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M. Cordier, T. Poitelon and W. Hecq

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Keywords: input-output model; marine habitat destruction; Restoration cost; shared environmental responsibility; burden-sharing; environmental tax.

JEL Classifications: C5, C6, E1, L9, Q01, Q5

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Abstract. For decades, industrial harbor expansion has been destroying coastal marine ecosystems. Many estuaries are sites for industrial harbors and critical fish nursery habitat. Considering fish population decreases and the global biodiversity crisis, restoring these habitats is justified and supported by international institutions. However, restoration programs can be prohibitively costly, particularly when considering the Polluter Pays Principle. While harbors destroy nurseries, at the same time they generate benefits for society and contribute to the public interest. This raises questions of who is responsible for environmental degradation and who can afford environmental restoration costs? One way to allocate restoration costs is in proportion of those who have benefitted from harbor activities. This paper addresses these questions by calculating burden-sharing scenarios with input-output matrix equations. These scenarios are based on a shared producer and consumer responsibility approach to distribute restoration costs among stakeholders that use, either directly or indirectly, harbor services. The scenarios are applied to the Seine estuary, France, and calculated as a function of sectorial value-added as well as 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.

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1. INTRODUCTION

Coastal wetlands provide critical supporting ecosystem services (Millennium Ecosystem Assessment 2005), including essential habitat for many species, and they play an important role in sustaining marine biodiversity and fishery resources. In spite of their significant ecological functions, estuarine nursery habitats around the world continue to be destroyed by harbor infrastructures (Turner et al. 2000, Yozzo et al. 2004, van der Veer et al. 2015, Dafforn et al. 2015, Decleret et al. 2016).

Harbor are major contributors to economic development in estuary regions. As a result, coastal wetlands have been lost because of harbor expansion (Pinder and Witherick 1990, 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 (European Commission 2011). In particular, they attract other economic sectors (Berköz 1999,
Dwarakish and Salim 2015); they support inland economic activities by connecting sea and land transport; they secure energy supply (Audrain et al. 2013), and they provide numerous direct and indirect jobs (Ferrari et al. 2012). Moreover, harbors produce a positive externality in that they contribute to climate change mitigation. The development of harbors helps increase the use of water transport for commodities, and CO₂ emissions for water transport are 34–188 times lower than air transport and 14–15 times lower than road transport per km and per ton of commodities transported (IPCC 2014: 610).

International institutions strongly encourage creating new habitats in the areas surrounding harbors as a means to mitigate pressures on marine biodiversity, fishery resources, and to offset past environmental degradation (e.g., European Commission 1999, IUCN France 2011, Schoukens and Cliquet 2016). However, restoration programs can be prohibitively expensive particularly when considering the Polluter Pays Principle (PPP). This raises questions of 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? One way to allocate restoration costs is in proportion of those who have benefitted from harbor activities. This paper addresses these questions by calculating burden-sharing scenarios with input-output matrix equations. These scenarios are based on a shared producer and consumer responsibility approach to distribute restoration costs among stakeholders that use, either directly or indirectly, harbor services. The distribution is calculated as a function of direct and indirect economic linkages between economic sectors and harbor activities. Connections with final consumers are also included.

Several authors raise justifications for the shared producer and consumer responsibility principle (Gallego and Lenzen 2005, Lennox and Andrew 2006, Lenzen et al. 2007, Lenzen 2007, Rodrigues and Domingos 2008, Lenzen and Murray, 2010). First discussions of this approach started at the national level regarding the sharing of environmental responsibilities between countries in the Kyoto Protocol (Hertwich and Peters 2009). In those discussions, it was suggested that switching from producer to consumer responsibility may change outcomes for emission reduction targets per country. Such a switch has, for example, already been applied in Denmark for electricity production (Munksgaard and Pedersen 2000). While this full switch to consumer responsibility may not be appropriate for all cases, a politically viable consensus probably lies somewhere between producer and consumer responsibility (Gallego and Lenzen 2005). At the company level, numerous firms have already traded conventional producer responsibility for the shared producer and consumer responsibility principle. This is used in companies that adopt the concept of eco-efficiency, Extended Producer Responsibility (EPR) frameworks, or environmental management standards such as ISO 14001 (Cerin 2002, Lenzen and Treloar 2002, McKerlie et al. 2006, Lenzen et al. 2007). In these cases, the corporations recognize their wider environmental responsibility in the supply chain when their suppliers or their customers degrade the environment. In 2008, a new standard for applying shared environmental responsibility to greenhouse gas reduction was developed by the Greenhouse Gas Protocol Initiative and named the “Corporate Value Chain (Scope 3) Standard” (WRI and WBCSD 2011). In 2010, 35 companies from various industries road tested the standard in a voluntary framework. The companies provided feedback together with 60 organizations and 350 stakeholders on the practicality and the acceptability of the standard. Overall, most respondents said they plan to use this standard when it is finalized (WBCSD and WRI 2011).

