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Methodological and Ideological Options

An Input-output Economic Model Integrated Within a System Dynamics Ecological Model: Feedback Loop Methodology Applied to Fish Nursery Restoration

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ABSTRACT

While environmentally extended input-output (IO) models are commonly used for capturing interactions between ecosystems and economic systems, this kind of modelling cannot reflect interactions within the ecosystem. Isard's (1968) model has been the only exception. He entered interactions occurring within the ecosystem into IO. Nevertheless, given the linearity of IO, he could only analyze environmental issues in a linear fashion. We propose an alternative that reverses Isard's model types: the economic system is modelled within the ecosystem (not the contrary), as one of the ecosystem's components. To demonstrate its feasibility, we develop an ecological-economic model by integrating conventional economic IO within system dynamics (SD). After describing the methodological issues, we "test" the IO/SD model on ecological and economic data by applying it to the destruction and restoration of the Seine Estuary, France, where Common soles live. Our model brings insight into the consideration of feedback loops in the modelling of interactions between the ecosystem and the economic system. We believe such a tool may be of help to decision makers in mixing economic and environmental issues like, in our application case, fish habitat and harbour development.

1. Introduction

Ecological-economic models are required to capture the complexity of ecological-economic systems, as complexity is an essential part of those systems (e.g. Levin et al., 1998; Limburg et al., 2002); otherwise severe misperceptions and policy failures can occur (Costanza, 1987). There are two main sources of complexity. The first one concerns the interactions between ecological systems and economic systems: an ecosystem's responses to human use are not linear, predictable, or controllable (Folke et al., 2002). Second, there are interactions between environmental elements within the ecological system: contrary to some economists' expectations, ecological systems are often nonconvex (Dasgupta and Mäler, 2003). This non-convexity of ecosystems often indicates the existence of nonlinearity, multiple equilibria, thresholds, and positive feedback loops in which marginal analysis is of little use.

Various modelling techniques have been developed to investigate ecological-economic systems. However, there is still much room for improvement with regard to their reflection of complexity. One commonly used approach is extended input-output (IO) models. They are interesting because they can estimate not only direct but also indirect effects of policy instruments (or ecosystem modifications).

Between the end of the 1960s and the beginning of the 1970s, environmentally extended IO models were developed to simulate interactions between ecosystems and economic activities. The first operational versions of such models were developed by Isard (1968), Leontief (1970) and Victor (1972). In those IO models, physical units are used to describe non-market natural resources and pollutant emissions free of any tax or payment system. Monetary units are used for market natural resources and pollutants for which a price must be paid as a counterpart to their emission (e.g. ecological taxes, cost for landfill disposal, emission trading schemes, etc.). All these models describe interactions occurring at the interface between the ecosystem and the economic system: *i*) flows of pollutants or human waste

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emitted from the economic system towards the ecosystem and *ii*) flows of natural resources extracted from the ecosystem towards the economic system. However, the impacts generated inside the ecosystem are not taken into account – for example, the impact of pollutants emitted into the sea on marine fish stocks. This means that feedback loops, defined as conditions whereby causal variables in the system (original causes) generate output variables (consequences) that will modify the initial causal variables through a series of relationships (Stepp et al., 2009; Deaton and Winebrake, 2000; Sterman, 2000), cannot be taken into account. For example, an economically-induced change (original cause) caused to marine fish populations (consequence) will have a feedback impact on the fishing sector and on other economic activities (original cause), but this is not considered in such extended IO models.

Most of the authors mentioned above have therefore disregarded interactions occurring inside the ecosystem, arguing the lack of data on ecosystem functioning (Victor, 1972). Moreover, those interactions are nonlinear and their impact on human activities is highly indirect. This makes them very difficult to model even if data were available, which explains why they have been largely neglected until now even though nonlinear dynamic ecological processes are at the productive source of final ecosystem services that impact human well-being (Cordier et al., 2014; Haines-Young and Potschin, 2010). Excluding such crucial interactions prevents ecological-economic models from analysing the impact of pollutant discharge or natural resource extraction on ecosystems. Isard (1968) was the first to enter into IO models interactions that occur inside the ecosystem. However, the lack of ecological data at that time drastically reduced the number of cases to which his model could be applied. In addition, given the linear property of IO models, he could only analyze linear environmental issues. Since then, not much improvement has taken place, either with extended IO models or computable general equilibrium (CGE)[1] models. Most researchers restrained their ecological-economic modelling to case studies related to predator-prey relations inside food webs, a typical purely linear relationship in ecosystems (e.g. Jin et al., 2003, 2012; Finnoff and Tschirhart, 2008; Hussain and Tschirhart, 2013). This is a considerable drawback given that nonlinearity is the rule rather than an exception in environmental issues. To our knowledge, one of the very few ecological-economic CGE models integrating nonlinear interactions inside the ecosystem is the one developed by Finnoff and Tschirhart (2011).

Another option for taking nonlinearity of ecosystems into account may be to build the model the other way around; that is, to put IO modelling into ecosystem models, rather than doing the opposite. We call this the "economic component principle": the economic system is modelled within the ecosystem, as one of the components of the ecosystem. This lifts the classical IO limitations that generally constrain the description of the ecosystem.

The choice of the type of model – IO, SAM (Social Accounting Matrix) or CGE – is crucial, since results differ depending on the model. The economic impacts (multipliers) from an IO model tend to be smaller than a SAM model but larger than a CGE model (Miller and Blair, 2009; West, 1995; West, 2002). Like in Mongelli et al. (2010), we adopted an IO model. Our reasons are as follows. First, our original motivation was to extend the ecological-economic IO model developed by Cordier et al. (2014), which targets the same study area. Second, because our focus is on methodological advancement rather than on policy implication, a simple IO seems to be a credible base for future extensions of our proposed modelling approach, as mentioned by West (1995). Third, IO models are suitable at the regional (sub-national) level and are one of the best options to planners, despite their known limitations (West, 1995). More complex models may require larger amounts of data. CGE models require, among other things, "hundreds or even thousands of elasticities of substitution to be quantified" (West, 2002), which is a huge challenge especially at regional levels. For example, at such subnational levels, price data are notoriously scarce, which strongly reduces the possibilities for the construction of CGE models (Rey, 1998). This is confirmed by various authors, among which are Sullivan and Gilless (1990), who encountered such difficulties for some price dependent functions, and others who claim that regional scale results are not always achievable with CGE models (Liew, 1988; Hudson and Jorgenson, 1974; West, 2002; Rey, 2000).

In order to apply the "economic component principle" in this paper, we develop an ecological-economic model based on the integration of IO within a system dynamics (SD) model. SD had its inception in the early 1960s, with Forrester (1961). It is a computer-aided approach based on differential equations (Richardson, 2013). It has been used for modelling ecological-economic systems (e.g., Costanza et al., 1998; Uehara, 2013; Uehara et al., 2015), as differential equations are suitable for capturing nonlinear dynamics. The central concept of system dynamics is to understand how elements in a complex system interact with one another over time. It deals with internal feedback loops, time delays, and stocks and flows that affect the behavior of the entire system (Forrester et al., 1997).

Applying SD concepts to IO modelling means that an IO model is embedded in an SD model as one of the components of the SD model. With such a perspective, the resultant IO/SD model represents an ecosystem where non-human components such as natural habitats, animals or plants interact with other components such as economic activities. In that perspective, the economic system is one component of the ecosystem.

