An Input-Output Economic Model integrated within a System Dynamics Ecological Model: a methodology for feedback loop applied to fish nursery restoration

Mateo Cordier a, b, Takuro Uehara c, Bertrand Hamaide d and Jeffrey Weih e

a Cultures-Environnements-Arctique-Représentations-Climat, Université de Versailles Saint-Quentin-en-Yvelines (CEARC-UVSQ), France.
b Centre d’Études Economiques et Sociales de l’Environnement, Centre Emile Bernheim, Université Libre de Bruxelles, (CEEE-CEB-ULB), Brussels, Belgium.
c College of Policy Science, Ritsumeikan University, Osaka, Japan
d Centre de Recherche en Economie, Université Saint-Louis (CEREC-FUSL), Brussels, Belgium.
e Senior Adult Learning Center, Portland State University, USA.

Abstract. While environmentally extended input-output (I-O) models are commonly used for capturing interactions between ecosystems and economic systems, this kind of modeling cannot reflect interactions inside the ecosystem. Isard’s (1968) model has been the only exception. He entered interactions occurring within the ecosystem into I-O. Nevertheless, given the linearity of I-O, he could only analyze environmental issues in a linear fashion. We propose an alternative that reverses Isard’s model types: the economic system is modeled 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 I-O within System Dynamics (SD), which captures nonlinear dynamics. The originality of our model is that, first, there has thus far been no synchronization of an SD model with I-O; previous models translated I-O into SD, which is laborious and inefficient. Second, SD-based I-O models in the literature have not incorporated ecological components. Third, our SD/I-O model incorporates five feedback loops between the ecosystem and the economic system. After describing the methodological issues, we “test” the SD/I-O 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 modeling of interactions between the ecosystem and the economic system. We believe such a tool may be of help to decision makers mixing economic and environmental issues like, in our application case, fish habitat and harbor development.

1 Introduction

Ecological economic models are required to capture the complexity of ecological economic systems, as the complexity is an essential part of that system (e.g. Levin et al., 1998; Limburg et al., 2002). There are two main
sources of complexity. First are the interactions between ecological systems and economic systems. The 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 economists’ expectations, ecological systems are often non-convex (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 models and modeling 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 I-O models. Input-output (I-O) models are used to simulate economic activities. I-O models are interesting because they can estimate not only direct but also indirect effects of policy instruments (or ecosystem modifications).

Between the end of the 1960’s and the beginning of the 1970’s, environmentally extended input-output (I-O) models have been developed to simulate interactions between ecosystems and economic activities. First operational version of such models were developed by Isard (1968), Leontief (1970) and Victor (1972). In their I-O model, 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, in addition to economic flows of goods and services on market, describe interactions occurring at the interface between the ecosystem and the economic system: i) flows of pollutants or human waste 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 cannot be taken into account. Feedback loops can be defined as a condition whereby causal variables in the system (original causes) generate output variables (consequences) that will modify the initial causal variable through a series of relationships (Stepp et al., 2009; Deaton and Winebrake, 2000; Sterman, 2000). For example, economically-induced changes (original cause) caused to marine fish populations (consequence) will have a feedback impact on the fishing sector and on other economic activities (original cause).

Most of the authors mentioned above have discarded 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 discarded until now although nonlinear dynamic ecological processes are at the productive source of final ecosystem services that impact human well-being (Cordier, 2014; Haines-Young and Potschin, 2010). Excluding such crucial interactions prevents ecological-economic models to analyse the impact of pollutant discharge or natural resource extraction on ecosystems. However, Isard (1968) was the only exception. He was the first to enter into I-O models interactions that occur inside the ecosystem. However, the lack of ecological data in that time reduced drastically the number of cases to which his model could be applied. In addition, given the linear property of I-O models, he could exclusively analyse linear environmental issues. This problem remains even in recent publications, either those that use I-O models solely or integrated to a full Computable General Equilibrium model (CGE).\footnote{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).}

Many of them restrain their ecological-economic model to case studies related to prey-predator relations inside food webs, a typical purely linear relationship in ecosystems (e.g. Jin et al., 2003 and 2013; Finnoff and Tschirhart, 2008; Hussain and Tschirhart, 2013). This is a considerable drawback given that non-linearity is rather a rule than an exception in environmental issues. To our knowledge, one of the very few ecological-economic CGE model to take into account to integrate non-linear interactions inside the ecosystem is the one developed by Finnoff and Tschirhart (2011, p. 1693).

