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The shared environmental responsibility principle: new developments applied to the case of marine ecosystems

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ABSTRACT

Estuaries provide advantageous sites for both harbors and fish habitats. In many countries, harbor expansion in estuaries contributed to the decline of fish populations with impacts at the global scale. Restoring these habitats is important to prevent a global biodiversity crisis but is costly and potentially unaffordable for polluters under the Polluter Pays Principle. Such affordability issues prompt decision-makers to reduce environmental targets of restoration programs. Harbor infrastructures destroy fish habitats but generate benefits for society and contribute to the public interest, raising some questions on who is responsible for environmental degradations and who can afford environmental restoration costs? One way to allocate restoration costs is to analyze the amount of harbor services consumed by economic sectors. This paper addresses these questions by computing burden sharing scenarios with an input–output matrix. These scenarios are simulated under the shared responsibility principle to distribute restoration costs among stakeholders in the Seine estuary, France.

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Input–output model; marine ecosystem destruction; shared responsibility; burden sharing; fish habitat

1. Introduction

In their meta-analysis, Worm et al. (2007) found that biodiversity is positively related to productivity, stability, and the supply of ecosystem services. However, they also found that there is a progressive and consistent loss of marine biodiversity that has overwhelmed fisheries worldwide. If this trend continues, by mid-century the world can expect an ecological crisis which will threaten global seafood resources (Pauly and Zeller, 2017). Anthropogenic disturbances such as fishing, dredging, dike constructions and harbor extensions are exerting an increasing pressure on marine ecosystems (Halpern et al., 2008). Estuarine environments are particularly responsive to these anthropogenic disturbances (McLusky and Elliott, 2004), which have impacted essential habitats for many species in marine

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ecosystems. However, in spite of their significant ecological functions, estuarine nursery habitats around the world continue to be destroyed by harbor infrastructures (Decleer et al., 2016). If nothing is done, greater adverse impacts are to be expected as port activities worldwide are projected to more than double their contribution to global value added by 2030 (OECD, 2017).

International institutions strongly encourage the development of marine protected areas and the creation of new habitats in the areas surrounding harbors as a means to mitigate pressures on marine biodiversity (e.g. Schoukens and Cliquet, 2016; OECD, 2017). However, as suggested in this paper (Section 4.1 and Figure A2 in the Appendix), the way the cost of restoration programs is shared may be relatively unaffordable for polluters when considering the Polluter Pays Principle. This raises questions regarding environmental degradation liabilities and restoration cost affordability. In other words, which economic sectors should pay for restoration and which sectors would be able to pay?

Harbors are major contributors to economic development in estuary regions. As a result, marine habitats located in coastal wetlands have gradually been lost because of harbor expansion (Courrat et al., 2009). One option for reducing marine habitat destruction is to decrease the extent of harbor infrastructure and development, but this plays against the public interest given the benefits harbors provide to society. In particular, harbors attract other economic sectors; they support inland economic activities by connecting sea and land transport; they secure energy supply, and they provide numerous direct and indirect jobs. Moreover, harbors produce a positive externality in that they contribute to climate change mitigation, as water transport emits 14–188 times less CO_2 than air or road transport per km and per ton of commodities (IPCC, 2014, p. 610).

One way to allocate restoration costs is to analyze the ratio of consumption by those who have benefitted from harbor activities, i.e. industries and final consumers of harbor services. In this paper, we calculate several allocation rules with input–output (IO) matrix equations based on environmental responsibility principles discussed in Rodrigues et al. (2006), Lenzen et al. (2007), Lenzen and Murray (2010) and Marques et al. (2012). More specifically, we base our calculations on shared producer and consumer responsibility approaches that rely on the principle of upstream responsibility (Rodrigues et al., 2006; Lenzen and Murray, 2010) – also named consumption-based responsibility (Marques et al., 2012) – to distribute restoration costs among stakeholders that use, either directly or indirectly, harbor services. This leads to the design of shared responsibility scenarios calculated as a function of sectorial value added, gross operating surplus (GOS) or return on investments (depending on the scenario considered) as well as a function of direct and indirect economic linkages between economic sectors and harbor activities. Economic linkages with final consumers (e.g. households) are also included. The shared environmental responsibility calculation developed in this paper shares restoration costs for previously damaged marine habitats between a wide-range of economic agents, thereby preventing industrial harbors from bearing expensive restoration costs alone, and making restoration more likely. This might, however, generate new difficulties since economic sectors who did not bear any restoration cost previously might not gladly accept to bear costs. Nevertheless, according to results from WBCSD and WRI (2011), there are companies that are open to the shared environmental responsibility principle and which might be willing to accept.

Several authors and international organizations have raised justifications for the shared producer and consumer responsibility principle. Read, *inter alia*, Gallego and Lenzen (2005), Lennox and Andrew (2006), Lenzen et al. (2007), Lenzen (2007), Rodrigues and Domingos (2008), Lenzen and Murray (2010) and WBCSD and WRI (2011). This paper is based on the upstream responsibility concept developed by Gallego and Lenzen (2005), Lenzen et al. (2007) and Lenzen and Murray (2010). We extend the conventional environmental responsibility – as considered in the Polluter Pays Principle – from the source (harbors) located upstream in the supply chain, to the intermediate users (industries and firms) and downstream to final users (households and other final demand categories).

The remainder of the paper is organized as follows. Section 2 presents the case study of marine ecosystem destruction in the Seine estuary, North-West France. In that section, we analyze a hypothetical but realistic case addressing habitat restoration to offset past habitat destructions. In Section 3, we develop methods to calculate environmental shared responsibilities to be applied to the case study. Section 4 is devoted to results and discussion while Section 5 is reserved for our conclusions.

2. Case study

The Seine estuary is located in northwest France and is home to the Grand Port Maritime du Havre (named harbor of Le Havre hereinafter). This industrial harbor is the biggest in France in terms of container shipment traffic and the second biggest in terms of crude oil imports. The Seine estuary is also the location for the Grand Port Maritime de Rouen, the second biggest harbor in France for transport of refined petroleum products. Combined, both harbors provide 50,000 direct jobs (HAROPA Ports de Paris Seine Normandie, 2013).