To our knowledge, there is currently no system dynamics model *synchronized* with IO, nor any application to ecological-economic systems. Previous system dynamics models incorporating IO *translate* IO into system dynamics (e.g., Braden, 1983; Diehl, 1985). This translation is uncommon, although not impossible – as shown in previous studies (e.g., Dudley, 2004; Moxnes, 2005) – but it is laborious and inefficient, and it significantly increases the complexity of the model architecture (e.g., Ford, 1999). However, when SD focuses on nonlinear dynamics in an ecological system, and IO is implemented in some other platform suitable for it, it seems possible to more appropriately capture the complexity of an ecological-economic system.

The first advantage of integrating IO with SD is that it allows us to estimate indirect and induced economic impacts of ecosystem modifications on other economic sectors involved in the supply chain (that is, on sectors that supply the sectors directly impacted by ecosystem changes). The second advantage is that it describes a detailed economic structure, as all sectors of the economy are included. Thereby, impacts of policy measures and ecosystem changes can be estimated for each economic sector, and trade-offs can be identified; i.e., determining which sector is advantaged or disadvantaged. Third, entering IO into an SD model allows the static property of IO to be reduced. SD is inherently dynamic, so the ecosystem variables interacting with IO are made dynamic. In other words, input variables of the ecosystem that enter the IO component are endogenised in the model. The evolution of those variables over time is no longer linear. An attempt at making parts of the economic system dynamic was already carried out by Cordier et al. (2014), but the ecosystem part of the model remained static and linear. In this paper, modelling the ecosystem part with an SD tool (Powersim) solves that problem. Fourth, entering IO into an SD model enables us to incorporate feedback loops between an ecosystem of fish natural habitats and a coastal economic system.

The remainder of the paper is structured as follows. Section 2 presents the study area. Section 3 is devoted to the methodology used: Section 3.1 explains how the economic component is embedded within the ecosystem modelling, Section 3.2 develops the economic component of the model (IO equations), and Section 3.3 details the ecosystem component of the model (SD equations).

[1] CGEs are made of an I-O table to which equations have been added to take into account the impacts of prices on economic production (e.g., price modification caused by environmental measures).

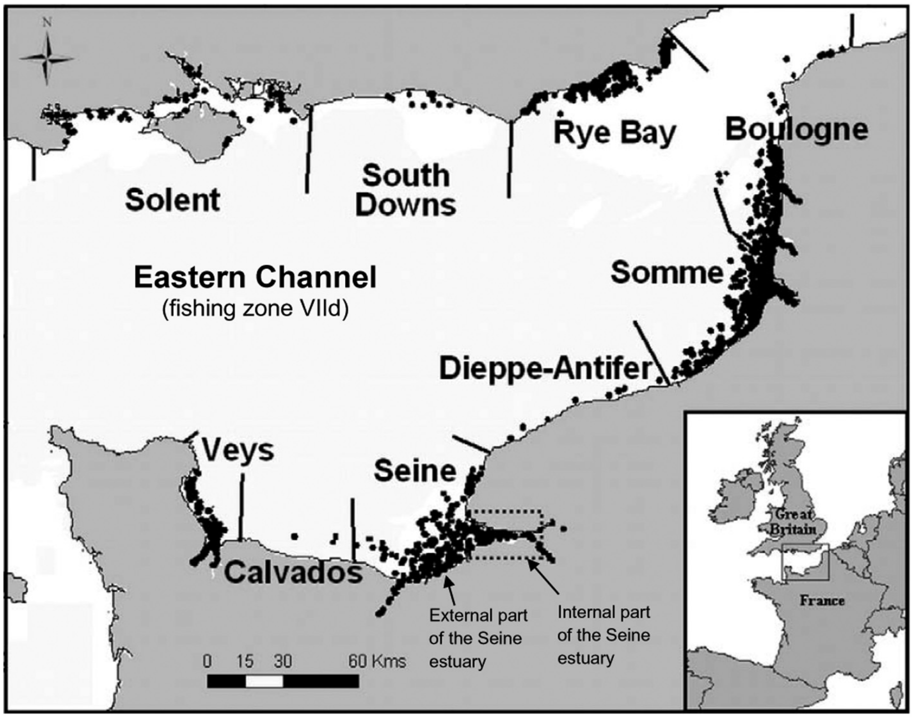

Fig. 1. The Eastern Channel, its sub-division into nine coastal and estuarine sectors, and the internal and external parts of the Seine estuary (inside and outside the dotted rectangle, respectively). *Note: this map of the Eastern channel represents fishing zone VIId (except the bottom left part that is out of the zone) as defined by ICES, the International Council for the Exploration of the Sea (website:* http://www.ices.dk/*). In this paper, when the Eastern channel is mentioned, it means the fishing zone VIId.*
Source of map: Rochette et al. (2010).

Section 4 displays the results while Section 5 discusses them and concludes.

2. Study Area

We apply the I-O/SD modelling to the case of the restoration of estuarine nurseries used as natural habitat by common sole juveniles (*Solea solea* sp.) in the Seine estuary. The estuary is located in the Haute-Normandie region of France, in the Eastern channel, as shown in Fig. 1. As natural capital, nursery areas provide habitat essential to the development and feeding of juvenile fish, and these areas contribute as such to the existence and maintenance of populations of marine fish. In spite of such an important ecological function, nursery habitats have been continually destroyed in the Seine estuary since 1850 by the construction of dykes and harbour extensions for the purpose of maritime transport (Rochette et al., 2010; Cuvilliez et al., 2009). In the internal part of the Seine estuary, the surface area of nurseries of high density was 181.91 km^2 in 1834, but dropped to 111.74 km^2 in 2004 (Fig. 2). In the Seine estuary, seven species of commercial fish depend on nursery habitats and could potentially be affected by their destruction: common sole, bass, flounder, plaice, pouting, poor cod, and whiting (Cordier et al., 2011).

3. Method

3.1. How Is the Economic System (IO) Modelled Within the Ecosystem (SD)?

Fig. 3 is a simplified representation of how the economic component is embedded in the ecological system of the study area. It presents the key variables (not all of the IO/SD model variables) to highlight the main relationships and feedback loops. While most of the economic variables are captured in Excel (inside the dashed box), some are captured in SD for technical efficiency.

"Sole caught originating from the internal part of the Seine estuary" is the key variable that connects the economic system and the ecological system. There are two negative feedback loops (B1 and B2 in Fig. 3)[2] that we describe in relation to this key variable; each loop directly involves both economic and ecological variables. For example, loop B1 shows that more "Sole caught originating from the internal part of the Seine estuary" results in less "Sole stock from the internal part of the Seine", leading to less "Catchable stock", leading further to less "Intermediate domestic consumption", discouraging "Sole caught originating from the internal part of the Seine estuary", and so on.

The integration of SD with IO allows a relaxation of the linear property of ecosystem variables modelled in the IO version developed in Cordier et al. (2014). With SD modelling, we can now introduce nonlinearity in order to better reflect the complex reality of ecosystems and their interactions with the economic system, as explained in the following sections.

The IO/SD model is developed in Powersim and Excel. The model simulates the relationships between the nursery areas and the economic activities. Powersim is able to synchronize an SD model with various datasets, including Excel. We use that property to connect the differential equation-based SD model with the final demand matrix **F** (shown in Table 1) of the IO Eq. (1). As shown in Fig. 3, four elements $f_{i,k}$ of matrix **F** from the IO equations in Excel make the link with the SD model in Powersim: $f_{i,4}$ (Investments), $f_{i,1}$ (Final consumption of all other services and products), $f_{i=soles,1}$ (Final domestic demand for soles) and $f_{3,7}$ (Foreign demand for soles). The calculation of these four elements is explained, respectively, in Section 3.2 at Eqs. (3)–(5) as well as in Section 3.3; this constitutes the key part of the integration of ecological and economic components in our analysis. The economic and ecological components make up the global IO/SD model. The architecture of the ecosystem model is based on SD principles, while the architecture of

[2] We follow a system dynamics convention of using B for a negative feedback loop; B stands for Balancing.