There is, however, another option to be considered for ecological-economic models to take into account non-linearities of ecosystems functioning: build the model in the other way around. This means that inversely to Isard’s model and other authors mentioned in previous paragraph, I-O modelling should be entered into ecosystem models, not the contrary. This is what we call the “economic component principle”: the economic system is modelled within the ecosystem, or in other terms as one of the components of the ecosystem. This prevents the architecture constrains of economic models to limit the possibilities to describe the ecosystem.

To apply the “economic component principle” in this paper, we develop an ecological-economic model based on the integration of I-O within a System Dynamics model (SD). SD started at the beginning of the 1960’s with Forrester (1961). It is a computer-aided approach based on differential equations (Richardson, 2013). It has been used for modeling ecological economic systems (e.g., Costanza et al., 1998; Uehara, 2013). 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, stocks and flows that affect the behaviour of the entire system (Forrester et al., 1997).

Applying SD concepts to I-O modelling means that an I-O model is embedded in a SD model as one of the components of the SD model. With such perspective, the 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 of the parts of the ecosystem. There are two major methodological contributions of our modeling approach. First, to our knowledge, there has been no system dynamic model synchronized with I-O: previous system dynamics models on I-O translate I-O into system dynamics (e.g., Braden, 1983; Diehl, 1985). Although it is not impossible as previous studies show, it is not common for SD to include detailed economic sectors composed of multiple subsectors (e.g., Dudley, 2004; Moxnes, 2005) as it is laborious, inefficient and increase the complexity of the model architecture far above what is required. When SD focuses on nonlinear dynamics in an ecological system and I-O is implemented in some other platform suitable for it, we can capture the complexity of an ecological economic system more appropriately. Second the abovementioned SD based I-O models do not incorporate ecological system components.

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

2 Ford (1999) demonstrates the laborious difficulty in replicating system dynamics models in a spatial model in which each grid cell interact with each other as industries in I-O interact with each other.
One of the feedback loops relate to the impact of the size of the population of sole fish in the marine ecosystem (“catchable stock”) on sole prices in the economic system. This is an original point since “[…] most fishery models ignore the variation of fish prices and unit variable costs with the harvest rate” (Moxnes, 2005).

This paper is structured as follows. Section 2.1 presents the case study, Section 2.2 develops the economic component of the model (I-O equations), Section 2.3 shows the ecosystem component of the model (SD equations), Section 2.4 explains how the economic component is embedded within the ecosystem modeling, Section 3 displays the results and Section 4 discusses them and concludes.

2 Method

2.1 Study area

We apply the I-O/SD modelling to the case of the restoration of estuarine nurseries used as a natural habitat by Common sole juveniles (Solea solea sp.) in the Seine estuary. The estuary is located in Haute-Normandie region (France) in the Eastern channel (fishing zone VIIId extending from the South of England to North of France). Nursery areas are a natural capital that provides a habitat essential to development and feeding of juvenile fish and contribute by such to the maintenance of the existence 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 of 181.91 km² in 1834 and dropped to 111.74 km² in 2004. In the Seine estuary seven species of commercial fish depend on nursery habitats and could be potentially affected by their destruction: Common sole, Bass, flounder, plaice, pouting, poor cod, and whiting (Cordier et al., 2011).

