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Accounting for the occupation of the marine environment as a natural resource in life cycle assessment: An exergy based approach

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ABSTRACT

The human population is rising and the availability of terrestrial land and its resources are finite and, perhaps, not sufficient to deliver enough food, energy, materials and space. Thus, it is important to (further) explore and exploit the marine environment which covers no less than 71% of the earth's surface. The marine environment is very complex but can roughty be divided into two systems: natural (e.g. wild fishing) and human-made (e.g. artificial islands). In this study, characterization factors (CF) for natural and human-made marine systems were calculated in order to be able to assess the environmental impact of occupying marine surfaces, which was not possible so far in life cycle assessment. When accounting for natural resources while occupying one of these systems, it is important to consider the primary resources that are actually deprived from nature, which differs between the natural and human-made marine systems.

In natural systems, the extracted biomass was accounted for through its exergy content, which is the maximum quantity of work that the system can execute in its environment. Reference flows for marine fish, seaweeds, crustaceans and mollusks were proposed and their correlated CF was calculated. For human-made systems, the deprived land resource is, in fact, the occupied area of the marine surface. Based on potential marine net primary production data (NPP), exergy based spatial and temporal CFs for ocean areal occupation were calculated. This approach was included in the Cumulative Exergy Extraction from the Natural Environment (CEENE) method which makes it the first life cycle impact assessment (LCIA) method capable of analyzing the environmental impact (and more specific the resource footprint) of marine areal occupation. Furthermore, the methodology was applied to two case studies: comparing resource consumption of on- and offshore oil production, and fish and soybean meal production for fish feed applications.

1. Introduction

1.1. Human demand for land resources

Through human history, it has become increasingly evident that the welfare of a population depends on the availability of land and its resources. An estimation of the United States Census Bureau (USCB) revealed a global world population of 7.122 billion people in 2013 which is expected to rise, leading to an increase in consumption of resources (Livi-Bacci, 2012). When the demand for resources is outspacing the capacity of the biosphere (biocapacity), it will strongly affects the Earth's ecosystems. The biocapacity indicates the potential of land and sea areas to serve particular uses and represents the ability of the biosphere to meet the human demand for resources and waste disposal (Ewing et al., 2010b). These areas support significant photosynthetic activity and production of biomass. Less productive areas such as deserts, glaciers and the open oceans are not included. To calculate the biocapacity available per capita, the total biologically productive area (land and sea) on earth was expressed in global hectares divided by the amount of people living on the planet (Kitzes et al., 2007). Today, the available biocapacity per capita is about 1.78 global ha person^{-1} (world average). In contrast, the global ecological footprint, which is the human demand expressed in land area, corresponds to

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2.7 global ha person^{-1}. This results in a 50% overshoot (ecological deficit) (Ewing et al., 2010a).

1.2. Land occupation as a sustainability issue

Obviously, it is not sustainable to put such a pressure on our planet because the ability of future generations to meet their own needs is diminished (United Nations, 1987). Therefore, the occupation and exploitation of productive areas is of great concern. When dealing with the sustainability of particular products that require land areas during their life cycle, the most scientifically sound methodology is Life Cycle Assessment (LCA) (Koellner and Scholz, 2007). This method makes it possible to identify opportunities to improve the environmental footprint of products at different phases of the life cycle and can be used for decision makers in industry and (non-) governmental organizations (International Organization for Standardization (ISO) 2006).

Over the last years, it has been found important to assess the issue of land occupation and its use. For example, many renewable products (e.g. biofuels) seem beneficial for the environment in comparison with the non-renewable alternatives, except for areal land use (Delucchi, 2010). Therefore, the assessment of terrestrial land use (or land occupation) has gained attention in LCA. The use of productive land can lead to several impacts, e.g. loss of soil quality, loss of biodiversity and resource depletion (Finnveden et al., 2009). Some LCIA methods are developed to include these impacts; enclosing midpoint (problem-oriented approach such as climate change) and/or endpoint (damage oriented-approach such as human heath) category indicators. For example, the Soil Organic Carbon (SOC) indicator of Milà i Canals et al. (2007) can be used to model loss of soil quality. Indicators developed to assess the impact on biodiversity are, amongst others, the Potentially Disappeared Fraction (PDF) of species from the RECIPE method (Goedkoop et al., 2009), the Solar Exergy Dissipation (SED) (Wagendorp et al., 2006) and Human Appropriation of Net Primary Production (HANPP) (Haberl et al., 2007). These last two indicators measure to what extend human activity alters the availability of energy (biomass) flows in ecosystems compared to natural processes. For the resource depletion aspect of land use, the ecological footprint can be used. This method makes use of equivalence factors to indicate the productivity of several land types (Huijbregts et al., 2008). Also, the Cumulative Exergy Extraction from the Natural Environment (CEENE) method is able to assess natural resource loss (Dewulf et al., 2007a). From a life cycle environmental point of view, the exploitation of the productive land areas can be accounted for through the amount of biomass harvested (e.g. Cumulative Energy Demand (CED), Hischier et al., 2009 and Cumulative Exergy Demand (CExD), Boesch et al., 2007) or alternatively by assessing the area and time required to deliver a certain amount of resources, in order to avoid double counting (Dewulf et al., 2007a).

