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Development of potential yield loss indicators to assess the effect of seaweed farming on fish landings

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A B S T R A C T

In recent years, several indicators have been proposed to assess the effect of human activities on ecosystems provisioning capacity. Some of these methods focus on the Net Primary Production (NPP) available for ecosystem functioning through the comparison between the Human Appropriated Net Primary Production (HANPP) and the ecosystem's initial NPP at a given reference year. While some approaches have been proposed for marine ecosystems, most of the HANPP studies focus on terrestrial systems. This study highlights the relation between the HANPP methods and the production of natural resources in marine ecosystems. The linkage between current overfishing and future fish provisioning (ecosystem service) is well known. However, less studied before, is the relation between seaweed aquaculture and fish provisioning through the marine food web. Seaweed growth requires nutrients and light that will consequently be no longer available for natural phytoplankton production. As seaweed is periodically harvested, a fraction of the ecosystem's NPP (HANPP) is no longer available for ecosystem production. The HANPP of aquaculture reduces the ecosystem carrying capacity and thus affects commercial fish stocks. Therefore, an integrative approach is proposed in this study to assess the potential effect of seaweed farming on fish landings in the Greater North Sea. Three indicators are proposed to assess the Lost Potential Yield (LPY) in fish landings: LPY_B, LPY_V and LPY_E, accounting respectively for reduction in biomass, monetary value and eco-exergy. For these three aspects, the LPY results remains smaller than the seaweed production, meaning that the overall natural resources balance for seaweed farming is positive.

1. Introduction

The pressures on natural resources are increasing as a consequence of the current trend in human population size. Since oceans cover the majority of the surface area of our planet, the diversification and the regulation of marine resources extraction are crucial to make the most of ocean's production potential. The recent development of the aquaculture sector is one way of diversification and does not only consist of fish and shellfish production. Indeed, the production of aquatic plants (mostly seaweed) accounts for 27.8% (wet weight based) of the total current aquaculture production [1]. Due to its wide range of applications (food, feed, nutraceuticals or biofuels) [2] and its role in eutrophication reduction [3,4], seaweed farming is no longer limited to Asia [5]. Several pilot cultivation test have been performed in the North Sea to grow the sugar kelp *Saccharina latissima* (Linneaus) (Laminariales, Phaeophyceae), a brown seaweed widely distributed in the European Atlantic [6–8]. The kelp is found on subtidal rocky substrates and is composed of a large frond, a stipe and a holdfast.

Nevertheless, the large-scale cultivation of seaweed affects the properties of the surrounding ecosystem by shading [6], artificial reef creation [9] and nutrients uptake [3,4]. Even in the eutrophic coastal areas, the phytoplankton productivity is limited by nutrients availability during the growth season, when light is not a constraint for growth [10]. Therefore, seaweed farming without the addition of nutrients is expected to reduce the magnitude of phytoplankton blooms in spring and summer. In other words, the production of seaweed biomass replaces a fraction of the phytoplankton biomass. While phytoplankton productivity has been proven to affect fisheries yield [11–13], large-

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scale seaweed farming has the potential to reduce fish landings, but this has not been documented so far to our knowledge. Thus, a good methodology is needed to tackle this issue. The existing frameworks for natural resources and ecosystem services are helpful to initiate a first intuitive approach for the impact assessment of seaweed farming on fisheries yield.

Many definitions for natural resources have been proposed and the lack of consensus can lead to misunderstandings while assessing pressures on the natural capital. This issue was considered by an experts group from the United Nation Environment Programme (UNEP) and from the Society of Environmental Toxicology and Chemistry (SETAC) proposing a common definition: "*Natural resources are material and non-material assets occurring in nature that are at some point in time deemed useful for humans*" [14,15]. This broad definition allows for a distinction between biotic and abiotic resources; both can be considered in terms of renewability and finiteness according to their stock and extraction rate. Within biotic resources, Crenna et al. [16] differentiate between *naturally occurring biotic resources* (e.g. wild fish) and *biotic resources resulting from human intervention* (e.g. fish from aquaculture). The production of naturally occurring biotic resources can be addressed from an ecosystem services perspective. The Millennium Assessment [17] defines ecosystem services as "*the benefits that people obtain from the ecosystem*". Three frameworks have been proposed in parallel for ecosystem services classification and all of them consider the production of biotic resources as a provisioning service [18]. Since these frameworks were developed, the socio-ecological link between human activities and the provision of ecosystem services has been investigated [17,19,20]. The human activities influence natural processes [21,22] through direct (e.g. land transformation) and indirect (e.g. changes in biogeochemical fluxes) pressure and thus reduce the intensity and diversity of ecosystem services.