2.2 The economic component: input-output (I-O) equations on Excel

We adopt the semi-dynamic I-O model developed in Microsoft Excel by Cordier et al. (2014) to represent the economic component of the SD model. The semi-dynamic property of the sub-model means that what happens in year $t-1$ has an impact on year $t$ except for input technical coefficients that remain constant in the I-O matrix (which explains why the I-O sub-model is not fully
dynamic). The architecture of the I-O sub-model is made of a regional *commodity by industry* matrix of 35 sectors located in the French region of Haute-Normandie that has been developed through a regionalization process of the national tables by Cordier (2011). Before entering the I-O sub-model in the SD global model, it has been aggregated to 12 goods and services \(i (i = 1, \ldots, n; n = 12)\) and 12 economic sectors \(j (j = 1, \ldots, m; m = 12)\). Although such aggregated results reduce the level of details of the economic system simulated, they reduce uncertainty margins compared to results displayed for each of the 35 sectors.

The general Equation (1) of *commodity by industry* I-O models calculates the direct and indirect impact on the production of output \(g\) of all other sectors based on changes in final demand (Lixon et al., 2008):

\[
g^{T} = \left[ (I - D^{T}B^{d})^{-1}D^{T} \right] f^{d^{T}}
\]

where \(g^{T}\) is an \(m \times 1\) column vector whose elements \(g_{j}^{T}\) are the total output per sector \(j\) produced during year \(t\) (exponent \(T\) means “transpose”) expressed in million euros, \(I\) is the \(n \times m\) identity matrix; \(B\) is a \(n \times m\) matrix of *input technical coefficients* \(b_{ij}\), \(D^{T}\) is a \(n \times m\) matrix of the *commodity output proportions* \(d_{ij}\), which are technical coefficients defined under the *industry-based technology* assumption. Both technical coefficients, \(B\) and \(D\), are calculated respectively on the basis of supply matrix \(V\) and the use matrix \(U\), as in Lixon *et al.* (2008). Any \(n \times m\) matrix is a square matrix \((n = m)\). Exponent \(d\) shows that consumption concerns inputs used inside the study area, which have been domestically produced in the study area; \(f^{d^{T}}\) is an \(n \times 1\) column vector representing the final demand in year \(t\) expressed in million euros and where each \(f_{i}^{d^{T}}\) represents the value of regionally produced commodities \(i\) consumed by the \(p\) categories of final demand \(k (k = 1, \ldots, p)\) that is to say: final consumption by households \((k = 1)\), NGO \((k = 2)\) and government \((k = 3)\), gross fixed capital formation (i.e. investments) \((k = 4)\), change in valuables \((k = 5)\), change in inventories \((k = 6)\), and international and interregional exports \((k = 7)\). In other terms, each \(f_{i}^{d^{T}} = \sum_{k=1}^{p} f_{ik}^{d^{T}}\). All prices mentioned in this paper are in 2007 prices and in million Euros (except when specified).

Regarding all commodities \(i\) except for sole products, 5 categories \(k\) of final demand \(f_{ik}^{d^{T}}\) (i.e. except final consumption by households and investments)\(^{3}\) are estimated as follows:

\(^{3}\) *Final consumption by households and investments are estimated by Cordier et al.’s Equation (2) and (5)* respectively (equation numbers corresponding to those in Cordier *et al.* (2014)).
\[ f_{i,k=2,3,5,6,7}^{d^t} = f_{i,k=2,3,5,6,7}^{d^{t-1}} (1 + \rho_k^t), \quad i = 1, \ldots, n \]  

Where \( f_{i,k=2,3,5,6,7}^{d^{t-1}} \) is the final demand (except for final household consumption and sole products) in previous year \((t - 1)\) and \( \rho_k^t \) is the annual growth rate in year \(t\) for each final demand category \(k\) given exogenously to our model. We exclude sole products from this equation for two reasons. First, final consumption for sole products by the categories \(k = 2\) to \(6\) equal zero in the statistics (i.e. in the I-O table of the reference year 2007). Second, we want as much as possible relate sole consumption to environmental conditions and environmental measures since this is precisely one of the way for our model to show how economic consumption is related to the environment. The calculation of final consumption of sole products (i.e. household consumption and exports) is explained in Section 2.3.

The direct impact of the cost of environmental measures on final household consumption is calculated as in Cordier et al. (2014, see their Equation (2))\(^4\) assuming that households purchase final commodities \(f_{i,k=1}^{d^t}\) in proportion to their income.

