canals et al., 2007), *i.e.* defining a quality index whose values for different uses could be compared and varying over time to reach a

Abbreviations: B_{MSY}, biomass stock at MSY; B_t, biomass stock at time t; BNR, Biotic Natural Resource; $A_{ecosystem}$, ecosystem area; E_t, fishing effort; E_{MSY}, fishing effort at the Maximum Sustainable Yield; F_{MSY}, fishing mortality at MSY; *f*, factor of conversion from kg of wet weight to organic matter (in primary carbon equivalent); GOODS, Global Open Oceans and Deep Seabeds; $I_{BNR,eco}$, Impact assessment of Biotic Natural Resource depletion at the ecosystem level; $I_{BNR,sp}$, Impact assessment of Biotic Natural Resource depletion at the species level; LSF, Life Support Functions; MEOW, Marine Ecoregions Of the World; MSY, Maximum Sustainable Yield; *m*, mass of fish uptake; M, natural mortality; $NPP_{mean,\ ecosystem}$, mean Net Primary Production in the ecosystem; NPP_{use}, Net Primary Production use; *Z*, total mortality; $NPP_{ecosystem}$, total Net Primary Production in the ecosystem; TE, Transfer Efficiency; TL, Trophic Level; C_t, yearly catch at time *t*.

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http://dx.doi.org/10.1016/j.jclepro.2014.01.087

new steady state after a certain time of restoration. They suggested the possibility of using an indicator expressing the life support capacity of marine ecosystems.

In the case of biomass removal by fishing activities, impacts are especially strong. First, one or more specific stocks of wild species can be depleted by direct biomass removal, and their future use by humans as a natural resource can be altered (*i.e.* impacts on Biotic Natural Resources (BNR) at the species level). The fish stock concept was developed for management purposes. Briefly, a fish stock is a population or several subpopulations of a particular species of fish for which the effects of immigration and emigration on its population dynamics are considered to be insignificant. Second, the total biomass available for ecosystem functioning is also diminished by this removal, as is the functioning of the whole ecosystem (*i.e.* impacts on Life Support Functions (LSF)). For marine ecosystems, assessing LSF constitutes a challenging issue in the present context of worldwide overfishing. Impacts on LSF can be assessed through the primary biotic production remaining in the environment for ecosystem functioning, as part of Ecosystem Services Damage Assessment. These effects on biotic primary production availability can also be related to the area of protection of natural resources, because they induce a form of BNR depletion at the ecosystem level. Biodiversity loss due to fishing can also be severe, in particular the alpha biodiversity of benthic species due to trawling and dredging on the seabed, with about 75% of global shelf area trawled worldwide every year (Kaiser et al., 2002). Commercial and by-catch species are also concerned due to a high intensity of direct capture (FAO, 2010).

As underlined by Udo de Haes et al. (2002), effects on BNR and LSF have to be assessed separately in LCA when biomass removal occurs. These authors explain in detail that there is no double counting because two different areas of protection are considered (natural resources and ecosystem quality, respectively), even if both account for biomass removal. Concepts of scarcity play a role in assessing damage on BNR, but not on LSF.

In this study, a distinction is made between the effects of biomass removal on BNR at the species and ecosystem levels. Two methods of impact assessment are proposed and detailed for BNR at the species and ecosystem levels, respectively. This work details and discusses methods to calculate characterisation factors (CFs) for these two BNR-impact pathways related to fishing activities. By definition, CFs are calculated during a methodological development stage. They should allow practitioners to assess impacts merely by multiplying CFs by inventory flows defined by the LCA practitioner (depending on the aim of the LCA study).

2. Methods

The perimeter of the study includes impact pathways from biotic resource uptake to the area of protection of natural resources (Fig. 1). One objective of the study was to provide results in comparable units.