In this paper, shared producer and consumer responsibility is based on the upstream responsibility concept (Gallego and Lenzen 2005, Lenzen et al. 2007, Lenzen and Murray 2010). Here environmental responsibility – as considered in the PPP – is extended from the original source (harbors) responsible for environmental degradation, located upstream in the supply chain, to the intermediate users (industries and firms) and, in the end, 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 habitat destruction in the Seine estuary, North-West France. Section 3 develops the methods used to calculate environmental shared responsibilities applied to the case study: the commodity-by-industry table.
regionalized to the scale of the Seine estuary (Sub-section 3.1), the scenarios of marine habitat restoration and cost sharing (Sub-section 3.2), and the mathematical formulations of environmental shared responsibility (Sub-section 3.3). Section 4 shows the results while Section 5 is devoted to discussion. After discussing the results, Sub-section 5.1 begins with a discussion on the theoretical possibility to allocate property rights within the Coase theorem instead of an environmental tax allocated within the shared environmental responsibility principle. Sub-Section 5.2 discusses grandfathering and the setting of reference year from which environmental responsibilities start to be accounted for. Section 6 concludes.

2. CASE STUDY

The Seine estuary is located in northwest France and is the site of the Grand Port Maritime du Havre. This industrial harbor is the biggest in France in terms of container ship 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. It is the biggest harbor in Europe for cereal exports and the second biggest harbor in France for transport of refined petroleum products. Both harbors together provide 50 000 direct jobs (HAROPA Ports de Paris Seine Normandie 2013).

Since the beginning of the 19th century, the growth of maritime transport has required the construction of dykes and extension of harbor infrastructure, resulting in on-going destruction of fish nurseries (Cuvilliez et al. 2009, Rochette et al. 2010). In the internal part of the Seine estuary, the surface area of potential nurseries of high density was of 181.91 km² in 1834 and progressively declined to 111.74 km² in 2004 (Figure 1). The degradation has affected biodiversity, particularly seven species of commercial fish (Cordier et al. 2011). Current trends in fish nursery destruction are worrying given that in European fishing zones, only 4% of the stock is sustainably harvested (ICES 2008).

![Figure 1. Observed evolution of potential nursery areas of the internal part of the Seine estuary. Note: Only potential nurseries with high density are considered, which includes estuarine areas with a density index of sole juveniles (< 12 months of age) higher than the internal estuary average (> 45 juveniles/km²). Source of data: Historical maps and habitat suitability model developed by Rochette et al. (2010).](image)

In our case study, nursery areas are protected by the European laws of the Birds Directive (European Parliament and Council of the European communities 2009) and the Habitats Directive (Council of the European communities 1992). Therefore, 1 km² of fish nursery habitat has been restored by the Grand Port Maritime du Havre to offset the destruction incurred during the extension project in 2002-2004. As a result, fishermen claims for financial compensation from port authorities were suspended. To comply with the Habitats Directive and avoid further claims, the authorities of the Grand Port Maritime de Rouen have been involved in restoration efforts. In 2014, they offered 3.6 km² of coastal areas to the Conservatoire du Littoral to offset degradation of supporting ecosystems services (HAROPA – Port de Rouen 2014) – the Conservatoire du Littoral is the national environmental agency in charge of littoral ecosystem preservation.
3. METHOD

When designing a shared producer and consumer responsibility framework to restore habitats destroyed in the past, it is important to develop a calculation method that results in burden sharing that is both proportional to environmental responsibility and affordable for those who bear the restoration costs. In this paper, we test four scenarios by which costs of environmental restoration could be distributed. In order to assign environmental responsibilities to direct and indirect agents participating in 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 (I-O) analysis. The I-O 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.

There are three major methodological contributions from our approach. First, we adapt the calculation method from Gallego and Lenzen (2005) and Lenzen et al. (2007) to the specific case of past habitat destruction. This requires a new vector of historical coefficients (Section 3.3) to be entered in Gallego and Lenzen’s equations. This vector modifies environmental responsibility shares in proportion to the life span of industries in each sector in order to take into account prior environmental destruction, as suggested by, *inter alia*, Page (2008) and Knight (2013). Second, we add a new set of coefficients to Gallego and Lenzen’s equations; these coefficients are based on Taylor expansion of the Leontief inverse (Section 3.3). This allows us to automate the calculation of shared responsibility for each sector at each round of the supply chain in an existing case study made of 63 economic sector categories. Third, the case study area to which we apply Lenzen’s equations is regional at the scale of the Seine estuary watershed, which corresponds to the Haute-Normandie region in France. This requires non-survey regionalization techniques to be merged with shared responsibility equations (Section 3.1). This is important given that environmental issues must also be managed at regional (i.e., sub-national) scales if we want community values to be taken into account as well as more strategic and targeted outcomes to be achieved (Farrelly 2005, Raymond et al. 2009).