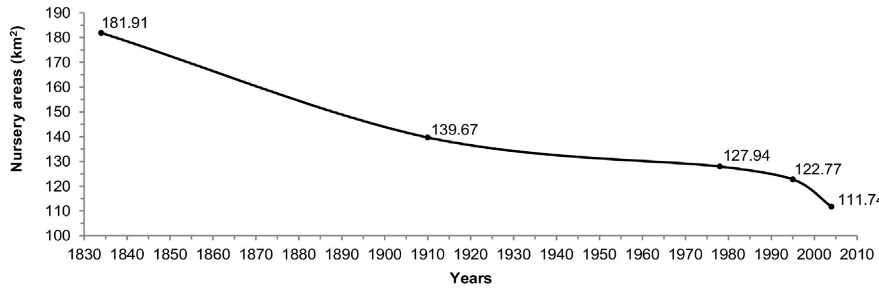

Fig. 2. Evolution of nursery areas in the internal part of the Seine estuary. *Note: This graph is based on five observations between 1834 and 2004 (the evolution between these observations being uncertain). It considers only those nurseries with an age 0 (<12 months) sole juvenile density index higher than the internal estuary average; i.e., >45 juveniles/km².*
Source of data: historical maps and habitat suitability model developed by Rochette et al. (2010).

the economic sub-model has been adapted to enable interactions with the SD model in an automatized way. That is, the economic sub-model and its IO equations provide economic outputs to the SD model and receive feedback inputs from the SD model for each year of the analysis. The model is made of the economic sub-system described in Section 3.2 (built on Excel), and the ecological system described in Section 3.3 (built on Powersim).

3.2. Input-output (IO) Modelling: The Economic Sub-system

The IO model represents the economic component of our IO/SD model, but instead of having the ecological component directly embedded in the IO model (as it is in classical ecological-economic IO), our approach captures it in the SD model to allow its dynamic behavior.

The IO model is made of a commodity-by-industry table (Miller and Blair, 2009) as shown in Table 1. It is defined by a) four matrices: **V**, the make matrix; **U**, the use matrix; **F**, the final demand matrix; **Y**, the primary input matrix; and b) eight vectors: **q**, **x**, **g**, **q**′, **x**′, **e**′, **mi**′, **mf**′, representing total commodity output, total industry output, total primary input, their transposes, a row vector of imports consumed by industries, and a row vector of imports consumed as final demand. Time notation is suppressed when it is not necessary for the argument.

The commodity-by-industry IO table for the study area (Haute-Normandie region) comprises 12 commodities and 12 industries for the year 2007. Since a regional table was not publicly available, we operated a regionalization of the French national table (available on Eurostat's website: http://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/data/workbooks), following techniques developed by Jackson (1998), Lahr (2001) and McDonald (2005), who were the first to develop non-survey regionalization techniques for commodity-by-industry IO tables (see the Supplementary document for details regarding the regionalization).

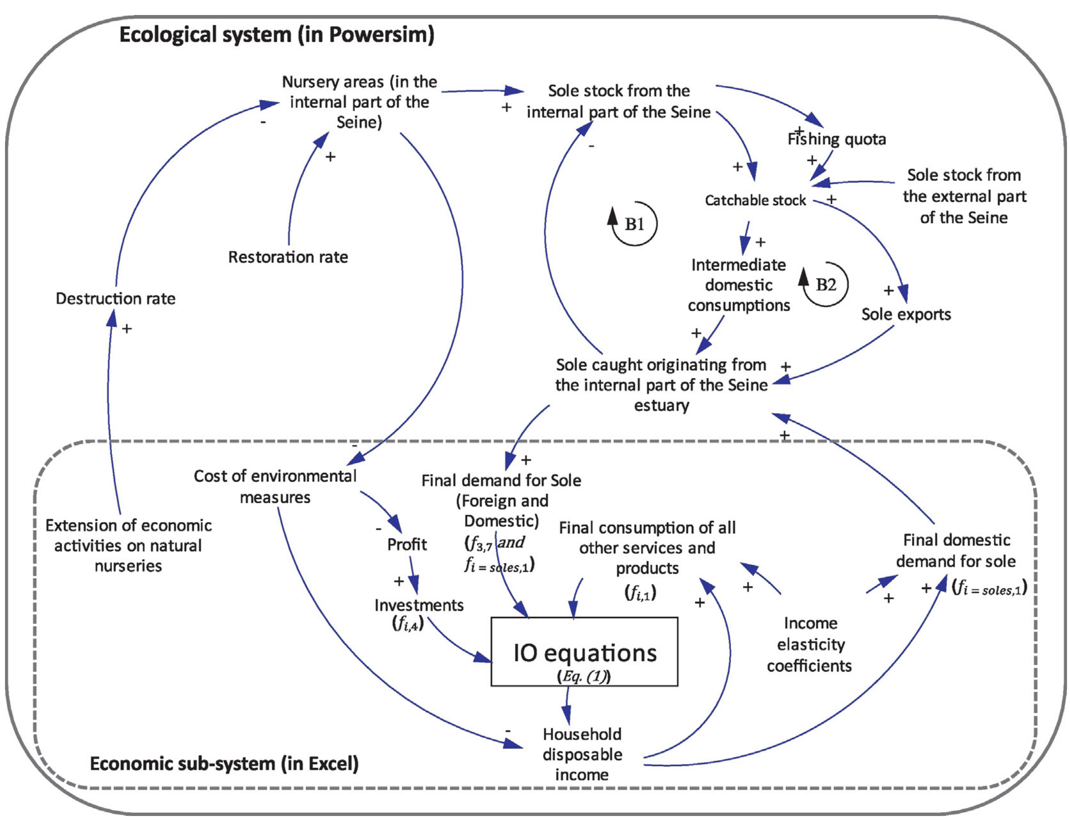

Fig. 3. Interconnections between the Economic sub-system and the Ecological system. *Note: "+" and "−" indicate variable changes in the "same" and "opposite" directions, respectively. The elements $f_{i,k}$ of matrix **F** that connect the economic sub-system (in Excel) to the ecological system (in Powersim) are in parentheses.*

Table 1
Commodity-by-industry IO table.
Note: Bold capital letters are used for matrices, bold lower case letters for vectors, and lower case letters for scalars (which, in the above table, are elements of vectors or matrices).

	Commodities ($i=1,\ldots,m; m=12$)	Industries ($j=1,\ldots,n; n=12$)	Final demand ($k=1,\ldots,f; f=8$)	Total output
Commodities ($i=1,\ldots,m; m=12$)		$\mathbf{U}$ u_{ij}	$\mathbf{F}$ f_{ik}	$\mathbf{q}$ q_i
Industries ($j=1,\ldots,n; n=12$)	$\mathbf{V}$ v_{ji}			$\mathbf{x}$ x_j
Imports		$\mathbf{mi}'$ mi_j	$\mathbf{mf}'$ mf_k	m
Primary Inputs ($l=1,\ldots,p; p=3$)		$\mathbf{Y}$ y_{lj}		$\mathbf{g}$ g_l
Total inputs	$\mathbf{q}'$ q_i	$\mathbf{x}'$ x_j	$\mathbf{e}'$ e_k	

We can derive the following relationship from the commodity-by-industry IO table shown in Table 1.[3]

$$\mathbf{x} = \left[\mathbf{D}(\mathbf{I}-\mathbf{BD})^{-1}\right]\mathbf{Fi} \tag{1}$$

I and **i** are respectively an identity matrix and a column vector of 1's known as a summation vector; **B** is the matrix of commodity input proportions which are input technical coefficients calculated from intermediate inputs in the use matrix **U**; **D** is the matrix of commodity output proportions which are output technical coefficients calculated from intermediate outputs in the make matrix **V**. The bracketed matrix is called an industry-by-commodity total requirements matrix (Miller and Blair, 2009) and Eq. (1) calculates the direct and indirect impacts of changes in the final demand on the industry outputs.