Since the beginning of the nineteenth century, the growth of maritime transport systems has increased the number of dykes and extension of harbor infrastructure on the sea resulting in the ongoing destruction of fish nursery habitats (Ducrotoy and Dauvin, 2008). In the internal part of the Seine estuary, the surface area of potential nurseries with a high density of juvenile fish was 181.91 km^2 in 1834 but has progressively declined to 111.74 km^2 in 2004 (Cordier et al., 2017). Additional destructions occurred from 2002 to 2005 due to an extension project initiated by the French authorities to build a new container terminal "Port 2000" in the harbor of Le Havre (Tecchio et al., 2016). These degradations negatively impacted biodiversity, particularly for seven species of commercial fish (Cordier et al., 2011), and in addition, fishermen requested financial compensations to harbor authorities. However, since nursery areas of the Seine estuary are protected by the European environmental laws of the Birds Directive (European Parliament and Council of the European communities, 2009) and the Habitats Directive (Council of the European communities, 1992), 1 km^2 of fish nursery habitat has been restored by the harbor of Le Havre to offset the destructions (Tecchio et al., 2016). As a result, the fishermen's claims for financial compensation from port authorities were deferred. The restoration took place within a broader compensatory action program initiated in 1995 – the Seine-Aval program – to preserve ecological functions in the Seine estuary (Dauvin et al., 2006). Without careful habitat restoration in the Seine estuary but also in other coastal areas of the English channel, stakeholders who depend on fish resources are potentially at risk: the fishing sector, food industries, restaurants, chemical industries, domestic final demand and extra-regional demand (i.e. interregional and international exports), some sport, recreational and touristic activities, and even the public health sector given the interesting nutritional properties of fish.

Three main stakeholder groups are involved in the environmental management of the estuary. The first is the GIP Seine-Aval (GIP stands for 'Group of Public Interest'). It is a legal entity designed to coordinate the Seine-Aval Program through public-private partnerships to address general public interest issues. The program is still ongoing. One of its aims is to provide knowledge required to understand how the Seine estuary functions in order to optimize the investments needed to restore environmental quality and to reconcile the users of the estuary involved in fishing, industry, tourism and leisure activities. The GIP Seine-Aval is funded by 12 stakeholder groups, which includes the Le Havre harbor, the Rouen harbor, the Seine Normandy Water Agency, the Chamber of Commerce and Industry of Le Havre, the Chemical Industry Federation – Normandie, and several public authorities such as the cities of Le Havre and Rouen, etc. (Ducrotoy and Dauvin, 2008).

The second important stakeholder group involved in the management of the Seine estuary is the 'La Maison de l'Estuaire'. This environmental association, created in 1992, is directed, *inter alia*, by representatives of the harbors of Rouen and Le Havre, the Chamber of Commerce and Industry of Le Havre, the University of Le Havre, environmental protection associations, fishermen, etc. La Maison de l'Estuaire has been entrusted by the State to manage the natural reserve of the Seine estuary, created in 1997 which now covers an area of 85.28 km^2 – most nursery habitats for juvenile fish are located in that area (Ducrotoy and Dauvin, 2008).

The third important stakeholder group is the Conservatoire du Littoral, an environmental agency governed by national, departmental and regional elected representatives. The Conservatoire du Littoral is in charge of land acquisition to secure ecosystem preservation and restoration in coastal areas. The management of land acquired is then systematically entrusted to regions, departments, municipalities, or environmental associations such as the La Maison de l'Estuaire. To further comply with the Habitats Directive and avoid further claims, the Grand Port Maritime de Rouen has offered 7.3 km^2 of coastal areas to the Conservatoire du Littoral over the period 2014–2016 to offset habitat degradation (Conservatoire du Littoral, 2016). Such acquisitions of coastal lands by the Conservatoire du Littoral are essential to ensure ecosystem restoration, which is vital to improving environmental quality since the Seine estuary is still under ecological stress (Tecchio et al., 2016).

3. Method

In this paper, we study five scenarios by which costs of environmental restoration could be distributed based on a shared producer and consumer responsibility framework to restore damaged habitats. In order to assign environmental responsibilities to direct and indirect agents benefitting from harbor extensions, one has to know the respective supply chains or inter-industry relations linked to harbor services. One method that deals with inter-industry relations is input–output (IO) analysis. The IO analysis developed in this paper relies on the national commodity-by-industry table for France, regionalized at the scale of the Seine estuary (Haute-Normandie region) for the year 2012, which is the reference year for this paper. This requires non-survey regionalization techniques to be merged with shared responsibility equations (Section 3.1).

3.1. The regional commodity-by-industry table

The commodity-by-industry table is composed of two square matrices: **V**, the supply matrix, and **U**, the use matrix (the matrices are indicated in bold capital letters, the vectors in bold lower-case letters, and the scalars in italic lower-case letters), where both are made of n commodities and n economic sectors; two rectangular matrices (**Y,** a $n \times f$ matrix representing the final demand and **W**, a $p \times n$ matrix of primary inputs – components of the added value) and six vectors (**x**, a $1 \times n$ column vector of total output per sector j; **q**, a $1 \times n$ column vector of the total demand per commodity i; both identities of the commodity-by-industry table are respected, $\mathbf{q} = \mathbf{q}$' and $\mathbf{x} = \mathbf{x}$', where the apostrophe in exponent means the vector is transposed; **mi**, a $1 \times n$ row vector of interregional plus international imports for intermediate input consumption; **mf**, a $1 \times f$ row vector of interregional plus international imports for final input consumption). All these variables are expressed in monetary terms.

The elements of the four matrices are defined as follows. Each v_{ji} represents the value of commodities i produced by each industrial sector j in the region Haute-Normandie ($j = 1, \ldots, n$; $i = 1, \ldots, n$). Each u_{ij} represents the value of regionally produced commodities i required by each industrial sector j to produce its own output. Each y_{ir} represents the value of regionally produced commodities i consumed by the r categories of final demand ($r = 1, \ldots, f$) which are the following: final consumption by households, non-for-profit organizations and government, gross fixed capital formation, change in valuables, change in inventories, and international and interregional exports. Leakages such as international and interregional imports have been subtracted from the intermediate and final inputs and put in a separate table in order to have domestic (regional) tables. To ensure identity between the use and the supply table, imports are added as a row vector in the use table, in which each mi_j and mf_r represents the imports used by sector j and final demand r respectively. Each w_{lj} is the value of primary input l ($l = 1, \ldots, p$) consumed by each industrial sector j. There are three categories of primary inputs: compensation of employees (i.e. wages and salaries including social contributions and income tax); net taxes on production; and GOS.

The regionalization techniques applied in this paper rely, *inter alia*, on Isard (1951), Jackson (1998) and Lahr (2001). We regionalize the national supply matrix, **V** (representing the outputs of commodity i produced by domestic industry j), and the national use matrix, **U** (representing intermediate demand for inputs of commodity i consumed by industry j), by applying a column-only reduction scalar based on the share of regional value added per sector in national value added per sector. Final demand categories are regionalized based on population statistics, disposable income per inhabitant and total regional intermediate demand per commodity i at regional and national scales. Cordier et al. (2017) provide detailed development of the techniques used to regionalize national commodity-by-industry tables, i.e. supply-use tables provided by Eurostat (accessed in 2017). The commodity-by-industry table obtained by the regionalization method is schematized in

Table 1. The commodity-by-industry table (adapted from Lahr, 2001; Miller and Blair, 2009).