3.1. The regional commodity-by-industry table

The regionalization techniques applied in this paper rely on Jackson (1998), Lahr (2001) and McDonald (2005: 141-160), who were the first to develop non-survey regionalization techniques for commodity-by-industry tables. Cordier (2011: 216-285) and Cordier et al. (2017: 49) provide a detailed development of the techniques used to regionalize the French national commodity-by-industry table at the scale of the Haute-Normandie region. The commodity-by-industry table obtained by the regionalization method is schematized in Table 1. The table is used to build an open, static and descriptive I-O model of the Haute-Normandie region in 2012.

The commodity-by-industry table is composed of two square matrices – for more details, read Lixon et al. (2008) and Cordier et al. (2017: 56 – online supplementary data): \( V \), the supply matrix, and \( U \), the use matrix (matrices are indicated in bold capital letters, vectors in bold italic lower-case letters, and scalar 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 \( (x, a \times n \) 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, \( q = q^T \) and \( x = x^T \), where ” \( T \) ” in exponent means the vector is transposed; \( m_i \), 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 \( v_{ij} \) 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, NGOs 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 \( m_{ij} \) and \( m_{fr} \) 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 gross operating surplus (i.e. companies’ profits).

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

<table>
<thead>
<tr>
<th></th>
<th>Commodities ( i = 1, \ldots, n ) ((n = 63))</th>
<th>Industries ( j = 1, \ldots, n ) ((n = 63))</th>
<th>Final Demand ( r = 1, \ldots, f ) ((f = 8))</th>
<th>Total Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commodities</td>
<td>( U ) ( u_{ij} )</td>
<td>( Y ) ( y_{ir} )</td>
<td>( q ) ( q_i )</td>
<td></td>
</tr>
<tr>
<td>Industries</td>
<td>( V ) ( v_{ij} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imports</td>
<td>( m_{ij} ) ( m_{fr} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Inputs</td>
<td>( W ) ( w_{ij} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Inputs</td>
<td>( q_i ) ( x_i )</td>
<td>( x' ) ( x'_i )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.2. Scenarios of marine habitat restoration and cost sharing

The regional commodity-by-industry table developed in section 3.1 has been used to calculate the distribution of the cost of nursery restoration. Four scenarios have been chosen. They mainly differ by the way the total cost of the restoration is distributed across sectors in the supply chain and, for the last one, by the level of restoration (Table 2). We calculated the annual cost based on the unit cost of restoration of intertidal fish nurseries, which is \( \text{M} \varepsilon 29.83 \) per \( \text{km}^2 \) restored (Port Autonome du Havre 2000), and the surface area restored each year in our offsetting scenarios. All prices mentioned in this paper are 2012 prices.

The “Single round scenario” applies the producer responsibility principle as in the PPP: costs of environmental restoration are borne by the economic sectors directly responsible for environmental degradation in the Seine estuary, that is, industrial harbors (first round of responsibility in Figure 2).

The “Two rounds scenario” is not considered in this paper since it does not bring additional insight.

In the “Three rounds scenario”, costs of environmental restoration are borne by the economic sectors directly responsible for environmental degradation in the Seine estuary (first round), all second round sectors (i.e., sectors that purchase services produced by the first round sector), and all third round sectors (i.e., sectors that purchase goods and services produced by second round sectors). The three first lines of Eq. (1) calculate the allocation to first, second and third round producers respectively as well as to final demand categories. Examples of sectors of first, second and third round responsibilities are shown in Figure 2.

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2 This document provides data on costs from previous restoration programs effectively implemented in the Seine estuary. For the cost of other restoration techniques, read *inter alia*, Yozzo et al. (2004).
The “Modified three rounds scenario” is the same as the “Three rounds scenario” except for two differences. First, we imagine a situation where it would be collectively decided that harbors are allowed to extend their restoration period from 11 to 18 years so the annual restoration cost would be lower. Second, other sectors as well as final consumers would accept to bear a part of harbors’ responsibility in nursery restoration. As an example and to test the idea, we arbitrarily propose they would accept to bear 8 km$^2$ proportionally with their gross operating surplus (for economic sectors) and to their income (for final demand categories). To make this option more attractive for companies, this would be something they could advertise that may improve their image.

The “Modified three rounds 1992 scenario” is the same as the previous except one difference: the reference year to which the Seine estuary would be restored would be collectively renegotiated and set to 1992 for all sectors, (i.e., the year the Habitat Directive was enacted), instead of 1979 as in the three preceding scenarios (i.e., the year the Birds Directive was enacted). This would reduce the total surface area to be restored to 19.43 km$^2$ as well as the annual total restoration costs (Table 2). Section 5.2 discusses the choice of these reference years in light of the grandfathering principle.