It is likely that economic sectors would not accept to bear the full cost of environmental measures \(\Psi^t\) through a reduction of their benefits. This is why we arbitrarily assume that they would agree to pay half the cost through a reduction of their benefits (gross operating surplus: \(\hat{GOS}\)) and the other half through a reduction of employment or salaries. The Gross operating surplus \((\hat{GOS}^t)\) is thus calculated as in Cordier et al. (2014, see their Eq. (3)).

This impacts final household consumption through the changes the costs of environmental measures cause to disposable income \(Y^t\). This change is calculated as in Cordier et al. (2014, see their Eq. (4)).

The costs of environmental measures also impact investment \(f_{i,k=4}^{d^t}\). This is calculated in Equation (5) in Cordier et al. (2014) where the positive effect of such investments \(\Psi^t\) on economic activities that are contracted to implement environmental measures are taken into account.

The direct plus indirect impact of changes in final demand (household consumption from Equation (2) and investment from Equation (5), both in Cordier et al. (2014)), on all other sectors of the economy in year \(t\) is calculated through the general Equation (1).

\(^4\) Equation (2) in Cordier et al. (2014) is calculated for all commodities except for sole products which are subtracted from fish products \(i = 3\) in order to avoid double counting between what is calculated in the I-O sub model on Excel and what is calculated in the SD global model on Powersim© in Section 2.3.
2.3 The surrounding ecosystem: system dynamics (SD) modelling on Powersim

The surrounding ecosystem is simulated with system dynamics (SD) modelling, a computational approach to capture dynamic complexities in a system: mathematically, it solves a system of coupled, nonlinear, first-order differential (or integral) equations (Richardson, 2011). Each component of the ecosystem is represented: plants, animals and natural habitats but also human activities within the I-O sub-model that is integrated to the SD.

With the aim to understand and quantify the relation between ecological systems and economic activities that destroy them, the SD model developed below simulates the relation between the nursery areas and economic activities related to harbor and maritime transport.

The SD model comprises mainly the economic sub-system described in Section 2.2 (built on Excel) and an ecological system built on Powersim in this Section. The main components of the ecological system are the nursery areas and the stock of soles. Figure 1 shows the stock and flow diagram of the ecological part of the SD model.

SD modeling captures the complex behavior of a system such as nonlinear dynamics and feedbacks, but is not suited for detailed (disaggregated) structures such as an economy. This drawback is palliated by the integration of the I-O sub-model to the SD model. Figure 1 shows this integration each time a bold arrow goes in or out of a circle. A bold arrow going out of a circle indicates that the value of the variable is transferred to the I-O sub-model on Excel. A bold arrow going into a circle indicates that the variable takes a number transferred from the I-O sub-model on Excel.

Inside the square boxes for a stock variable, circles for a flow variable, and diamonds for a constant from the conceptual model in Figure 1, there are equations. Arrows are an information arrow and indicate the direction of its influence. Since there are many equations and some of which are technical, we address only key equations and provide the full model description upon request.

There are two stock variables: nursery areas and sole stock in the internal of the Seine estuary.
Figure 1. The global SD model of the surrounding ecosystem and its economic component. Numbers between brackets refer to the corresponding equation described below. A bold arrow out of a circle indicates that the value of the variable from the circle is transferred from Powersim to the I-O sub-model on Excel. A bold arrow into a circle indicates that the variable takes a number transferred from the I-O sub-model on Excel to Powersim. A square box, a circle, a diamond and a cloud indicate a stock, an auxiliary variable, a constant and the model’s outer limits respectively.
The area of the nursery in the internal of the Seine estuary will be affected by the restoration and the destruction of the area as calculated in Equation (3):

\[
Nursery\ areas^t = \sum_{k=1}^{21} \int_{t_0}^{t} (Restoration\ rate_k^t - Destruction\ rate_k^t) \, dt + \frac{Nursery\ areas_{t_0}}{Nursery\ areas^t}
\]  

(3)