2.1. *Fishing activities and biotic-resource extraction impact assessment at the species level*

The goal of biotic-resource depletion impact assessment is to estimate to what extent current biotic extractions decrease the ability of human society to cover future needs, due to fish-stock reductions (Udo de Haes et al., 2002). One commonly used reference to assess fish stocks is Maximum Sustainable Yield (MSY), which is the highest fish catch that can be sustained in the long term (Graham, 1935; Schaefer, 1954). MSY (in t yr^{-1} of wet weight), a function of non-fished stock biomass and population growth rate, results from the assumption that current yearly catches by the fisheries exploiting the given stock at time t (C_t) can be increased up to a maximum level by increasing the fishing effort (E_t) because the catches are compensated by an equivalent fish production. Above the MSY and its corresponding E_{MSY}, renewal of the resource (reproduction and body growth) cannot keep pace with the removal caused by fishing and natural mortality. In this case, further increases in exploitation lead to reduced yields (Fig. 2). MSY can be estimated either with a variety of stock-assessment methods or empirically (Hilborn and Walters, 1992). Rough stock assessments are performed by the Food and Agriculture Organization (FAO), but the most useful database is the RAM Legacy Stock Assessment Database, which includes biological reference points for over 361 stocks, of which 138 have MSY values (Ricard et al., 2012).

We propose to assess the impacts of BNR depletion at the species level ($I_{\text{BNR,sp}}$) as a function of the uptake of a mass (m) of a given marine species and its MSY. The variable m is the inventory flow (t of wet weight) for which LCA practitioners aim to assess impacts. As part of the inventory data, it does not belong to the impact assessment stage. This differentiates fish species according to the size of their stocks and the proportion that can be sustainably removed. The environmental impact on BNR ($I_{\text{BNR,sp1}}$) is thus calculated as:

$$I_{\text{BNR,sp1}} = m \times \frac{1}{\text{MSY}} \tag{1}$$

where 1/MSY is the CF. Thus, impacts of biotic-resource extraction are expressed as a maximum potential regeneration time (in years),

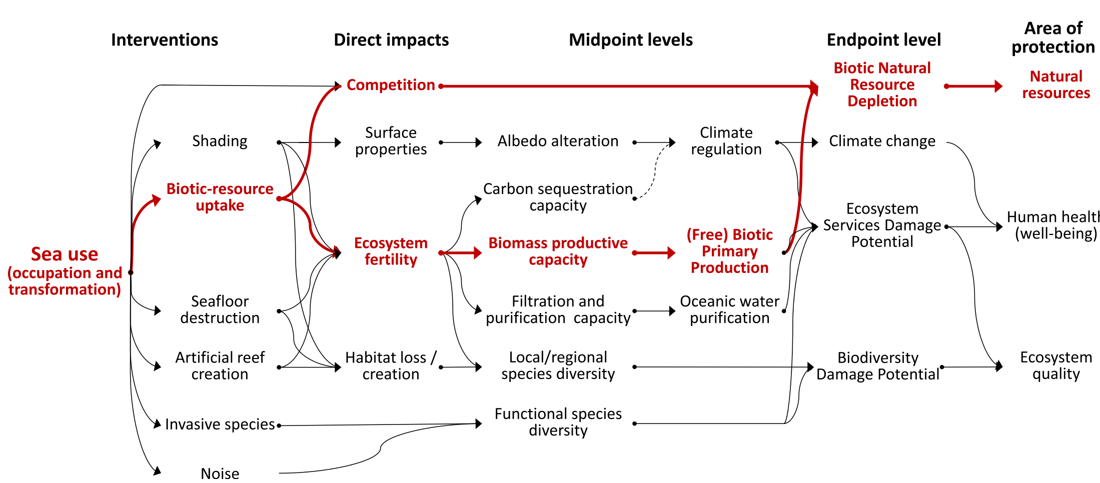

Fig. 1. Impact pathways for biotic natural resource depletion due to biomass removal from the sea (in bold and red) and their location in the global cause-effect chain of sea use. Adapted from Langlois et al. (accepted). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)