	Commodities	Industries	Final demand	Total outputs
	($i = 1, \ldots, n$; with $n = 64$)	($j = 1, \ldots, n$; with $n = 64$)	($r = 1, \ldots, f$; with $f = 8$)	
Commodities ($i = 1, \ldots, n$; with $n = 64$)		$\mathbf{U}$ u_{ij}	$\mathbf{Y}$ y_{ir}	$\boldsymbol{q}$ q_i
Industries ($j = 1, \ldots, n$; with $n = 64$)	$\mathbf{V}$ v_{ji}			$\mathbf{x}$ x_j
Imports		$\boldsymbol{mi}$ mi_j	$\boldsymbol{mf}$ mf_r	m
Primary Inputs ($l = 1, \ldots, p$; with $p = 3$)		$\mathbf{W}$ w_{lj}		
Total Inputs	$\boldsymbol{q'}$ q_i	$\boldsymbol{x'}$ x_j		

Table 1 (the full table is available in the supplementary materials). The table is used to build an open, static and descriptive IO model of the Haute-Normandie region in 2012.

3.2. Scenarios of marine habitat restoration and cost sharing

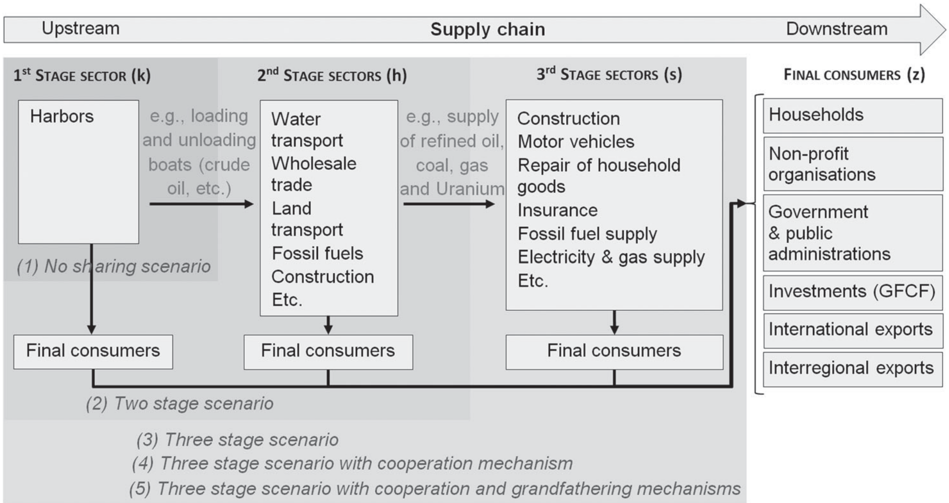
In five offsetting scenarios, we simulate restoration of intertidal nurseries where a high density of juvenile soles are encountered. Restoration activities are expected to last for 11 years starting in 2012 and ending in 2022 (up to 2029 for harbors and the water transport sector in the two last scenarios). The choice of the level of restoration, 23.72 km^2 in the four first scenarios, is based on the decision from local stakeholders who agreed that restoring the area to a level corresponding to the years 1979–1980 would be the most desirable scenario (Cordier et al., 2017).

The regional commodity-by-industry table developed in Section 3.1 is used to calculate the distribution of the cost of nursery restoration in the five scenarios. In the first scenario, restoration costs are not shared while in the following four scenarios, costs are shared among the stages of responsibility across the supply chain (Figure 1) and among economic sectors within each stage. The stages determine the distance of a sector within the supply chain starting from the primary producer directly responsible for habitat destruction, that is, industrial harbors (first stage). Direct industrial customers of harbor services are located in the second stage; industrial customers of commodities produced by second stage sectors are located in the third stage, etc.

The five scenarios mainly differ by the way the total cost of restoration is distributed across sectors in the supply chain (Table 2). We calculate the annual cost based on the surface area restored each year and the unit cost of restoration of intertidal fish nurseries of previous restoration programs effectively implemented in the Seine estuary, i.e. M€ 29.83 per km^2 restored (Port Autonome du Havre, 2000). All prices mentioned in this paper are 2012 prices.

The 'No sharing scenario' applies the Producer Responsibility Principle as in the Polluter Pays Principle: costs of environmental restoration are borne by the economic sectors directly responsible for environmental degradation, that is, industrial harbors (first stage of responsibility).

Figure 1. Shared producer and consumer upstream responsibility across the supply chain of harbor services.



In the 'Two stage scenario', costs of environmental restoration are borne by (*i*) harbors, (*ii*) second stage sectors, which are sectors that purchase services produced by harbors and (iii) final consumers (listed in Section 3.1) who purchase goods and services produced by first and second stage sectors.

In the 'Three stage scenario', costs of environmental restoration are borne by harbors, all second stage sectors, all third stage sectors (i.e. sectors that purchase goods and services produced by second stage sectors) and final consumers of goods and services produced at each stage. Examples of sectors in first, second and third stage responsibilities are shown in Figure 1.

The 'Three stage scenario with cooperation mechanism' is similar to the 'Three stage scenario' with two exceptions. First, sectors that are heavily impacted in terms of profit losses are allowed to extend their restoration period from 11 to 18 years so their annual restoration costs would be lower. Second, other sectors, including final consumers, would agree to bear part of harbors' and water transport's responsibility in nursery restoration (this is the cooperation mechanism). As an example and to test the idea, we arbitrarily propose they would agree to bear 8 km^2 proportional to their GOS (for economic sectors) or to their income (for final demand categories). To make this option more attractive for companies, this might be something they could advertise to improve their image.

The 'Three stage scenario with cooperation and grandfathering mechanisms' is similar to the previous scenario with one exception: the reference year to which the Seine estuary would be restored would be collectively renegotiated and set to 1992 (i.e. the year the Habitat Directive was enacted), instead of 1979 as in the four preceding scenarios (i.e. the year the Birds Directive was enacted). This would reduce the total surface area needed to be restored to 19.43 km^2 instead of 23.72 km^2 (Table 2). The novelty of this scenario is the Grandfathering Principle. In environmental legislation, grandfather clauses stipulate that specific regulations are not applicable to firms or products already active in the market at the time legislation was implemented (Robertson, 1996; Knight, 2013). In the

Table 2. Variables and scenarios used to allocate restoration costs of fish nursery habitats.

	No sharing scenario	Sharing scenarios			
	Single stage	Two stages	Three stages	Three stages with cooperation	Three stages with cooperation and grandfathering
Variables					
Grandfathering reference year	1979	1979	1979	1979	1992
Additional restoration burden for non-harbor sectors (km^2)	0	0	0	8	8
Restoration period for sectors with financial difficulties (years)	11	11	11	18[a]	18[a]
Calculation of sharing rules between stages based on:					
• Value added/net output	No	Yes	Yes	Yes	Yes
• Net GOS/output	No	Yes	Yes	Yes	Yes
• Return on investment	No	Yes	Yes	Yes	Yes
Impacts on restoration					
Total restoration of nursery areas (km^2)	23.72	23.72	23.72	23.72	19.43
Annual total restoration cost on the 2012–2022 period (M€)	64.31	64.31	64.31	58.57–60.76[b]	48.75–51.31[c]

[a] The period extension is exclusively applied to the harbor and the water transport sectors. For the latter, the restoration period is extended to 18 years only in scenarios whose stage sharing is based on Net GOS/output and on ROI (in both scenarios, the additional restoration burden – 8 km^2 – borne by non-harbor sectors are half subtracted from harbors responsibility and half from water transport responsibility).