1.3. Accounting for marine resources in LCA

Although many LCIA methods today include the impact of terrestrial land occupation on ecosystems, none of them considers the occupation of the much larger ocean surface area (Langlois et al., 2011). Nevertheless, it is important to quantify the environmental impact of this occupation because ever more products are delivered by marine operations, such as wild and farmed fish, seaweed, wind energy and minerals from the seabed (Allard, 2009). Most of these marine operations use relatively young technology. Therefore, the use of marine resources (area and biomass) should be accounted for in LCA studies through the development of LCIA methods that can handle marine areal occupation and resource extraction.

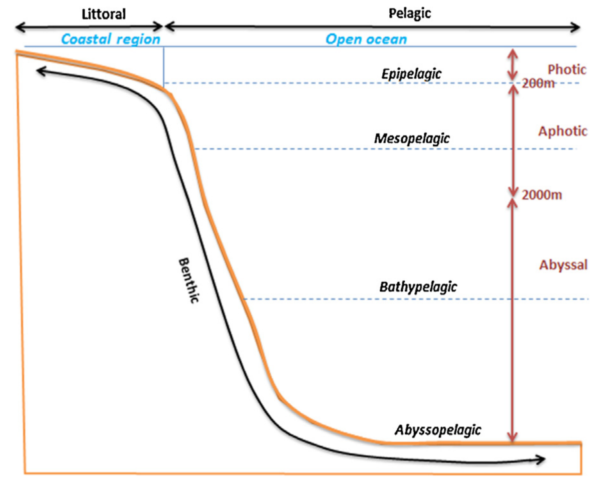

Fig. 1. Zonation of the marine environment. The three large ecological regions are the littoral (organisms living near the shore), benthic (organisms living at near the sea floor) and pelagic zone (organisms living in the open ocean). The latter has 4 large subdivisions: epipelagic, mesopelagic, bathypelagic, abyssopelagic. According to the light availability, three vertical zones can be detected: photic (0–200 m), aphotic (200–2000 m) and abyssal (2000 m-sea floor).

1.3.1. Marine environment

In order to develop the LCIA methods, it seems necessary to understand the complexity of the marine environment, which has an average salinity of about 35 g/kg sea water (Reddy, 2001). Three vertical zones dependent upon the availability of light are usually identified: (1) the (eu)photic zone, which is the water column down to approximately 200 m depth, receives sufficient light for photosynthesis and contains nearly all primary production, (2) the aphotic below the photic zone, reaching down to a depth of about 2000 m, where light is sufficient for vision but not for photosynthesis, (3) the abyssal zone below 2000 m depth, where complete darkness takes place from a biological point. There are also several ecological regions such as the littoral zone, the benthic zone and the pelagic zone. The littoral zone is close to the shore; extends from the high tide mark to the edge of the continental shelf (coastal regions). The benthic zone contains all life in or at the seafloor, from the shore to the deep ocean and the pelagic zone is typically separated into 4 horizontal layers in the open ocean: epipelagic, mesopelagic, bathypelagic, abyssopelagic (Jain and Sharma, 2004) (Fig. 1). Of these zones, the coastal one along the continental shelves is best known and most exploited commercially. It is highly biologically productive and close to the continent, allowing different activities to take place (e.g. aquaculture, tourism, fishing, oil and gas industry).

1.3.2. LCIA method to account for marine resources

To account for natural resources when occupying marine area by different oceanic activities, the CEENE method was used. It is considered as one of the two best thermodynamic resource indicators, mostly through including an approach for assessing land occupation (Liao et al., 2012; Rugani et al., 2011). This method is based on thermodynamics through quantification of resources by their amount of exergy. Exergy is the maximal work a system can deliver in equilibrium with its environment via a reversible process and provides an indication of the quality and quantity of the resource (Wall, 1977). In that way, all resources can be expressed in the same unit; this in turn facilitates interpretation and comparison of results (Dewulf et al., 2007b). The resources are divided in 8 categories: renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water resources, land occupation and atmospheric resources (Dewulf et al., 2007a). In this study, one extra category was added: marine resources. This category included resources from natural and human-made marine systems.