The final demand **F** comprises seven categories: household ($k=1$), NGO ($k=2$), government ($k=3$), investment (gross fixed capital formation) ($k=4$), change in valuables ($k=5$), change in inventories ($k=6$), and international and interregional exports ($k=7$). The IO model is open (in the conventional sense) with respect to these final demands (Miller and Blair, 2009). Household, investment, and sole products are treated endogenously in the IO/SD model as explained below, with regard to Eqs. (3)–(5) respectively.

Five of the seven categories of final demand *f* for all commodities *i* (except for sole products, as explained hereinafter) are assumed to change every year, as follows:

$$f_{ik}^{t} = f_{ik}^{t-1}\left(1+\rho_k^{t-1}\right), i = 1, \ldots, m; k = 2, 3, 5, 6, 7 \tag{2}$$

where ρ_k^{t-1} is the annual growth rate at $t-1$ for final demand category k, which is given exogenously in our model.

The households' final domestic demand ($k=1$) for all other services and products i (Fig. 3) except for sole products is given as:

$$f_{i1}^{t} = f_{i1}^{t-1}\left(1+e_i\frac{Y^t-Y^{t-1}}{Y^{t-1}}\right), i = 1, \ldots, m \tag{3}$$

f_{i1}^{t} depends on the income elasticity[4] (e_i) and changes in household disposable income (Y^t) from $t-1$ to t, which in turn is a function of the cost of environmental measures (ψ_i^t) paid by industries. This shows a first link between the economic sub-system and the ecological system (Fig. 3).

[3] The derivation process is explained in the Supplementary document. Also, the full IO model is available from the authors upon request.
[4] The income elasticities are adopted from Gohin (2005).

A second link concerns investments, as they also depend on the cost of environmental measures:

$$f_{i,4}^{t} = \left(\sum_{j=1}^{n}\widehat{GOS}_{inv}^{t-1}\right)\widehat{cap}_i + \psi_i^t, i = 1, \ldots, m \tag{4}$$

$\sum_{j=1}^{n}\widehat{GOS}_{inv}^{t-1}$ and $\widehat{cap}_i$ are, respectively, the part of the total gross operating surplus ("*Profit*" in Fig. 3) invested in $t-1$ by all industries j, and the fixed capital formation coefficients. The second term, ψ_i^t, is the cost of environmental measures (see Fig. 3) paid by industries ($\psi_i^t = 27.7$ M€$_{2007}$/km$^2 \times$ *Restoration rate*),[5] whose value varies with the size of the area restored and the cost allocation scenarios.

The final domestic demand for sole is excluded from the above equations for final demand because we relate sole consumption to environmental conditions and environmental measures. This is one of the ways our model shows how economic consumption is related to the environment – this is the third link between the two systems. We focus on modelling the household and export demand ($k=1$ and 7) for sole, as there is a zero value for sole in categories $k=2$ through 6 in the commodity-by-industry IO table we use. The final domestic demand for sole is calculated in tons in the economic sub-system as follows:

$$\left(f_{i=sole,\ 1}^{t}\right)^{tons} = \left(f_{i=sole,\ 1}^{t-1}\right)^{tons}\left(1+e_{i=sole}\frac{Y^t-Y^{t-1}}{Y^{t-1}}\right) \tag{5}$$

where $(f_{i=sole,1}^{t})^{tons}$ enters the SD model. Its value is computed within the SD model, as explained in Eq. (12) (Section 3.3), as a function of catchable stock, intermediate domestic consumptions, and sole exports; that is, as a function of economic and environmental measures.

3.3. System Dynamics (SD) Modelling: The Ecological System

The ecological system is simulated with system dynamics (SD). In other words, the two stocks in the ecosystem – nursery areas (Eq. (6)), and sole stock in the internal part of the Seine estuary (Eq. (8)) – are modelled with SD. Fig. 4 shows the stock and flow diagram of the ecological part of the IO/SD model.

SD modelling captures the complex behavior of a system such as nonlinear dynamics and feedbacks, but is not suited for detailed disaggregation at the economic sector levels. This drawback is mitigated by integrating the economic sub-system model with the SD model. Fig. 4 shows this integration each time a bold arrow goes into or out of a circle. A bold arrow going out of a circle indicates that the value of the variable is transferred to the economic sub-system model. A bold arrow going into a circle indicates that the variable takes a number transferred

[5] Source: Port Autonome du Havre (2000). Note: all prices mentioned in this paper are in M€$_{2007}$, which means millions of 2007 Euros.

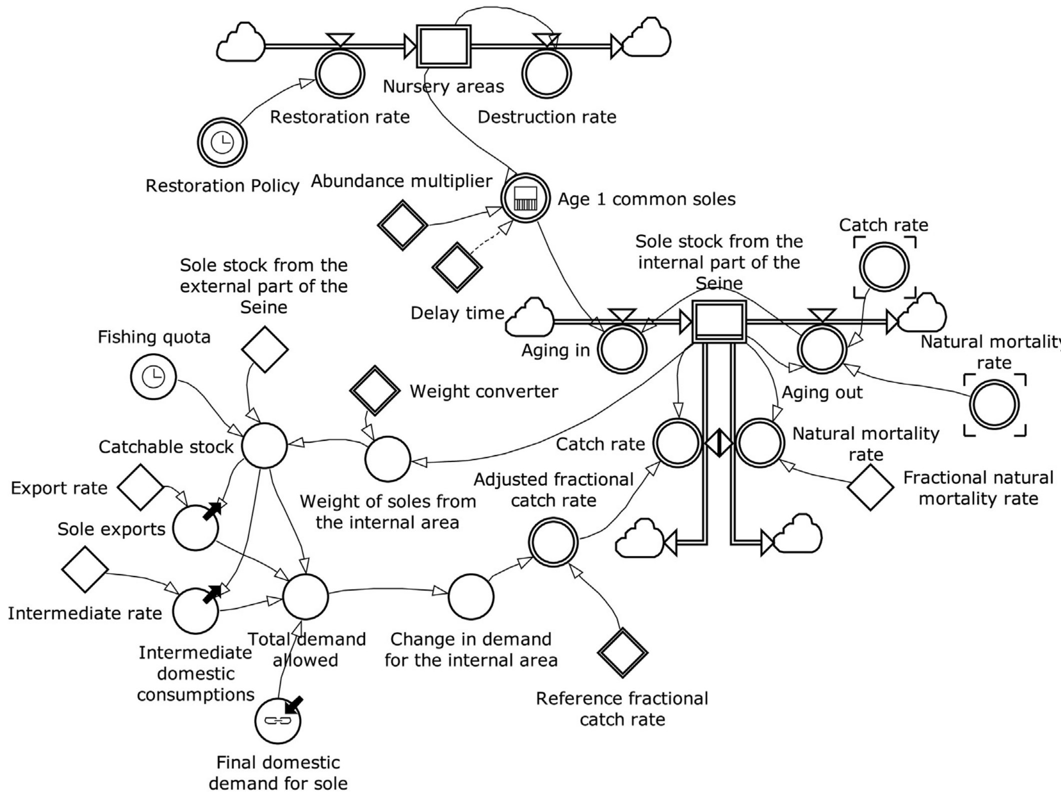

Fig. 4. The global IO/SD model of the ecological system and its economic components. *Notes: Boxes, double arrows, circles, and diamonds represent stocks, flows, auxiliary variables, and constants, respectively. Clouds indicate infinity and mark the model boundaries. Bold arrows into and out of auxiliary variables respectively indicate data transfer to and from the economic sub-system (in Excel).*

from the economic sub-system model. Key equations are described hereunder, and the full model with information about parameters used in the SD model is available from the authors upon request. There are two stock variables: Nursery areas (Eq. (6)) and Sole stock from the internal part of the Seine estuary (Eq. (8)), while Restoration rate (Eq. (7)), Aging in (Eq. (9)) and Catch rate (Eq. (8)), among others, are flow variables.