[b] 58.57 M€ when stage sharing is based on net GOS/output, 59.90 M€ when based on ROI and 60.76 M€ when based on value added/net output.

[c] 48.75 M€ when stage sharing is based on net GOS/output, 49.84 M€ when based on ROI and 51.31 M€ when based on value added/net output.

four first scenarios in Table 2, stakeholders implicitly apply grandfathering to marine habitat destruction by setting the reference year to 1979, i.e. the year the Birds Directive was enacted to preserve bird habitats, some of which also serve as fish nursery habitats. This means any economic activity that destroyed nursery areas before the Birds Directive was enacted would be exempted from restoring those nurseries. However, in the 'Three stage scenario with cooperation and grandfathering mechanisms' – the last one in Table 2 –, we set the grandfathering reference year to 1992, i.e. the year the Habitat Directive was enacted.

As the number of responsibility stages increases, the transaction cost may also increase since more producers and consumers are included (OECD, 2004). With this in mind, the restoration scenarios exclusively consider firms with annual gross earnings over M€ 2, reducing the scope of responsible producers from 215,954 total companies in the Seine estuary to 4393 companies (our own calculation in the Orbis database produced by the Bureau van Dijk – A Moody's Analytics Company, 2014).

3.3. *Mathematical formulation of shared responsibility*

The mathematical formula of upstream shared responsibility has been developed by Gallego and Lenzen (2005). They divide the responsibility of environmental degradation between all agents throughout the supply chain in a way that reflects their contribution to the production and consumption process. They start from sector k, the initial sector directly responsible for environmental degradation – harbors in our case study. They make sector k accountable for a fraction $(1-\beta_k)$ of its final demand y_k plus a fraction $(1-\alpha_{kh})$ of its intermediate output. The responsibility for the remaining fraction α_{kh} of the sector's intermediate output is assigned to its intermediate downstream users (2nd stage sectors in Figure 1). Lastly, the responsibility for the remaining fraction β_k of the sector's final demand is assigned to final consumers (households, non-profit organizations, government, investors, interregional and international exports). Thus, the responsibility for the commodity's output k – harbor services – is distributed to all sectors and final demand categories in stage 1. In a similar equation, Gallego and Lenzen (2005) calculated the way the amount assigned to the 2nd stage of the supply chain is distributed between the sectors of that stage (Figure 1). The same distribution process repeats itself as we move down the supply chain, from sectors h (2nd stage) to sectors s (3rd stage), etc. Calculating the first and the second line of each Gallego and Lenzen equation (2005, p. 374) leads to each line of Equation 1. This equation gives the total responsibility for the environmental impact of the commodity output q_k of an upstream sector k across the stages of the supply chain:

$$q_k = \begin{cases} \overbrace{\Phi_k}^{\text{Historical coefficient}} & \overbrace{[\beta_k y_k}^{\text{Final consumers}} + \overbrace{(1-\beta_k)y_k + (1-\alpha_{kh})(q_k - y_k)]}^{\text{Producers}}, \text{ Stage 1} \\ \sum_h (\alpha_{kh} a_{kh} \Phi_h & [\beta_h y_h + (1-\beta_h)y_h + (1-\alpha_{hs})(q_h - y_h)]), \text{ Stage 2} \\ \sum_s (\alpha_{kh} \alpha_{hs} a_{kh} a_{hs} \Phi_s & [\beta_s y_s + (1-\beta_s)y_s + (1-\alpha_{st})(q_s - y_s)]), \text{ Stage 3} \\ & + \\ & \text{etc.} \end{cases} \quad (1)$$

Calculating the result of each line of Equation 1 gives the total responsibility for each stage. In addition, calculating the left and right terms of the equation separately for each line gives the responsibility of final consumers (i.e. final demand categories) and producers (i.e. economic sectors) respectively. To compute the results shared below, we apply Equation 1 except we drop the sum symbols Σ_h and Σ_s to calculate the responsibility of each of the 64 sectors j ($j = 1, \ldots, n$; $n = 64$, see Table 1) at each stage instead of the total responsibility of the stage with all sectors together.

Equation 1 can be read as follows: of any impact that a producer j inherits from upstream or causes on site, this producer j passes on a fraction α_j to other next stage producers, and a fraction β_j to final consumers. The same producer j retains the responsibility for fractions $1-\alpha_i$ and $1-\beta_j$. Hence, the parameters α_j (the producer responsibility share) and β_j (the consumer responsibility share) are numbers between 0 and 1. The responsibility share of q_k allocated to final consumers (*$\beta_k\, y_k$, $\beta_h\, y_h$, $\beta_s\, y_s$, etc.)*, is distributed among 6 categories r of final consumers (see Figure 1) in proportion to their total final consumption across the 64 commodities i and the 6 categories r of the use table as follows: $\Sigma_i\, y_{i,r} / \Sigma_{i,r}\, y_{i,r}$. As in Lenzen et al. (2007, p. 34) in Equation 1, we calculate $1-\alpha_{kh}$, $1-\alpha_{hs}$, $1-\beta_k$, $1-\beta_h$, and $1-\beta_s$ as follows for each sector j:

$$(1-\alpha_j)^b = (1-\beta_j)^b = \left(\frac{w_j}{x_j - \tau_{jj}}\right)^b, \quad (2)$$

where b signals that Equation 2 is calculated at each stage k, h and s. And we calculate α_j as follows:

$$\alpha_j = 1 - \frac{w_j}{x_j - \tau_{jj}}, \tag{3}$$

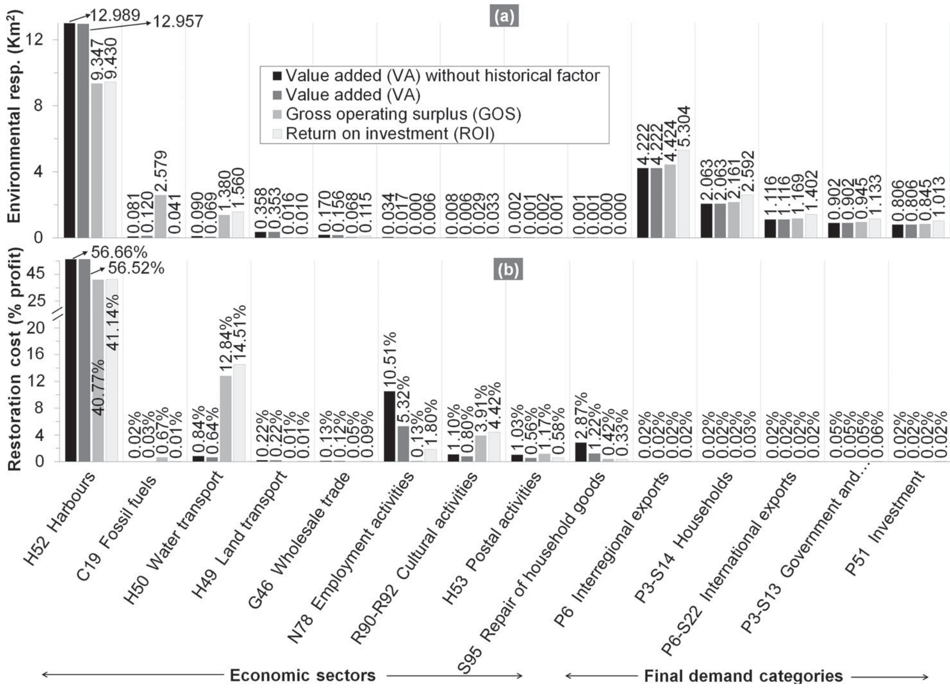
where $w_j = \sum_l w_{l,j}$ (for $l = 1, \ldots, p$; see Table 1) is the value added of sector j that consumes an intermediate input from an upstream sector in the supply chain related to the original harbor production ($i = 34$) at the first, second or additional stages. $x_j - \tau_{jj}$ is the total output produced by sector j minus intra-industry transactions, in other words, it describes the net output. Lenzen et al. (2007) proposed an Equation 2 as a solution to avoid arbitrariness (e.g. 50–50% sharing between consumers and producers or 25% sharing between each of the four responsibility stages). As a result of Equation 2, $\alpha_j$and β_j are now only a function of the value added, total output and inter-industry transactions of industry j, and hence, α_j can replace β_j.

Historical coefficients were not included in Gallego and Lenzen (2005) and Lenzen et al. (2007)'s equations because they address environmental degradation in the form of flows (e.g. pollutant emissions) occurring in present time. However, in this paper we address environmental degradation occurring in the past with a cumulated effect over time in the form of stock (e.g. stock of remaining marine habitat). Since we apply Gallego and Lenzen's equations to the specific case of past habitat destruction, it requires a new vector of historical coefficients (Table A1 in the Appendix) to be entered in the equations. This vector modifies environmental responsibility shares in proportion to the life span of industries in each sector in order to take into account the time companies have been contributing, either directly or indirectly, to marine habitat destruction, as suggested by, *inter alia*, Knight (2013). The historical coefficients are calculated as follows: $\Phi_j = (e_j^{2012}/\bar{e}_j^{2012})\psi_{\text{adjust}}$, where e_j^{2012} is the average life span of sector j since its creation date up to 2012 calculated across all companies of sector j as given by the Orbis database produced by the Bureau van Dijk – A Moody's Analytics Company (2014); $\bar{e}_j^{2012}$ is the average life span calculated across all the n sectors $\left(\sum_{j=1}^{n} e_j^{2012}/n\right)$. As a result, a sector with companies older than the average will have a higher coefficient Φ_j value than a sector made of younger companies. $\psi_{\text{adjust.}} = (\psi_{\text{sectors}}^{\text{No historical factor}}/\psi_{\text{sectors}}^{\text{With historical factor}})$ is an adjustment factor to ensure that historical factors do not change the allocation between final demand categories and economic sectors since no historical factors are applied to the former (i.e. $\Phi_j = 1$) whereas historical factors are applied to the latter (i.e. $\Phi_j \neq 1$), where $\psi_{\text{sectors}}^{\text{No historical factor}}$ is the total surface area of nurseries restored by economic sectors (final consumers excluded) when historical factors are not applied.

In the end, to compute the environmental responsibility displayed in Figures 2(a)– 4(a) as well as Figures A1(a) and A2(a), we multiply each line of Equation 1 by the environmental factor calculated as follows: total nursery area restored per year (ψ^t) / total harbor output in 2012 ($x_{j=34}^{t=2012}$). This environmental factor represents the amount of nursery area to be restored annually per unit of output.

In Equation 1, the coefficients 1; a_{kh}; and a_{kh} a_{hs} before the brackets express respectively the share of commodity output q_k produced by sector k in the first stage of the supply chain, the share a_{kh} of this production q_k that is supplied to second stage sectors h, the share a_{kh} a_{hs} of q_k used and transformed by second stage sectors to supply third stage

Figure 2. Two stage scenario: (a) Sharing of responsibilities for nursery habitat destruction and (b) annual nursery restoration cost (2012).



Notes: in Figures 2(a)–4(a) and A1(a)–A2(a), the environmental responsibility ('Environmental resp'.) represents the surface area each sector and the final consumer should restore to offset its environmental responsibility in nursery habitat destructions. Results in Figures 2–4 and A1–A2 include historical factor weighing except when specifically mentioned.

sectors *s*, etc. We calculate these share coefficients with the Taylor expansion of the Leontief inverse $(\mathbf{I}-\mathbf{A})^{-1}$ (Lenzen et al., 2007): $(\mathbf{I}-\mathbf{A})^{-1} = \mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\ldots$ where $\mathbf{I}$ is the $n \times n$ identity matrix (Miller and Blair, 2009), and $\mathbf{A}$ is the $n \times n$ matrix of technical coefficients calculated by matrix equations as in Miller and Blair (2009) with the commodity-by-industry table schematized in Table 1. Taylor expansion of the Leontief inverse allows us to automate the calculation of shared responsibility for each sector at each stage of the supply chain in an existing case study made of 64 economic sector categories.

Taylor expansions of the Leontief inverse are usually calculated in an industry by industry table. It is possible, however, to obtain them from a commodity-by-industry table since an entire supply-use block can be inverted; there is no need to transform into IO form (Lenzen and Rueda-Cantuche, 2012). We proceeded as follows to calculate $\mathbf{A}$ in supply-use form as in Table 1: the Leontief inverse takes the form of $[\mathbf{D}(\mathbf{I}-\mathbf{BD})^{-1}]$ in commodity-by-industry tables where the bracketed matrix is called an industry-by-commodity total requirements matrix (Miller and Blair, 2009); $\mathbf{D}$ is a $n \times n$ matrix of technical coefficients $d_{ji} = v_{ji}/q_i$ named *commodity output proportion* calculated from intermediate outputs in the make matrix $\mathbf{V}$; $\mathbf{B}$ is a $n \times n$ matrix of technical coefficients $b_{ij} = u_{ij}/x_j$ named *commodity input proportion* calculated from intermediate inputs in the use matrix $\mathbf{U}$ (Lahr, 2001; Miller and Blair, 2009;). As a result, $\mathbf{A}$ is calculated as follows:

if $(\mathbf{I}-\mathbf{A})^{-1}=\mathbf{D}(\mathbf{I}-\mathbf{BD})^{-1}$, then $\mathbf{A}=\mathbf{I}-[\mathbf{D}(\mathbf{I}-\mathbf{BD})^{-1}]^{-1}$. Similar to Lenzen et al. (2007, pp. 39–40), we adapt the Taylor expansion to calculate the shared responsibility as follows: $(\mathbf{I}-\boldsymbol{\alpha}\#\mathbf{A})^{-1}=\mathbf{I}+\boldsymbol{\alpha}_{kh}\#\mathbf{A}+\boldsymbol{\alpha}_{kh}\boldsymbol{\alpha}_{hs}\#\mathbf{A}^2+\ldots$; where $\mathbf{I}$ is the identity matrix from which we take the coefficient for the harbor sector at the first stage, $\mathbf{A}$ is the matrix of elements a_{kh}used at the second stage of responsibility, $\mathbf{A}^2$ is the matrix of elements resulting from the multiplication $a_{kh}\,a_{hs}$ used at the third stage, etc. In other words, each a_{kh} and $a_{kh}\,a_{hs}$ are an element A_{ij}, and A^2_{ij} of the $n\times n$ matrix $\mathbf{A}$ and $\mathbf{A}^2$ respectively (with $n=64$; $i=1,\ldots,n$; and $j=1,\ldots,n$). These matrices are calculated in the regional *commodity-by-industry table* from Table 1, also known as a structural path, with our case study being the path of a marine habitat destructions caused initially by industry sector k (harbors), and passed on via industry sectors h, s and to final consumers as illustrated in Figure 1. The symbol '#' means element-wise multiplication.

3.4. Alternative mathematical formulas of shared responsibility

In Equations 2 and 3, Lenzen et al. (2007) calculate the share of environmental responsibility between the three stages based on the value added/net output ratio. In this sub-section, we propose two alternative allocation rules between the four responsibility stages (final demand is included as the fourth one): the first is based on the share of profit in the annual gross earning (net GOS/output) and the second is based on return on investment (net GOS/capital, named ROI hereinafter). We apply these alternative ratios to the four sharing scenarios presented in Section 3.2. Regarding Equation 1, it remains the same. However, we modify Equations 2 and 3 as follows:

$$(1-\alpha_j)^b=(1-\beta_j)^b=\begin{cases}\dfrac{NetGOS_j}{x_j}\\[2ex]\dfrac{NetGOS_j}{k_j}\end{cases}. \tag{4}$$

Then, we calculate α_j as follows:

$$\alpha_j=\begin{cases}1-\dfrac{NetGOS_j}{x_j}\\[2ex]1-\dfrac{NetGOS_j}{k_j}\end{cases}. \tag{5}$$

where $NetGOS_j$ is the gain from investment (i.e. the GOS of sector j earned in the current year) less the cost of investment (i.e. investments made by sector j in the current year). This gives the net gain, i.e. the part of GOS which sector j can use for any other purpose (e.g. to find ecological solutions to marine habitat destructions) and would not need to invest to renew old fixed capital. The ratio $NetGOS_j/k_j$ is ROI, i.e. the share of net gain earned by sector j in the current year thanks to investments accumulated in past years which have formed the stock of total gross fixed capital (k_j).

4. Results and discussion

4.1. Sharing rule based on value added

Figure A2(a) (Appendix) shows the 'No sharing scenario' where harbors take on the entire restoration cost as if a conventional Polluter Pays Principle were applied. Figure A2(b) shows the annual restoration cost borne by harbors in that scenario represents 103.5% of their annual profit (hereinafter, profit is measured by the GOS in 2012). This means a 3.5% deficit for that sector if it does not take other offsetting financial measures (e.g. slowing down salary evolution for its employees, reducing shareholder profits, etc.).

Figure 2(a) displays the 'Two stage scenario' in which environmental responsibility is predominantly distributed between three sectors – harbors, land transport and wholesale trade (entire names of sectors are provided in Table A1 in the Appendix) – as well as five final demand categories: consumers from outside the region (interregional exports), households, foreign consumers (international exports), governments and public administrations, and investors. Figure 2(b) shows that among the sectors and final consumers mentioned above, only the harbor sector would be significantly impacted by annual restoration costs.

Unexpectedly, in this scenario, the four sectors that are responsible for an extremely low level of environmental degradation bear annual restoration costs representing a relatively high share of their profit. This includes Employment activities (e.g. temporary employment agency), Repair of household goods, Cultural activities and Postal activities. This can be explained by the relatively small amount of profit these sectors generate compared to the amount of annual restoration costs allocated to them. In addition, since restoration cost allocation among sectors within a stage n is proportional to the amount of commodities purchased to upstream sectors located in stage $n-1$, it does not take into account the amount of profit (profits are, however, specifically taken into account in Section 4.2). If no alternative solutions or compensation measures are taken, the implication for these four sectors might be an unjustified loss of competitiveness (e.g. reduced investment capacity compared to their competitors in other regions or countries, highest production cost with the risk they need to transfer part of the cost onto the prices of their good or services, etc.), which might result in employment or salary cuts. However, when the historical factor is applied, it takes companies' lifespans into account in their share of environmental responsibilities, therefore, the annual restoration cost drops drastically for these four sectors.

Figure 3(a) and (b) display the 'Three stage scenario' in which environmental responsibility and annual restoration cost distribution across sectors and final demands follow the same pattern as in the previous scenario. The only difference with the 'Two stage scenario' is that the values are slightly higher for non-harbor sectors because they bear a third stage responsibility in addition to the second stage.

Figure 4(a) and (b) show the results for the 'Three stage scenario with cooperation mechanism' while Figure A1 (a) and (b) (Appendix) display the results for the 'Three stage scenario with cooperation and grandfathering mechanisms'. As previous figures, they show that historical factors succeed in reducing restoration costs for sectors heavily impacted in terms of profit losses. They also show that applying a cooperation mechanism helps in that sense too, and in an even greater extent when it is applied with a grandfathering mechanism.

Figure 3. Three stage scenario: (a) Sharing of responsibilities for nursery habitat destruction and (b) annual nursery restoration cost (2012).