<table>
<thead>
<tr>
<th>Table 2. The four restoration scenarios: five distinctive variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenarios Variables</strong></td>
</tr>
<tr>
<td>Additional restoration burden for non-harbor sectors (km$^2$)</td>
</tr>
<tr>
<td>Restoration period for harbors (years)</td>
</tr>
<tr>
<td>Total restoration of nursery areas (km$^2$)</td>
</tr>
<tr>
<td>Annual total restoration cost on the 2012-2022 period (M€)</td>
</tr>
</tbody>
</table>

In the four scenarios, we restore intertidal nurseries for high density of juvenile soles. Restoration activities would last for 11 years starting in 2012 and ending in 2022 (up to 2029 for harbors in the two last scenarios in Table 2). The choice of the level of restoration, 23.72 km$^2$ in the three first scenarios in Table 2, is based on the wish of local stakeholders from scientific institutions, fishing and hunting associations, environmental organizations, industries, regional authorities, the water agency, industrial harbor companies, etc. Over the course of several meetings organized in 2004, those local stakeholders agreed that restoring the area to a level of environmental quality corresponding to the years 1979-1980 would be the most desirable scenario for the Seine estuary (Préfecture de Région de Haute-Normandie 2008). Based on consultations with experts in the hydro-sedimentology of the Seine estuary, the natural evolution of these nursery areas combined with the restoration of 23.72 km$^2$ over 11 years is estimated to result in 127.5 km$^2$ of total high fish density nursery habitat by 2022. This was the level present in 1979 (Figure 1). Such restoration reduces the risk of crossing into a danger zone where undesired and irreversible ecosystem changes become unavoidable, especially given that current scientific knowledge does not know the minimum threshold for total nursery surface area required to maintain marine fish populations. In absence of scientific thresholds, expert assessment together with democratic consultation of local stakeholders resulted in the chosen option. The expected impact of nursery restoration is a growth in fish stocks, which should increase the resilience of fish populations and their capacity to regenerate the stock in the future.

As the number of responsibility rounds in shared responsibility scenarios increases, the transaction cost may increase as well since more producers and consumers are included (transaction costs include management activities that would be undertaken by the Conservatoire du Littoral to calculate and collect the environmental handling charge for each producer and consumer, monitoring activities ensuring ecological functions of restored nurseries are maintained through time, etc.). This has caused operational problems in practical experiences (Cole and Grossman 2002, OECD, 2004). With this in
mind, the restoration scenarios from Table 2 and Figure 2 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 4,393 companies – our own calculation based on Bureau van Dijk (2014).

In all scenarios, within the same sector \( j \), the environmental handling charge is shared between firms proportionally to their annual gross earning so that small and medium-sized enterprises would bear lower restoration costs than large enterprises. Such an allocation rule is simple and straightforward, and reduces transaction costs. Regarding the category of households’ final demand in the three last scenarios in Table 2, the environmental handling charge is equally shared between households: for more practicality, they all pay the same amount. The 795,324 households living in the Seine estuary would collectively pay a maximum amount of M€ 10.7 during the restoration period. This amount is expected to be well accepted and perceived as legitimate by the population of the Seine estuary. First because the amount to be paid per household would not exceed € 13.5 per year and second because the maximum annual amount that each household would be willing to pay for wetland restoration (including nurseries) is much higher, at an estimated € 47.14 per year on average (Beaumais et al. 2008).
Figure 2. Shared producer and consumer upstream responsibility across the supply chain of harbor services. Note: the bold arrows represent the service or the product sold by upstream sectors to downstream sectors (with an example written right above the bold arrow). Smaller arrows represent the service or the product sold to final consumer categories.
3.3. Mathematical formulation of upstream shared responsibility

A mathematical formulation of upstream shared responsibility as illustrated in Figure 2 has been developed by Gallego and Lenzen (2005). They divide the responsibility for 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\(^2\). The responsibility for the remaining fraction \( \alpha_{kh} \) of the sector’s intermediate output is assigned to its intermediate downstream users (2nd round sectors in Figure 2). And the responsibility for the remaining fraction \( \beta_k \) of the sector’s final demand is assigned to final consumers (households, non-profit organizations, government, investors, interregional and international exports). In this way, the responsibility for the commodity’s output \( k \) – harbor services here – is distributed to all sectors and final demand categories in round 1. Then, in a similar equation, Gallego and Lenzen (2005) calculate the way the amount assigned to the 2nd round of the supply chain is distributed between the sectors of that round (Figure 2). The same distribution process repeats itself as we move down the supply chain, from sectors \( h \) (2nd round) to sectors \( s \) (3rd round), to sectors \( t \) (4th round in Figure 2), etc. Summing the first and the second line of each Gallego and Lenzen equation (2005: 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 rounds of the supply chain:

\[
q_k = \left\{ \begin{array}{c}
\Phi_k \left[ \beta_k y_k + (1 - \beta_k) y_k + \frac{\sum_h (\alpha_{kh} a_{kh} \Phi_h)}{(1 - \alpha_{kh}) (q_k - y_k)} \right], \text{ Round } 1 \\
\sum_h (\alpha_{kh} a_{kh} \Phi_h) \left[ \beta_h y_h + (1 - \beta_h) y_h + \frac{\sum_s (\alpha_{hs} a_{hs} \Phi_s)}{(1 - \alpha_{hs}) (q_h - y_h)} \right], \text{ Round } 2 \\
\sum_s (\alpha_{hs} a_{hs} \Phi_s) \left[ \beta_s y_s + (1 - \beta_s) y_s + \frac{\sum_t (\alpha_{ts} a_{ts} \Phi_t)}{(1 - \alpha_{ts}) (q_s - y_s)} \right], \text{ Round } 3 \\
\sum_t (\alpha_{ts} a_{ts} \Phi_t) \left[ \beta_t y_t + (1 - \beta_t) y_t + \frac{\sum_j (\alpha_{jt} a_{jt} \Phi_j)}{(1 - \alpha_{jt}) (q_t - y_t)} \right], \text{ Round } 4 \\
\end{array} \right.
\]

Calculating the result of each line of equation (1) gives the total responsibility for each round. And 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 Eq. (1) except we drop the sum symbols \( \Sigma_h \), \( \Sigma_s \), and \( \Sigma_t \) to calculate the responsibility of each of the 63 sectors \( j \) \((j=1, \ldots, n; n=63\), see Table 1) at each round instead of the total responsibility of the round with all sectors together.

Eq. (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 \( \alpha_j \) to other next round producers, and a fraction \( \beta_j \) to final consumers. The same producer \( j \) retains the responsibility for fractions \( 1 - \alpha_j \) and \( 1 - \beta_j \). Hence, the parameters \( \alpha_j \) (the producer responsibility share) and \( \beta_j \) (the consumer responsibility share) are numbers between 0 and 1. The responsibility share of \( q_i \) allocated to final consumers \( (\beta_t y_t, \beta_s y_s, \beta_h y_h, \beta_y, \text{ etc.}) \), is distributed among 6 categories \( r \) of final consumers (see Figure 2) in proportion to their total final consumption across the 63 commodities \( i \) and the 6 categories \( r \) of the use table as follows: \( \sum_i y_{ir} / \sum_r y_{ir} \). As in Lenzen et al. (2007, p. 34) in equation (1), we calculate \( 1 - \alpha_{kh} \), \( 1 - \alpha_{hs} \), \( 1 - \alpha_{ts} \), \( 1 - \beta_k \), \( 1 - \beta_h \), \( 1 - \beta_s \), and \( 1 - \beta_t \) as follows for each sector \( j \):

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

\(^2\)Intermediate outputs are the goods and services exchanged between businesses, for example, raw materials or semi-finished products sold to other industries to produce their own final goods and services, which will be sold to households and other final consumers.
where $b$ signals that Eq. (2) is calculated at each round $k$, $h$, $s$ and $t$. And we calculate $\alpha_j$ as follows:

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

(3)

Where $w_j = \sum_l w_{lj}$ (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 first, second or more rounds. $x_j - \tau_{jj}$ 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 equation (2) as a solution to avoid arbitrariness (e.g., 50%-50% sharing between consumers and producers or 25% sharing between each of the 4 responsibility rounds as in Cordier et al. 2015). As a result of equation (2), $\alpha_j$ and $\beta_j$ are now only a function of the value-added, total output and inter-industry transactions of industry $j$, and hence, $\alpha_j$ can replace $\beta_j$.

We adapt Gallego and Lenzen’s equation by adding historical coefficients $\Phi_k$, $\Phi_h$, $\Phi_s$, $\Phi_t$ to Eq. (1) to take into account the time companies have been contributing, either directly or indirectly, to marine habitat destruction. Historical coefficients were not included in Gallego and Lenzen (2005) nor in 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). The historical coefficient is calculated per sector $j$ from the ORBIS financial database (Bureau van Dijk, 2014) and is a function of the average lifespan calculated across all companies. A sector with companies older than the average will have a higher coefficient $\Phi$ value than a sector made of younger companies. In the end, to compute the environmental responsibility displayed in Figures 3 - 7, we multiply each line of Eq. (1) by the environmental factor calculated as follows: total nursery area restored per year / total harbor output in 2012. This environmental factor represents the amount of nursery area to be annually restored per unit of output.