The Nursery areas\(^t\) comprise 21 area categories (k) with different sole abundance based on depth and seabed sediments. We assume they are independent since it is not clear how each area interact with each other. The areas change according to their restoration and destruction and to the total nursery area. Restoration rate is determined by a restoration policy and Destruction rate is proportional to the size of the area. Regarding this size, Nursery\ areas\(^{t_0}\) = 196.38 km\(^2\) at the reference year\(^5\) in the internal part of the Seine estuary (sources: Cordier et al (2011, p. 1666) based on the estimations of the habitat suitability model developed by Rochette et al.(2010)). Restoration Rate depends on how nursery areas are restored as calculated in Equation (4):

\[
Restoration\ rate^t = Restoration\ Policy \times Nursery\ areas^t
\]  

(4)

Where Restoration Policy is expressed as the percentage of Nursery areas\(^t\) that is restored with an effect on Restoration Rate delayed by 1 year to take into account the fact that when a natural area is restored, it takes time before ecological functions work properly and create the conditions of a natural habitat. Restoration Rate is the area of nursery restored expressed in km\(^2\)/year.

In Equation (3), we assume a constant annual Destruction Rate for simplicity but this is one of the points we should further investigate as we discuss in the discussion section.

Destruction rate\(^t\) is a vector of the percentage of nursery areas destroyed each year. For each of the 21 categories of nursery areas (the categorisation is based on the sediment type – gravel, sand or silt – and the depth), a destruction rate is entered in the model. In this version of the model, the destruction rate\(^6\) is estimated to 0.48% for high density areas (i.e. more than 45 individuals of juvenile soles of age 0 (<12 months) per km\(^2\)) and to

---

\(^5\) The reference year in the model is the average on the period 2002-2011 for ecosystem variables. However, in the case of this variable, the reference year is 2004 because it is the last date to which a value was available.

\(^6\) The destruction rate of 0.48% has been estimated after consultation of experts in sedimentology and hydro-morphological dynamics of the Seine estuary.
0% for other nurseries. High density nurseries include mostly all nurseries (gravel, silt and sand) that are located at depths between [-3 and 5] m cmh.

The dynamics of sole stock in the internal of the Seine is computed using a cohort structure, age 1 through age 10 as calculated in equation (5) here below:

\[
\text{Sole stock internal of the Seine}^i_t = \int_{t_0}^{t_n} \left( \text{Aging in}^i_t - \text{Aging out}^i_t - \text{Catch Rate}^i_t - \text{Natural mortality rate}^i_t \right) dt + \text{Sole stock internal of the Seine}^{i_0}
\]

\( i \in (1, \ldots, 10) \)

Aging in is a transfer from a previous age and aging out is a transfer to a next age: \( \text{Aging in}^i_t = \text{Aging out}^i_{t-1} \) for \( i \in (2, \ldots, 10) \). Note that the number of age 1 (fish younger than 12 months) is not a function of the adult sole population: rather it is a function of the nursery area. This is because soles lay thousands of eggs so that the amount of juveniles fish recently borne depend less on adults in reproduction age than on the chemical and physical conditions that ensure the survival of the juveniles recently borne. The surface of nursery areas is one of the important physical conditions that may influence their survival.

Hence \( \text{Aging in}^1_t \) from Eq. (5) is computed as follows:

\[
\text{Aging in}^1_t = \sum_{k=1}^{21} \left( \text{Abundance Multiplier}_k \times \min(\text{Nursery areas}^{t-1}, \text{Nursery areas}^t) \right)
\]

The nursery areas applied to compute \( \text{Aging in}^1_t \) is the smaller of the two periods: \( t \) or \( t-1 \). That is, expressed by the minimum function \( \min(\text{Nursery areas}^{t-1}, \text{Nursery areas}^t) \) in Eq. (6). The logic reflects an expert’s advice: it may take time for age 1 sole to move into a newly restored area on the one hand; when an area is destructed, age 1 sole disappears instantaneously on the other hand.