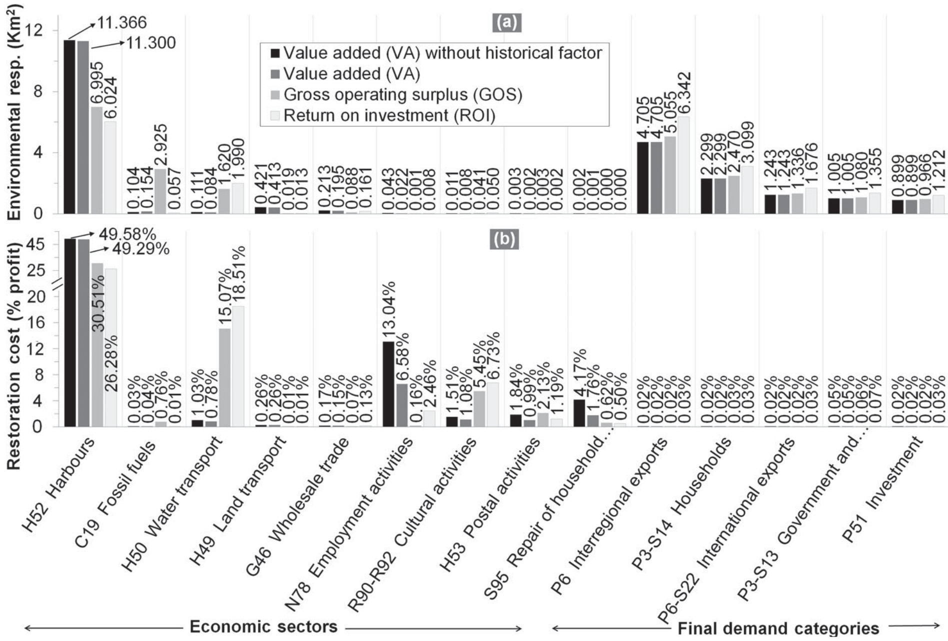
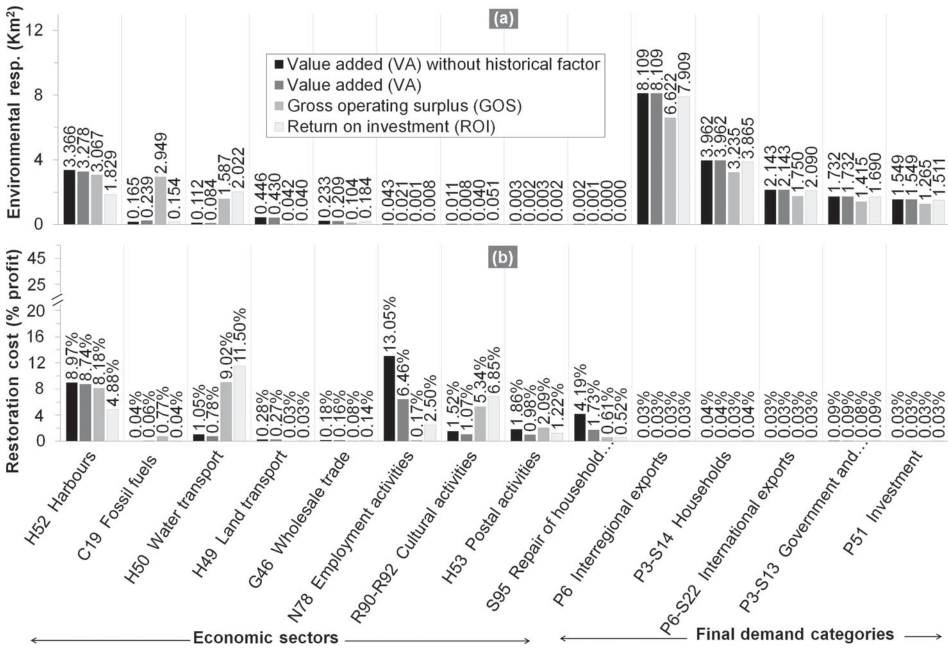


Figure 4. Three stage scenario with cooperation mechanism: (a) Sharing of responsibilities for nursery habitat destruction and (b) annual nursery restoration cost (2012).



4.2. Sharing rules based on GOS and return on investment

Sub-section 4.1 suggests that calculating an allocation rule based on value added (Equation 3) weighed by historical factors within the 'Three stage scenario with cooperation and grandfathering mechanisms' could markedly reduce annual restoration costs for each sector and allocate them more evenly – i.e. the peaks are lower for heavily impacted sectors in Figure A1(b) compared to Figures 2(b)–4(b). However, results are not so beneficial to the sector of Employment activities which, in spite of its little environmental responsibility, bears an annual restoration cost amounting to 5.2% of its profit (Figure A1(b)).

Applying the alternative ratios based on GOS (Equation 6) or ROI (Equation 7) with historical factor weighing offers a solution: annual restoration costs for Employment activities do not exceed 2.5% of their profit whatever sharing scenario is considered (Figures 2(b)–4(b) and A1(b)). Moreover, annual restoration costs for harbors are lower in most scenarios compared to allocation results obtained with the value added ratio (Section 4.1). However, two new sectors become significantly involved in the environmental responsibility sharing: the water transport and the fossil fuel sectors. The water transport sector bears an annual restoration cost that represents 12.8% of its profit in the 'Two stage scenario' calculated with the GOS ratio and 14.5% with the ROI ratio. Those percentages are much lower for the fossil fuel sector (0.67% and 0.01%, respectively) in spite of a much higher environmental responsibility. The 'Three stage scenario with cooperation mechanism' in Figure 4(b) is successful to significantly reduce the water transport burden to more acceptable levels. However, the annual restoration cost becomes quite high for the sector of Cultural activities in spite of its low environmental responsibility (Figure 4(a)). The 'Three stage scenario with cooperation and grandfathering mechanisms' is successful to reduce annual restoration costs for both, cultural activities and the water transport sectors (Figure A1(b) in the Appendix).

Applying the GOS ratio within the 'Three stage scenario with cooperation and grandfathering mechanisms' might contribute to improving the social legitimacy of the shared environmental responsibility principle since annual restoration costs are markedly reduced for non-harbor and non-water transport sectors. However, the annual restoration cost for the water transport sector increases more noticeably and reaches 7.3% of its profit (Figure A1(b)). This can, however, be justified by its huge responsibility as a second stage sector in the supply chain. It directly consumes harbor services and is, thereby, indirectly responsible for harbor development and extensions on marine habitats. The same goes for the fossil fuel sector, which has to restore between 2.4 and 2.9 km^2 when the GOS ratio is applied in scenario calculations. This represents quite a high environmental responsibility. However, the financial impact on the fossil fuel sector is very low due to the huge amount of profits it generates each year. Including more significantly the fossil fuel sector in the shared environmental responsibility principle also increases the legitimacy of the principle since the fossil fuel sectors represents 51% of commodities transiting through the industrial harbors of the region in 2012 (HAROPA Ports de Paris Seine Normandie, 2013). They bear, therefore, as a second stage sector, a huge indirect responsibility for harbor extensions on marine habitats.