The nursery areas in the internal part of the Seine estuary are affected by the restoration and destruction rates of those areas; they are defined as[6]

$$\mathit{Nursery\ areas}_i^t = \int_{t_0}^{t_n} \left(\mathit{Restoration\ rate}_i^{t-1} - \mathit{Destruction\ rate}_i^t\right) dt + \mathit{Nursery\ areas}_i^{t_0},\ i \in (1, \ldots, 21) \quad (6)$$

They comprise 21 area categories *i* with different sole abundance; the categorization being based on the sediment type – gravel, sand, or silt – and the depth. We assume they are independent, since it is not clear how these areas interact with each other. The destruction rate[7] is estimated at 0.48% for high density areas; i.e., >45 juvenile sole individuals of age 0 (<12 months) per km^2, and at 0% for other nurseries. High density nurseries include most of the nurseries (gravel, silt, and sand) that are located at depths between −3 m and 5 m [cmh].[8] The restoration rate is the area (in km^2) of nursery restored per year and is defined as:

$$\mathit{Restoration\ rate}_i^t = \mathit{Restoration\ Policy} \times \mathit{Nursery\ areas}_i^t\ \ i \in (1, \ldots, 21) \quad (7)$$

Here
Restoration Policy is expressed as the percentage of *Nursery areas*$_i^t$ restored per year, with an effect on *Restoration rate* delayed by 1 year (as reflected in Eq. (6)) to take into account the fact that when a natural area is restored it takes time before its ecological functions work properly to re-create the conditions of a natural habitat.

The dynamics of sole stock in the internal part of the Seine estuary is computed using a cohort structure, age 1 through age 10 as follows:

$$\begin{aligned} &\mathit{Sole\ stock\ from\ the\ internal\ part\ of\ the\ Seine}_j^t \quad (8) \\ &= \int_{t_0}^{t_n} \left(\mathit{Aging\ in}_j^t - \mathit{Aging\ out}_j^t - \mathit{Catch\ Rate}_j^t - \mathit{Natural\ mortality\ rate}_j^t\right) dt \\ &+ \mathit{Sole\ stock\ from\ the\ internal\ part\ of\ the\ Seine}_j^{t_0},\ j \in (1, \ldots, 10) \end{aligned}$$

Sole stock from the internal part of the Seine$_j^{t_0}$ is computed from ICES (2012) and Rochette et al. (2010), and *Natural mortality rate*$_j^t$ is assumed to be 10% for each age as in ICES (2012). *Aging in* is a transfer from a previous age and *Aging out* is a transfer to a next age: $\mathit{Aging\ in}_j^t = \mathit{Aging\ out}_{j-1}^t$ *for* $j \in (2, \ldots, 10)$. Note that the quantity of sole of age 1 (12 months ≤ sole age < 24 months) is not a function of the adult sole population, but rather a function of the nursery area. This is because soles lay thousands of eggs, so that the number of juveniles recently hatched depends less on the number of adults of reproductive age than on the physical and chemical conditions that ensure the survival of the juveniles. Nursery area surface is one of the important physical conditions that influences their survival.

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[6] Note that, instead of using integrals, the stock-flow equations can also be defined as Euler 1st order approximation of differential equations and written as difference equations. This can be applied to Eqs. (6) and (8).

[7] The destruction rate of 0.48% has been estimated after consultation with experts in sedimentology and hydro-morphological dynamics of the Seine estuary.

[8] In the cmh reference system (cote marine du Havre), negative and positive depth values are respectively above and below the sea level at the lowest tide of the year.

Hence $Aging\ in_1^t$ is computed as

$$Aging\ in_1^t = \sum_{i=1}^{21} \left(Abundance\ Multiplier_i \times \min\left(Nursery\ areas_i^{t-1}, Nursery\ areas_i^t\right)\right) \tag{9}$$

The logic for selecting nursery areas as the smaller number between periods t and $t-1$ reflects expert advice: it may take time for age $t = 1$ soles to move into a newly restored area, but when an area is destroyed, age $t = 1$ soles immediately disappear.

The $Catch\ Rate_j^t$ of Eq. (8) is determined by sole stock in the internal part of the Seine estuary, and by changes in demand for soles from the internal area through the adjusted fractional catch rate, as follows:

$$\begin{aligned} Catch\ Rate_j^t &= Adjusted\ Fractional\ Catch\ Rate_j^t \\ &\quad \times Sole\ stock\ from\ the\ internal\ part\ of\ the\ Seine_j^t, j \in (1, \ldots, 10) \end{aligned} \tag{10}$$

$Adjusted\ Fractional\ Catch\ Rate_j^t$ changes according to the total demand allowed as follows:

$$\begin{aligned} &Adjusted\ Fractional\ Catch\ Rate_J^t \\ &\quad = \left(Total\ demand\ allowed^t / Total\ demand\ allowed^{t_0}\right) \\ &\qquad \times Reference\ fractional\ catch\ rate \end{aligned} \tag{11}$$

where *Reference fractional catch rate* is the share of the sole population caught by fishermen at each age category (percentages taken from ICES (2012)), and $Total\ demand\ allowed^t$ of sole depends on whether the total demand exceeds catchable stock (computed based on the fishing quota), according to the following equation:

$$\begin{aligned} &Total\ demand\ allowed^t \\ &\quad = \min\left(\left(Sole\ exports^t + Intermediate\ domestic\ consumptions^t \right.\right. \\ &\qquad \left.\left. + Final\ domestic\ demand\ for\ sole^t\right), Catchable\ stock^t\right) \end{aligned} \tag{12}$$

where $Final\ domestic\ demand\ for\ sole^t$, $(f_{i=sole,1}^t)^{tons}$, is expressed in tons and calculated in Eq. (5) in the economic sub-system model in Excel. $Sole\ exports^t$ and $Intermediate\ domestic\ consumptions^t$ of soles (i.e., all economic sectors that use fish as a raw material: restaurants, food industries, chemical industries, etc.), are assumed to be a constant share of catchable stock and calculated in the SD model in Powersim by multiplying the $Catchable\ stock^t$ by a constant percentage; respectively, 5.2% and 6.7%, which are based on the respective shares of $Intermediate\ domestic\ consumptions^t$ and $Sole\ exports^t$ in the $Catchable\ stock^t$ observed in the reference year. Hence, $(f_{i=sole,1}^t)^{tons}$ may be constrained by these other demanded quantities and $Catchable\ stock^t$. These two values are embedded into the economic sub-system model.