The global economy relies on resource consumption and as abiotic resources are finite, the concept of bio-based economy has progressively emerged. It is defined as the "*economic activities resulting from the production, use and development of biological products and processes*" [23]. The shift toward a bio-based economy does not mean that our society is automatically more sustainable. The renewability of the naturally occurring biotic resources depends on their extraction rate and their regeneration period [16,24]. On the other hand, the biotic resources resulting from human interventions affect the ecosystem functioning and thus the ecosystem capacity to sustain services such as provision of naturally occurring biotic resources [25]. Since most of the services are not marketable, the evaluation of the ecosystem's capacity to provide services is challenging. The net primary production (NPP) of an ecosystem is stated to be a good proxy to assess the flow of services [26–28]. The NPP is the net amount of carbon assimilated by primary producers and is available at the basis of the ecosystem's food web. The higher trophic level's abundance in the ecosystem depends on the NPP, which determines the energy available in the trophic chain. This was illustrated for fish by Capuzzo et al. [11] who highlighted the correlation between marine NPP and fish abundance. The decreasing NPP trend in the North Sea was associated with a reduction in fish stock. This clearly shows the link between NPP and ecosystem services since fish abundance affects fisheries yield in the marine environment. In this case, a NPP decrease affects negatively the naturally occurring biotic resources in upper trophic levels and thus, ecosystem provisioning services.

Because NPP is considered as a proxy for the flow of ecosystem services, the concept of Human Appropriated Net Primary Production (HANPP) is relevant to study the sustainability of biotic resources production (both naturally occurring and resulting from human intervention). The HANPP is quantified as the difference between the NPP in the pristine environment and the NPP in the anthropic environment [29,30]. As global agricultural crop production is increasing to support the world population growth using more bio-sourced products [31–33], the global HANPP is increasing [34] and thus, ecosystems are more affected and less effective in the intensity and diversity of goods and services. HANPP has been mapped for terrestrial systems based on satellite data [30,35]. However, because the oceans currently provide 2% of the calories ingested per capita [36], it is equally relevant to assess potentially declining NPP values in marine ecosystems due to human activities, especially as this contribution is expected to increase with global food demand. Pauly and Christensen [37] quantified the amount of primary production required to sustain fisheries based on the landings and the trophic levels. With this methodology, HANPP resulting from fisheries can be estimated from the fish biomass uptake. Most of the studies assessing pressures from fisheries on ecosystems consider Pauly and Christensen's equation for the evaluation [38]. Similar approaches have been developed for the shading impact of seaweed aquaculture on ecosystem functioning [6,39].

In parallel to NPP, ecosystems health can be studied from a thermodynamic point of view because natural systems tend to move away from the thermodynamic equilibrium by storing energy in biomass [40]. Jorgensen et al. [41] developed a thermodynamic method called "eco-exergy", weighting the energy in the living biomass with their respective genome size. Eco-exergy assesses how far a system is from the reference state, a system made of detritus (i.e. the dead organic matter). The eco-exergy is measured in term of detritus equivalent and can be converted in Joules considering the averaged energy content of detritus [41,42]. This methodology is mainly used for marine ecosystem studies: e.g. to develop a recovery indicator of the benthic community exposed to fish trawling [43], as a goal function in ecosystem modelling [44,45] and as an index for ecosystem health assessment [46–48]. Eco-exergy discerns different kind of biomass according to their genetic complexity and therefore, this approach is relevant to assign specific values to the biotic resources extracted.

While NPP- and eco-exergy-based developments assess human pressures on ecosystem health, Emanuelsson et al. [49] consider the consequences on ecosystem provisioning capacity. This study uses a population dynamic model for fish stocks to compute the "Lost Potential Yield" (LPY) indicator. The LPY estimates the amount of missing caught fish due to current overfishing compared to a sustainable fishing scenario. The calculation of the potential losses in naturally occurring biotic resources extraction due to bad management is particularly relevant to support policy decisions since it shows concretely the impact for human society.

Since the potential impact of seaweed production on fisheries yield has not been assessed yet, this study aims to model the NPP from the seaweed *Saccharina latissima* in aquaculture and develop indicators to assess the potential reductions in fisheries yield due to large-scale seaweed farming in a given zone. This study balances seaweed production (HANPP) and possible reduction in naturally occurring biotic resources (fish landings) in term of biomass, monetary value and eco-exergy. The seaweed productivity is modelled from experimental data and the values are benchmarked to phytoplankton productivity. The impact of seaweed farming on the fisheries yield for the ten most fished species in the North Sea is estimated from phytoplankton depletion (Fig. 2).

2. Materials and methods

Similarly to Emanuelsson et al. [49], we propose to estimate the potential losses in naturally occurring biotic resources due to the production of biotic resources resulting from human intervention. A method is proposed for the evaluation of the effect from seaweed production on fish landings through the LPY indicator in term of biomass (LPY_B), monetary value (LPY_V) and eco-exergy (LPY_E).

2.1. Spatial scale of the analysis

The International Council for the Exploration of the Sea (ICES) identifies ecoregions within the European seas in order to develop an