In Eq. (1), the coefficients $1; a_{ih}; a_{kh} a_{hs}; a_{kh} a_{hs} a_{st}$ before the brackets express respectively the share of commodity output $q_k$ produced by sector $k$ in the first round of the supply chain, the share $a_{kh}$ of this production $q_k$ that is supplied to second round sectors $h$, the share $a_{kh} a_{hs}$ of $q_k$ used and transformed by second round sectors to supply third round sectors $s$, etc. We calculate these share coefficients with the Taylor expansion of the Leontief inverse $(I - A)^{-1}$ (Lenzen et al., 2007): $(I - A)^{-1} = I + A + A^2 + A^3 + \ldots$ where $I$ is the $n \times n$ identity matrix (Miller and Blair, 2009), and $A$ 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.

4. RESULTS

Among the 63 sectors from Table 1, only those with salient results are shown in the graph presented below. Figure 3(a) shows the “Single round scenario” for sharing environmental responsibility in nursery destruction where harbors take on the entire restoration cost. Figure 3(b) shows the annual restoration cost borne by harbors in that scenario represents 103.5% of their annual profit (measured by the gross operating surplus in 2012).

Figure 4(a) displays the "Three rounds scenario" in which environmental responsibility is predominantly distributed between the harbors and 10 other sectors: Land transport (includes transport via pipelines), Wholesale trade, Construction, Water transport, Fossil fuel industry, Retail trade, Food industry, Non-metallic minerals, Real Estate, and Chemicals$. Figure 4(b) shows that only the harbor sector would be significantly impacted by annual restoration costs: the restoration cost represents

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$A$ is calculated in supply-use form as in Table 1. It can be so since an entire supply-use block can be inverted; there is no need to transform into IO form (for more explanations reed Lenzen and Rueda-Cantuche, 2012).

$^4$ Entire names and full description of sectors are available in European Communities (2008).
49.6% of its profit without the historical factor and 49.2% with the historical factor. The cost borne by the 10 sectors mentioned does not exceed 1% of their profit.

Unexpectedly, in this scenario five sectors that were allocated a very low level of environmental responsibility bear restoration costs representing a relatively high share of their profit. This includes: Employment activities, Cultural activities, Insurance, Postal activities, and Repair of household goods. However, when the historical factor is applied to these five sectors it takes companies’ lifespans into account in their share of environmental responsibilities, and the annual restoration cost drops drastically. For the sector of Employment activities it drops to 6.6% of its profit, and it becomes less than 2% of the profits for the other four sectors.

Figures 5 (a) and (b) show the results for economic sectors in the “Modified three rounds scenario”. All sectors bear greater environmental responsibility and annual restoration costs than in previous scenarios but the main observations remain similar. Annual restoration costs never exceed 2% of a sector’s profit except for three sectors: harbors (9.0%), Employment activities (13.1%), and Repair of household goods (4.2%). However, these percentages drop to 8.7%, 6.5% and 1.7% respectively when the historical factor is applied.

Figures 6 (a) and (b) display the results for economic sectors in the “Modified three rounds 1992 scenario”. There are two main differences from the “Modified three rounds scenario”. First, all sectors bear lower environmental responsibility and annual restoration cost. Second, harbors’ annual restoration cost drops to 3.5% of their profit without the historical factor and 3.4% with the historical factor.

Figures 7 (a), (b), and (c) present the results of calculating environmental responsibility sharing for final demand categories in the “Three rounds”, “Modified three rounds”, and “Modified three rounds 1992” scenarios. In all three scenarios the category of final demand bearing the highest share of environmental responsibility is Interregional exports, which represents industrial and final consumers in other French regions who import goods and services from the Haute-Normandie region. Nevertheless, Figures 7 (d), (e), and (f) show that in the three scenarios, the restoration cost reaches the highest income percentage for the Government and public administrations in Haute-Normandie. However, this percentage never exceeds 0.092% of the Government and public administration’s annual income. For households, the value is even lower and never exceeds 0.041% of gross annual income.
Figure 3. Single round scenario: Sharing of responsibilities for nursery area destruction (a) and annual nursery restoration cost (b) (2012).
Figure 4. Three rounds scenario: Sharing of responsibilities for nursery area destruction (a) and annual nursery restoration cost (b) (2012).

Note: H52, H49, C23, etc. are NACE Codes for sector categories (European Communities, 2008).
Figure 5. Modified three rounds scenario: Sharing of responsibilities for nursery area destruction (a) and annual nursery restoration cost (b) (2012).
Figure 6. Modified three rounds 1992 scenario: Sharing of responsibilities for nursery area destructions (a) and annual nursery restoration cost (b) (2012).
Figure 7. Sharing of responsibilities between final demand categories for nursery area destruction (a, b, c) and annual nursery restoration cost calculated as a percentage of final consumers’ income (d, e, f) (2012).