The $Catchable\ stock^t$ is the amount of the sole population that is allowed to be caught in the sea. It is calculated by multiplying the *Fishing quota* (set at 11.7%, representing the 2011 statistics) by the total fish population in the Eastern Channel.

$$\begin{aligned} &Catchable\ stock^t \\ &\quad = Fishing\ quota \\ &\qquad \times \left(Sole\ stock\ from\ the\ external\ part\ of\ the\ Seine^t \right. \\ &\qquad \left. + Sole\ stock\ from\ the\ internal\ part\ of\ the\ Seine^t\right) \end{aligned} \tag{13}$$

Finally, in order to estimate the effects on the economy of changes caused to nursery areas (either through destruction or environmental restoration), the amount of soles consumed by households must be expressed in monetary units and entered into the economic sub-system model to be summed with the other final demand categories in vector f^t from Eq. (1). This is calculated as follows[9]:

$$f_{i=sole,\ 1}^t = Price \times \left(f_{i=sole,\ 1}^t\right)^{tons} \tag{14}$$

where *Price* is the price of soles in the Haute-Normandie region and is equal to 0.0116 million Euros per ton.[10]

4. Results

This section covers simulation results particularly focusing on nonlinearity, uncertainty, and policy implications to provide insights into the IO/SD model. The simulation is run yearly from 2007 – the reference year t_0 – to 2020 (following expert advice, the reference year for ecosystem variables is taken as the average of the period 2002–2011). The baseline run in this section assumes no restoration policy.

4.1. Nonlinearity

In a linear system, all fractional rates that determine flows remain constant (Blanchard et al., 2006; Sterman, 2000). However, some of the fractional rates are not constant in the IO/SD model, which is therefore a nonlinear system. For example, *Adjusted fractional catch rate* in Fig. 4 changes according to the total demand allowed (Eq. (11)). *Sole Caught originating from the internal part of the Seine Estuary* in Fig. 3, which corresponds to *Catch rate* in Fig. 4, constitutes a key feedback loop that links the ecological system and the economic sub-system. And it is the adjusted fractional catch rate that determines the catch rate, along with the sole stock (Eq. (10)).

We compared, for the baseline scenario (that is, without restoration), the dynamics of the adjusted fractional catch rate in the IO/SD model with and without the feedback loop between the ecological system and the economic sub-system. Fig. 5 shows that this catch rate changes over time with the feedback, and that it is constant without the feedback.

4.2. Uncertainty

We then investigated the sensitivity of the model to uncertainty. There are three types of sensitivity: numerical, behavior mode, and policy (Sterman, 2000). We focus on behavior mode sensitivity (i.e., the patterns of behavior generated by the model), because for this paper it is more important to understand how the model behaves with the integration of the ecological and economic systems than to undertake numerical precision or to derive optimal policies.

As comprehensive sensitivity analysis is generally impossible (Sterman, 2000), we focus on the sensitivities of two parameters that influence *Sole stock from the internal part of the Seine*: i) *Abundance multiplier* (Fig. 4), and ii) *Fractional natural mortality rate* (Fig. 4).

For the sensitivity analyses, we used the Latin hypercube method available in Powersim and did 50 runs for each parameter. Because we did not know the probability distribution of either parameter, we simply adopted the uniform distribution and chose arbitrary ranges based on the best information available. More precisely, i) *Fractional natural mortality rate* ranges from 0.05 to 0.20, because the baseline value assumed by ICES (2012) is set at 0.10, and ii) *Abundance multiplier* varies negatively and positively by 20% around the baseline values estimated with the habitat suitability model developed by Rochette et al. (2010) for 21 nursery categories.

[9] The result can be considered as the total final domestic consumption of sole products (except sole exports). (Because there is no sole consumption by the final demand categories k = 2 to 6, their value is zero in the IO table of the reference year 2007.)

[10] Fixed price based on fish statistics from France AgriMer (2009).

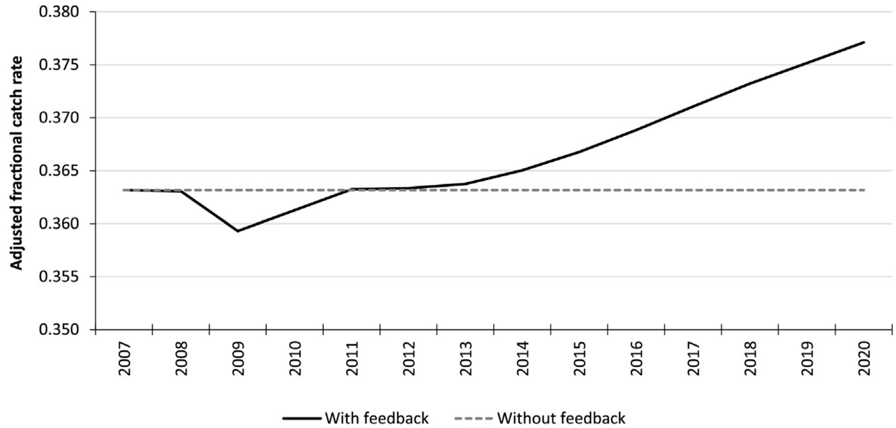

Fig. 5. Comparison of adjusted fractional catch rate with and without the feedback. *Note: For simplicity, we take an average of the fractional rate for each year by applying* $\text{Adjusted Fractional Catch Rate}^t = \frac{1}{10}\sum_{j=1}^{10}\text{Adjusted Fractional Catch Rate}_j^t$.

The upper bound, lower bound and baseline results displayed in Fig. 6.1 and 2 show interesting behaviors; depending on the parameters' values, the sole stock could potentially increase, at least for a while, or it can steadily decrease. As a matter of fact, Fig. 6.1 shows that the ICES value, as well as any higher mortality rate of our range, brings about a steady reduction in the number of soles. However, if mortality rates reach lower ranges, this first contributes to higher increases in the *Sole stock from the internal part of the Seine*, until the point where further destruction of the estuary and increases in the sole catch driven by the growth of regional GDP (Gross Domestic Product) take place and begin to reduce the sole stock. Conversely, in Fig. 6.2, the abundance multiplier estimated by Rochette et al. (2010) shows that the number of individuals will decrease as years go by. However, would the abundance multiplier be 20% higher, the number of soles would only start decreasing after a lag period of 5 years without restoration.

This shows how important it is to collect information about possible ranges of each parameter, as precise information would enable us to estimate whether the sole stock continuously decreases, or increases first before decreasing later in time.

4.3. Policy Implications

The aim of the policy simulation is to demonstrate how the IO/SD model behaves in alternative restoration scenarios, rather than to find the optimal restoration policy. The current IO/SD model favors realism over precision, and realism over generality (that is, representing a broad range of systems' behaviors with the same model) (Costanza et al., 1993).

We tested two scenarios: 1) no restoration (i.e., baseline), and 2) restoration targeted to areas with high density of sole for the eleven years from 2007 through 2017. The degree of restoration for the second scenario is based on the preferences of local stakeholders (scientists, fishermen, industry representatives, policy-makers, etc.), who commonly agreed in several meetings organized in 2004 that coming back to the level of environmental quality reached in 1979–1980 would be the most desirable scenario for the Seine estuary (AESN–DIREN Haute-Normandie, 2004; Préfecture de Région de Haute-Normandie, 2008).