However, if the 'Three stage scenario with cooperation and grandfathering mechanisms' seems promising in terms of social acceptability for most stakeholders, some sectors might claim that the cooperation mechanism (Section 3.2) is unfair in itself. Why should they pay a part of restoration costs for companies with financial difficulties? Such sectors might prefer the 'Three stage scenario' whose sharing calculation rules rely exclusively on direct and indirect environmental responsibilities. However, applying the value added ratio in that scenario causes such an impact on profits (Figure 3(b)) that the feeling of inequity and illegitimacy might be even greater. The GOS or the ROI ratios might then be preferred since they offer a more satisfying solution for the most impacted sectors. In that case, the cultural sectors might be willing to negotiate its inclusion into the cooperation mechanism given the relatively high financial impact it bears (when compared to its small environmental responsibility).

5. Conclusion

Our paper suggests that allocating the costs of habitat restoration exclusively to economic sectors responsible for direct habitat destructions may be unaffordable for them. This might prompt decision-makers to lower restoration targets or otherwise play against the public interest when direct polluters generate benefits and positive externalities for society. This is why we developed the shared environmental responsibility principle in which companies and households that purchase goods and services to direct polluters are also made responsible for environmental degradations.

There are several reasons why the shared environmental responsibility calculations presented in this paper are likely to be more acceptable for businesses and households compared to other burden sharing calculations. First, our method succeeds in markedly reducing profit losses per economic sector and income losses for final consumers bearing costs of marine habitat restoration, especially when weighing by historical factors. Second, as proposed in Gallego and Lenzen (2005), the cost allocation rules between various responsibility stages is less arbitrary and based on indicators that measure suppliers' and recipients' financial control, innovation potential, their influence over production processes and their options to substitute suppliers or buyers (Global Reporting Initiative, 2002; Lenzen et al., 2007). This is of the utmost importance because without a good level of acceptability for stakeholders, burden sharing has little chance of being applied, which reduces the likelihood of costly habitat restoration and its significant positive impacts for marine ecosystems.

In addition to the value added ratio used by Lenzen et al. (2007), to compute the indicator above mentioned, we used two alternative indicators: the return on investment (ROI) and the net GOS. Both might offer a more reliable measure since it is what gives control to a company over its industrial process and shows its financial capacity to invest in green innovations and develop more environmentally friendly production processes.

Our results show how shared environmental responsibility calculations could help stakeholders find legitimate ways to acceptably fund marine habitat restoration. This can be achieved by organizing participative discussions between stakeholders about the choice of at least five types of variables used in the shared environmental responsibility calculations (see Table 2): (*i*) the variables selected to share costs between stages across the supply chain, i.e. value added/net output, net GOS/output, or ROI; (*ii*) the variable used to share costs between economic sectors within a same stage (intermediate inputs, i.e. raw materials and semi-finished products); (*iii*) the grandfathering reference year; (*iv*) the extra share of responsibility for some sectors to help offset costs for more financially impacted sectors; and (*v*) the length of the restoration period for more financially impacted sectors. Playing with those five variables to compute restoration cost allocation rules might also help increase social acceptability of the shared environmental responsibility principle in environmental policies in general.

We also show that switching from the value added ratio to the GOS or the ROI ratios in shared responsibility calculations allows for two additional sectors to be included in marine habitat restoration activities: fossil fuel and water transport companies. This might help to increase social acceptability of the shared environmental responsibility principle since both sectors have a significant indirect environmental responsibility at the second stage in the supply chain.

The next steps in our work are aimed at applying the shared environmental responsibility principle to a concrete application in the Seine estuary, France. Here, the GIP Seine-Aval is a key stakeholder group (see Section 2), with a role as a legal entity in charge of coordinating the Seine-Aval Program, an environmental program aimed at studying how optimizing the investments needed to restore the environmental quality and at reconciling the users of the estuary (fishermen, industries, tourism services, etc.). A key advantage for making the GIP Seine-Aval a stakeholder in shared responsibility initiatives are its funders. Many of them are important companies from economic sectors involved in direct and indirect habitat destructions, for example, the harbors of Le Havre or the Chemical Industry Federation-Normandie (Union des Industries Chimiques-Normandie) which includes fossil fuel industries such as ExxonMobil and Total. These companies are typically good candidates for the shared environmental responsibility principle because of the environmental damages they cause and the need to improve their public image (e.g. oil spill in the Bretagne region caused by the Erika's shipwreck in 1999, a ship that transported oil for the French company Total; the heavy smoke emitted into the air in Normandie in 2018 after a technical incident in an ExxonMobil factory, etc.).

The GIP regularly organizes workshops and annual scientific conferences with local stakeholders – e.g. private companies, harbors, scientists, fishermen, decision-makers – to address environmental management and the ecological, social and economic evolution of the Seine estuary. Our plan unfolds in three steps. The first is to present the shared environmental responsibility principle at one of these meetings. The second is to lead a participative workshop supported by the GIP to discuss with local stakeholders the five types of variables above mentioned and adapt them according to stakeholder needs and constraints. This will help to reach a consensus on a set of rules that will condition the calculations of the shared environmental responsibility principle and that will be written by local stakeholders themselves. The third is to invite stakeholders to co-design a detailed plan for a real implementation of the principle. Participative workshops will be organized based on the experience of the Greenhouse Gas Protocol Initiative that applied the shared environmental responsibility principle to the case of greenhouse gas reduction. In 2010, 35 companies involved in the Greenhouse Gas Protocol Initiative road tested the principle in a voluntary framework. The companies provided feedback together with 60 organizations and 350 stakeholders on the practicality and the acceptability of the principle (WRI and WBCSD 2011).

The GIP does not have the power to impose compulsory rules. The shared environmental responsibility principle will necessarily be proposed to be joined on a voluntary basis.

Companies that decide to join would benefit from an improved public reputation through advertisements and public support from environmental associations such as La Maison de l'Estuaire, from national environmental agencies such as the Conservatoire du Littoral, and from public authorities of the region of Haute-Normandie or the city of Le Havre and Rouen. La Maison de l'Estuaire, as well as the Universities of Rouen, Le Havre, Caen, and Agrocampus Ouest, demonstrated in the past their capacity to monitor the outcomes of a restoration program in the Seine estuary (e.g. regular observation and measure of restored marine habitats in the sea to make sure they do not silt up, hydrodynamic and sedimentary modeling to estimate future evolutions, biological modeling to estimate the amount of juvenile fish sheltered in marine habitats, etc.). These organizations will have a stake in the design of a monitoring plan during the participative workshops to assess the ecological, social and economic outcomes of marine habitat restoration undertaken under the shared environmental responsibility principle."

There is room for further research regarding extra-regional impacts of the shared environmental responsibility principle developed. The way we included interregional and international trade in the shared environmental responsibility principle involves two options. The first, exporters of commodities that transit by industrial harbors of Haute-Normandie would pay an environmental charge either on a voluntary or on a compulsory basis. The second would be that industrial and final consumers located outside the region who purchase commodities from Haute-Normandie would directly bear restoration costs. For international trade, such options may be considered as tariff barriers and this requests case-by-case law studies (McIntosh et al., 2015).

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