Note: Graphs (a) and (d) correspond to the Three rounds scenario, graphs (b) and (e) to the Modified three round scenario, and graphs (c) and (f) to the Modified three rounds 1992 scenarios. For the categories of non-profit organizations, interregional exports, and international exports, data on income were not available. Instead we used total expenses as a proxy. P3-S4, P3-S15, etc. are NACE codes for final demand categories (European Communities, 2008).
5. DISCUSSION

The “Modified three rounds 1992 scenario” seems the most promising scenario in terms of acceptability for stakeholders. First, because restoration costs are more evenly shared among economic sectors (Figure 6(a)). Second, because they are also more evenly shared between economic sectors and final demand categories, which include domestic households, foreign consumers (exports), governments and public administrations, non-profit organizations (Figure 7(a)). Third, because the gap between harbors and the other economic sectors is much smaller than in the three other scenarios. For example, harbors restore everything alone in the single round scenario (Figure 3(a)). Regarding the three other scenarios, if we compare harbors with the sector bearing the second highest environmental responsibility – the land transport sector –, they restore a surface area 27 times higher than land transport in the “Three round scenarios” (Figures 4(a)), 7 times higher in the “Modified three rounds scenario” (Figures 5(a)) and only 3.6 times higher in the “Modified three rounds 1992 scenario” (Figures 6(a)). Fourth, because the “Modified three rounds 1992 scenario” succeeds restoration cost to remain below 6% of companies’ profits and even much less for most companies (Figure 6(b)). This requires, however, stakeholders to accept burden-sharing calculations to be weighted by the historical factor.

5.1. The Coase theorem and environmental tax incidences

The shared environmental responsibility approach developed in this paper could lead to calculating an environmental tax, that is, an environmental handling charge paid by economic sectors and final consumers to fund habitat restoration. This, however, raises Coase’s theorem (Coase 1960, Steenge 2004, Lenzen et al. 2007), which proposes: “basically, public authorities should confine themselves to establishing and maintaining a system of property rights” rather than a system of corrective taxes and subsidies (Pigou 1920) because in such a system of property rights, if parties are bound to each other via the price mechanism and full information is available, the allocation of environmental liability does not matter (Perman et al. 2003).

Unfortunately, full information is rarely available for natural areas, even if habitat legislation is in place (Oi 1973, Muradian et al. 2010). The Seine estuary illustrates this problem: there is a lack of scientific knowledge on interactions between fish populations and their habitat and, the few papers there are do not address the question of the minimum nursery surface area required to ensure the existence of fish populations (e.g., Rochette et al. 2010). Here, fish nursery areas in wetlands show the limits of Coase’s theorem, since full information is not available (Turner et al. 2000) and, as such, it may very well matter to whom liabilities and rights are assigned (Dahlman 1979, Zweifel and Tyran 1994). In this example, Coase’s approach to bargaining between the “offenders” that degrade marine habitats (industrial harbors) and the “victims” (fishermen and the Conservatoire du littoral) does not fully take into account the risk of negative externalities in the mid- to long-term (e.g., loss of income for fishermen, collapse of the marine food web and marine biodiversity, etc.). While bargaining is likely to achieve Pareto efficiency in the short- or mid-term, Pareto efficiency is not sufficient to guarantee sustainability, in this case, of the fish population (Bromley 1998, Gerlagh and Keyzer 2003).

Moreover, Steenge (2004) points out that traditionally, Coase's point was only exemplified for a few actors at any one time (Lenzen et al. 2007). In reality, there will be a multitude of actors who are interconnected in the sense that they use each other's outputs, either directly or indirectly. In such a context, the idea of “offenders” and “victims” seems less justified. Rather, the entire economy should be held responsible given existing interconnections. Put another way, we could go so far as to say this interconnectedness makes everyone responsible to some degree (Cerin and Karlson 2002, Steenge 2004, Cerin 2006).

Since the Coase theorem cannot be applied to the case of marine habitat restoration in the Seine estuary, environmental taxes remain an option. In this paper, we consider the case where such environmental tax would be allocated to stakeholders under the shared environmental responsibility principle. However, an alternative to the shared environmental responsibility principle would consist
in letting market mechanisms freely share the burden of environmental restoration. In that case, direct polluters would take on the entire cost of restoration as in the “Single round scenario” and industrial harbors would probably transfer part of the cost onto prices for harbor services. In doing so, this approach does not resolve the need for industrial harbors to share the cost of environmental restoration, since they serve the general public interest and provide positive externalities for all (see the Introduction Section).

Nevertheless, without considering the impacts of market mechanisms carefully, shared environmental responsibility policies might be unfair for consumers. If shared environmental responsibility is applied and upstream direct polluters transfer their share of restoration costs onto the price of their service, downstream sectors and final consumers would pay several times for restoration costs. This raises the issue of tax incidence, i.e. the analysis of the fraction of the tax paid by firms – the environmental handling charge mentioned above – that ends up being borne by final consumers and the fraction that is borne by firms (Marion and Muehlegger, 2011; Cullenward et al., 2013). In response to a tax, firms are likely to raise the price of the products they sell. After all, the tax increases the costs of supplying the products and basic economic principles predict a price increase for final consumers when the supply curve shifts up. It is possible to quantify tax incidence in a further step using statistical regression between price and tax changes. Meanwhile, the analysis developed in this paper cannot address the question of who will effectively pay for restoration in the end but addresses the question of who currently benefits from harbor activities and argues that this should be a target for allocating costs fairly across different stakeholder groups. That being said, the impact on prices in the Modified three rounds 1992 scenario is likely to be relatively small given that the restoration cost is well-shared among producers and consumers (Figure 6(b) weighted by historical factor). Consequently, restoration cost in that scenario does not significantly increase production costs for any company, neither represents it a notable share of their profits.