In the first scenario, due to the continuing destruction, nursery areas steadily decline (solid line in Fig. 7.1). In the second scenario, nursery areas are restored for the first 11 years (dashed line in Fig. 7.1); they increase until 2018 and decrease thereafter. The effect of natural nursery

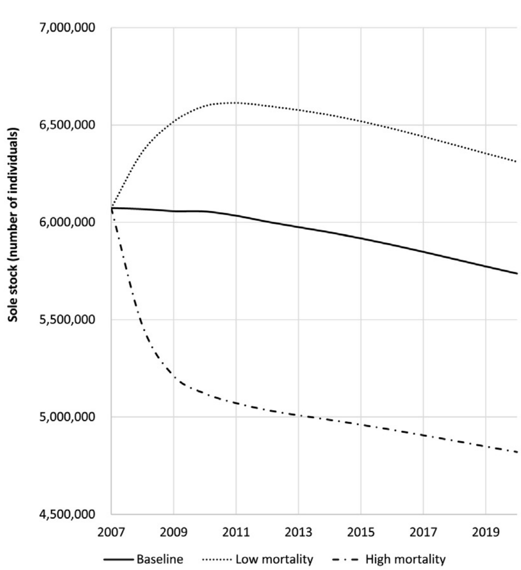

Figure 6.1 Sensitivity of sole stock to fractional natural mortality (without restoration)

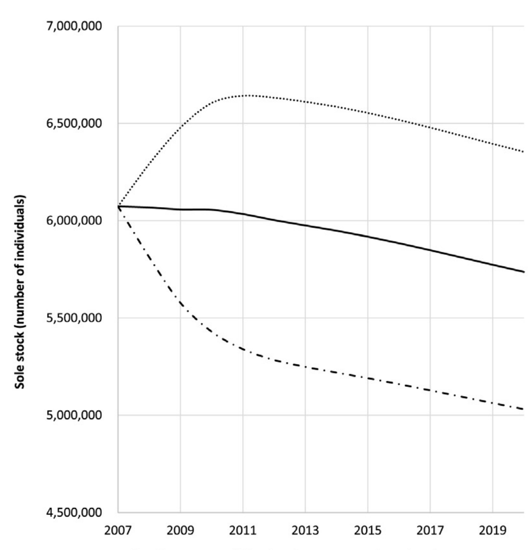

Figure 6.2 Sensitivity of sole stock to abundance multiplier (without restoration)

Fig. 6. 1. Sensitivity of sole stock to fractional natural mortality (without restoration). 2. Sensitivity of sole stock to abundance multiplier (without restoration).

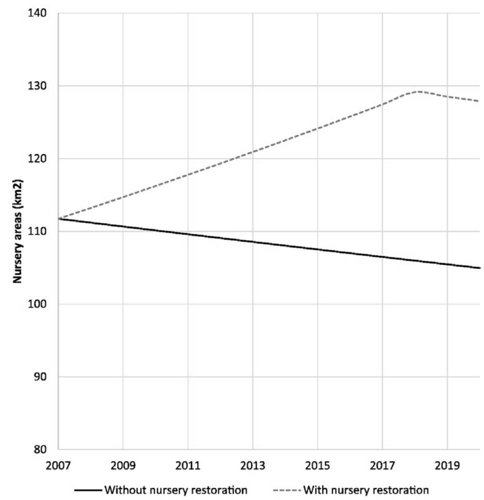

Figure 7.1 Nursery areas

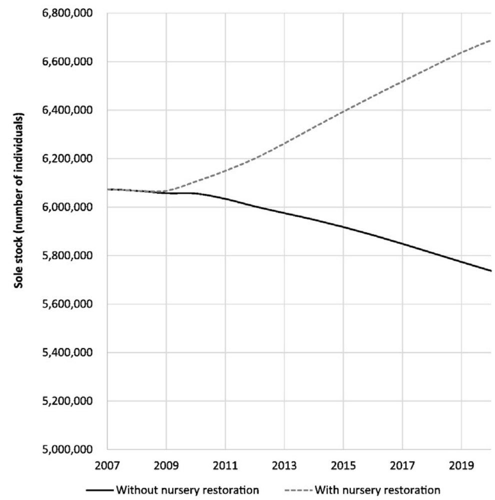

Figure 7.2 Sole stock from the internal part of the Seine estuary

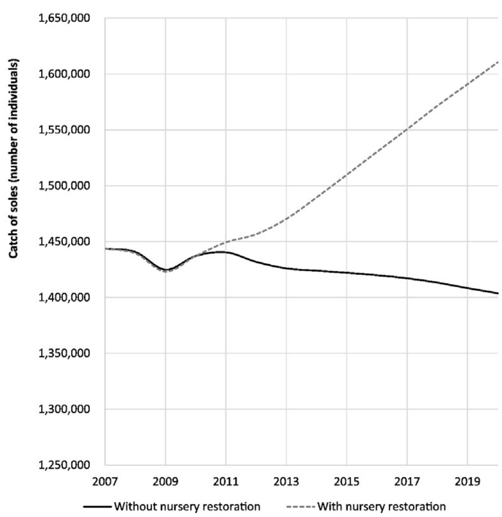

Figure 7.3 Catch of soles originating from the internal part of the Seine estuary

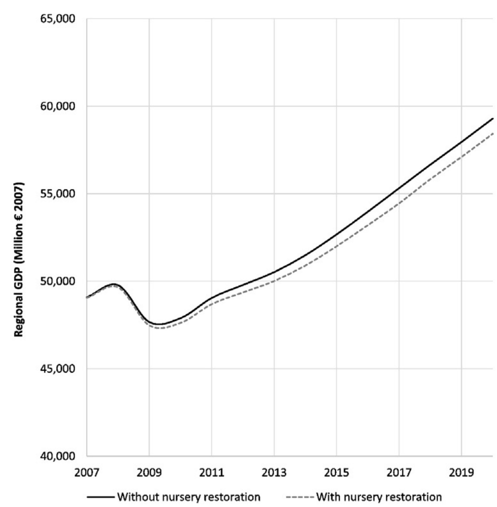

Figure 7.4 GDP of Haute-Normandie

Fig. 7. 1. Nursery areas. (It considers only those nurseries with an age 0 (<12 months) sole juvenile density index higher than the internal estuary average; i.e., >45 juveniles/km^2.) 2. Sole stock from the internal part of the Seine estuary. 3. Catch of soles originating from the internal part of the Seine estuary. 4. GDP of Haute-Normandie.

area evolution (following natural destruction paths), coupled with restoration activities, results in a high fish density nursery area totaling 127.9 km^2 in 2020 (dashed line in Fig. 7.1). This equals the level assessed in 1978. The cost of environmental measures implemented to restore nurseries (Ψ^t from Section 3.2) amounts to M€ 59.72 per year.

Fig. 7.2 shows that sole stock increases with restoration (dashed line), while the opposite holds without restoration (solid line). The same conclusion is valid for Fig. 7.3 concerning the catch of soles originating from the internal part of Seine estuary.

Fig. 7.4 shows that GDP tends to be lower with restoration (dashed line). This is because of the cost of environmental measures implemented to restore nursery areas: while it positively impacts investment ($f^t_{i,4}$), leading to increased levels of economic activity needed for implementing environmental measures, it dampens final household consumption ($f^t_{i,1}$): the latter outweighs the former. It is assumed that economic sectors pay half the cost through a reduction of their profits (gross operating surplus) and the other half through a reduction of employment or salaries; both factors decrease household incomes.

The results indicate that the restoration policy improves both the sole stock and sole catch, but slightly reduces regional GDP. However, as the reduction seems very limited, it might suggest that restoring vast areas of marine habitat is possible without significantly impacting the regional economy. However, these are partial results. If all costs of nursery restoration were to be included in the model, a portion of ecosystem services could not be assessed in terms of their positive impact on economic activities because appropriate data and knowledge do not exist yet. Only the provisioning ecosystem service of sole[11] for human consumption could be economically assessed. If, without considering all the benefits from ecosystem services, our results show little negative macro-economic impact in terms of regional GDP, extending the assessment to the five other ecosystem services[12] provided by

[11] However, studying sole is interesting because it is an overfished species whose population is at risk in the Eastern channel (ICES, 2008) and because it has a high commercial value (and as such provides an important service to the economy).

[12] i) provisioning service of six commercial fish other than *Solea solea* (common sole): *Dicentrarchus labrax*, *Platichthys flesus*, *Pleuronectes platessa*, *Trisopterus luscus*, *Trisopterus minutus*, and *Merlangius merlangus* (Bass, flounder, plaice, pouting, poor cod, and whiting); ii) life support service provided to these six species; iii) regulating service of flood control; iv) cultural services of recreational fishing and v) regulating services of natural contaminant buffering.

nurseries would probably demonstrate that nursery restoration has positive macro-economic impacts. Moreover, since IO/SD is highly complex, further simulation analyses (particularly policy sensitivity analysis (Moxnes, 2005)) are required in order to elicit robust policy implications. Also, besides sole stock and catch and changes in regional GDP, other criteria such as equity and intergenerational effects may also need to be considered.

5. Discussion and Conclusion

In this paper, we model an ecological-economic system based on two approaches: SD modelling (in Powersim) for the ecological system coupled with IO modelling (in Microsoft Excel) for the economic system. They have different characteristics and are complementary. For example, on the SD side, the non-convexity of ecological systems can be simulated with differential equations. And on the IO side, an IO table can capture detailed direct and indirect impacts of economic activities such as pollutant emissions and natural resource depletion. Moreover, in most developed countries, IO tables are sufficiently well maintained, thus allowing our modelling approach to be transferred to other case studies.

Although there has been little academic research using IO/SD models, in businesses where practical solutions are required there exist SD models that can be synchronized with other programs, including decision support programs and databases.[13] There may be both theoretical and technical reasons for the lack of development of this type of approach in the academic literature. First, while IO adopts constant technical coefficients and constant returns to scale using linear equations, SD emphasizes nonlinearity and dynamics using differential equations (e.g., Sterman, 2000). Second, while IO is based on a matrix architecture, SD is based on a stock-and-flow diagram architecture.

Despite these differences between IO and SD, we believe that their integration has many advantages. First, it can better capture the complexity of an ecological-economic system. Second, in SD models, all causal links are shown explicitly, reducing the possibility that important links would be forgotten in the description of the ecological-economic system. Third, in the coupled model IO is free from its almost sole dependency on “hard data” (Sterman, 2000), because the SD architecture and methodology open up the possibility for experts with proper knowledge and experience to estimate the parameters for which data are not available. For example, the destruction rate of nursery areas is based on previous observational data and expert consultations.

One of the disadvantages of IO models is that they employ constant technical coefficients, which could be inaccurate if we wanted to simulate a time period longer than 10 years (or 15 years, as in Wydra, 2011). Over longer time periods, productive relationships may change and economic structures may substantially evolve (Markaki et al., 2013). As an illustration, the static version of the regional IO model used in this paper gives error margins ranging between −27% and +21% (depending on the variable considered) over an 8-year period.[14] In order to expand this period of time to 14 years (2007–2020) while keeping error percentages at a lower level, the regional IO model has been made partially dynamic: companies' investments and final household demand have been made dynamic. And making technical coefficients dynamic would allow simulation over a longer period (e.g., a 35 year period, as in Hamilton (1997)).

Although our model still needs improvement, it brings insight into the relevance of feedback loops in the modelling of interactions between the economic system and the ecosystem. This is an improvement over most modelling techniques in ecological economics that omit feedback impacts on the economic system generated by ecological changes previously caused by that economic system. Many papers do consider feedback within the economic system; for example, between final consumers and producers (Cabo et al., 2014; Cosmi et al., 2013). Also, many papers do consider feedback impacts within the ecosystem; for example, the feedback between phytoplankton and upper ocean circulation (Nakamoto et al., 2007), or the feedback between Antarctic glaciation and the carbon cycle (Zachos and Kump, 2005). However, a few papers take into account feedback between the economic system and the ecosystem; for example, the feedback impact between agriculture and human genes (O'Brien and Laland, 2012), or the bio-economic feedback between ranch farming and the vegetation cover conditions (Domptail and Nuppenau, 2010). We believe this paper is an improvement in that direction as it not only considers feedbacks between the economic system and the ecosystem as in the above-mentioned research; it also synchronizes IO with SD so as to make dynamic environmental parameters (which is uncommon within an IO) and so as to describe a detailed economic structure (which is uncommon within SD).

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Any remaining errors and omissions are of course our sole responsibility.

Appendix A. Exogenous parameters and endogenous variables

Table 2 shows the parameters of the model IO-SD model that are exogenous to the model (data taken from scientific literature) and the variables that are endogenous (that is, computed within the model).

Table 2
Endogenous and exogenous variables and parameters of the IO-SD model.

	Endogenous		Exogenous	
Ecological system	• *Nursery areas*$_i^t$	(Eqs. 6, 7, 9)	• All parameters and variables in t_0	
	• $(f_{i=sole,\ 1}^t)^{tons}$	(Eq. 5)	• *Restoration rate*$_i^t$	(Eqs. 6, 7)
	• *Sole stock from the internal part of the Seine*$_j^t$	(Eqs. 8, 10, 13)	• *Destruction rate*$_i^t$	(Eq. 6)
	• *Aging in*$_1^t$; *for* $j=1$	(Eqs. 8, 9)	• *Restoration Policy*	(Eq. 7)
	• *Catch Rate*$_j^t$	(Eqs. 8, 10)	• *Aging out*$_j^t$	(Eq. 7)
	• *Adjusted Fractional Catch Rate*$_j^t$	(Eqs. 10, 11)	• *Aging in*$_j^t$	(Eq. 8)
	• *Total demand allowed*^{t}	(Eqs. 11, 12)	• *Natural mortality rate*$_j^t$	(Eq. 8)

(continued on next page)

[13] For instance, the Powersim program can synchronize with Oracle, SAP, Excel, and GIS programs.

[14] Error margins are obtained after combining a sensitivity analysis (that takes into account random errors) with a retrovalidation (that takes into account systematic errors).

Table 2 (*continued*)

	Endogenous		Exogenous	
	• *Sole exports^t*	(Eq. 12)	• *Abundance Multiplier$_i$*	(Eq. 9)
	• *Intermediate domestic consumptions^t*	(Eq. 12)	• *Reference fractional catch rate*	(Eq. 11)
	• *Final domestic demand for sole^t*	(Eq. 12)	• *Fishing quota*	(Eq. 13)
	• *Catchable stock^t*	(Eq. 12)	• *Sole stock from the external part of the Seine^t*	(Eq. 13)
Economic sub-system	• f_{ik}^t ; *for* $k=2,3,5,6,7$	(Eq. 2)	• All parameters and variables in t_0	
	• f_{i1}^t ; *for* $k=1$	(Eq. 3)	• ρ_k^{t-1}	(Eq. 2)
	• Y^t	(Eq. 3)	• e_i	(Eq. 3)
	• $f_{i,4}^t$; *for* $k=4$	(Eq. 4)	• $\widehat{cap}_i$	(Eq. 4)
	• $\widehat{GOS}_{inv}^{t-1}$	(Eq. 4)	• Unit restoration cost = 27.7 M€/km^2	(Eq. 4)
	• ψ_i^t	(Eq. 4)	• Restoration rate	(Eq. 4)
	• $f_{i=sole,\ 1}^t$	(Eqs. 5, 14)	• *Price* = 0.0116 M€ per ton	(Eq. 14)

Appendix B. Supplementary Data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2017.04.005.

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