Another issue is the estimated profit loss of nearly 50% for harbors in the “Three rounds scenario” (Figure 4(b)). This might not be well accepted by harbors and if this were the case, blocking behaviors to lower restoration targets would be expected. To prevent this, shared responsibility calculations (Eq. (1)) could be part of a participatory approach where producers and consumers use results from Figure 4 as a starting point to open negotiations and adapt the theoretical equations (Eq. (1)) to their actual situation. The “Modified three rounds” and “Modified three rounds 1992” scenarios (Figures 5 and 6) simulate the possible outcomes of such a negotiation where three variables of the shared environmental responsibility program would be discussed: the grandfathering reference year, the length of the restoration period for the most financially-impacted sectors (i.e., harbors), and the possibility for less impacted sectors to take on a greater share of restoration costs (Table 2).

Although price increase remains a question for further investigation, this risk must be considered along with several advantages expected from the shared environmental responsibility principle: improvement of companies’ image, companies’ early adaptation to future environmental legislations, greater acceptability by direct polluters (given lower cost per individual polluter) and hence fewer attempts from polluters to make environmental legislation less stringent or to by-pass such legislation entirely, and possibilities to improve environmental quality to a greater extent since a greater number of stakeholders would fund marine habitat restoration activities. In future research, a price I-O model (Miller and Blair 2009) will be developed to estimate potential price increases and verify they would be acceptable for producers and consumers.

5.2. Grandfathering

In environmental legislation, grandfather clauses stipulate that specific regulations are not applicable to firms or products that were already active on the market at the time legislation was passed (Robertson 1996, Knight 2013). Grandfathering has mostly been applied to pollutant emissions and waste disposal in American legislation (Robertson 1996, Wilson et al., 2008, Schwarzman and Wilson 2011). It has also been tested theoretically on natural resource extraction (e.g., Gerlagh and Keyzer 2003). In the “Single round”, “Three rounds” and “Modified three rounds” scenarios (Section 3.2),
stakeholders implicitly apply grandfathering to marine habitat destruction by setting the reference year to 1979 (Table 2), i.e., the year the Birds Directive was enacted to preserve bird habitats, which also serve as fish nurseries at high tide in the Seine estuary. This means any economic activity that destroyed nursery areas before the Birds Directive was enacted would be exempted from restoring those nurseries. In the “Modified three rounds 1992 scenario”, we set the grandfathering reference year to 1992 (Table 2), i.e., the year the European Habitat Directive was enacted. This scenario shows how setting a more recent reference year for grandfathering can reduce annual restoration costs, making them more acceptable for economic sectors, especially for harbors (Figure 6). However, grandfathering conflicts with the precautionary principle and increases the risk for environmental targets not to be met (Robertson 1996, Ackerman 1999, 2016, Nash and Revesz 2007). This is the case here since the total area restored in the “Modified three rounds 1992 scenario” leads to the recovery of total nursery area from 1992 – 123.8 km² (Figure 1) – whereas stakeholders collectively decided that recovering the total area from 1979 – 127.5 km² – would be preferred.

6. CONCLUSION

There are several reasons why the shared environmental responsibility calculation method presented in this paper is likely to be more acceptable for businesses and households compared to other burden sharing calculation approaches, such as those published by, inter alia, Gallego and Lenzen (2005) or Cordier et al. (2011, 2014, 2015). First, our method succeeds in markedly reducing profit losses per economic sector and income losses for final consumers bearing costs of marine habitat restoration (compare Figure 3(b) with 4(b) and the latter with Figure 6(b)), especially when weighting by historical factor (Sections 3 and 3.3). Second, as in Gallego and Lenzen (2005), the cost allocation rule between various responsibility rounds is less arbitrary and based on value-added as an indicator to 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 utmost importance because without a good level of acceptability to stakeholders, burden sharing has little chance of being applied, which consequently reduces the likelihood of costly habitat restoration and its significant positive impacts for marine ecosystems.

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 variables in the shared environmental responsibility calculations: i) value-added used to share costs between rounds; ii) intermediate outputs (raw materials and semi-finished products) used to share costs between economic sectors; iii) grandfathering reference year; iv) extra charge of responsibility for some sectors to help offset costs for more financially-impacted sectors; v) length of the restoration period for more financially-impacted sectors.

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