The \( \text{Catch Rate}^i_t \) from Eq. (5) is the number of individuals of soles that are caught. It is determined by sole stock in the internal of the Seine and changes in demand for soles in the internal area through adjusted fractional catch rate as follows:
\[ \text{Catch Rate}_i^t = \text{Adjusted Fractional Catch Rate}_i^t \times \text{Sole stock internal of the Seine}_i \]

\[ i \in (1,\ldots,10) \quad (7) \]

\[ \text{Adjusted Fractional Catch Rate}_i^t \text{ changes according to the total demand allowed as} \]

\[ \text{Adjusted Fractional Catch Rate}_i^t = \left( \frac{\text{Total demand allowed}^t}{\text{Total demand allowed}^{\text{ref}}} \right) \times \text{Reference fractional catch rate} \]

\[ (8) \]

\textit{Reference fractional catch rate} is the share of sole population caught by fishermen at each age category (percentages taken from ICES (2012)).

\[ \text{Total demand allowed}^t = \min(\text{Sole exports}^t + \text{Intermediate domestic consumptions}^t + \text{Final domestic demand}^t, \text{Catchable stock}^t) \]

\[ (9) \]

The \textit{Total demand allowed}^t of sole fish depends on whether the total demand exceeds catchable stock computed based on fishing quota. The \textit{Final domestic demand}^t for sole fish, \( \left( f_{i=s,\text{sole},k=1}^t \right)^{\text{tonnes}} \), is calculated in the I-O sub-model on Excel with an equation identical to Equation (2) in Cordier et al. (2014) but applied exclusively to sole commodities and expressed in tons. It also depends on foreign sole consumption (\textit{Sole exports}^t) and \textit{Intermediate domestic consumptions}^t of sole fish (i.e. all economic sectors that use fish as a raw material: restaurants, food and chemical industries, etc.), both expressed in tonnes. Where \textit{Intermediate domestic consumptions}^t of sole fish and \textit{Sole exports}^t are calculated as a constant share of the \textit{Catchable stock}^t (respectively 5.2\% and 6.7\% – calculated based on shares observed in the reference year).

The \textit{Catchable stock}^t is the amount of the sole population that is allowed to be caught in the sea. It is calculated as follows multiplying the variable \textit{Fishing quota} (=11.7\% of the sole population = value for the year 2011 and assumed to be constant in the current version of our model) by the total population in the fishing zone VIIId of the Eastern Channel (in Figure 1, this total population is calculated as follows: 'Weight of Common soles from the internal area' + 'Sole stock external of the Seine').
Fishing quota is a percentage of sole stock in the internal and external of the Seine.

In the end, to estimate the effect of changes caused to nursery areas (either through destruction or environmental restoration) on the economy, the amount of soles consumed by households must be expressed in monetary units and entered into the I-O sub-model on Excel to be summed to the other final demand categories in vector \( f^d_t \) from Equation (1). This is calculated as follows:\(^7\):

\[
\left( f^d_{\text{sole},k=1} \right)_{\text{Euros}} = \frac{\text{Price}}{1000} \times \left( f^d_{\text{sole},k=1} \right)_{\text{tons}}
\]

Where \( \left( f^d_{\text{sole},k=1} \right)_{\text{tons}} \) is calculated in the I-O sub-model on Excel with an equation identical to Equation (2) from Cordier et al. (2014) but applied exclusively to sole commodities and expressed in tons; \text{Price} \ is the price of 1 kg of soles in the region Haute-Normandie expressed in €/kg and calculated through the following regression equation:

\[
\text{Price}^t = e^{-4.488086793} \times (VA^{t-1})^{0.777322352} \times (Total\ Catch^t)^{-0.130727997}
\]

Where \( e = 2.718 \) \text{Total Catch}^t \ is expressed in kg per month and is calculated as the sum of Soles exports, Intermediate domestic consumptions of soles, and Final domestic demand for sole fish \( \left( f^d_{\text{sole},k=1} \right)_{\text{tons}} \). \( VA^{t-1} \) is the regional value added of Haute-Normandie in previous year expressed in million Euros at current prices (the results of the regression is converted after into constant prices of the year 2007). This regression is based on 261 observations of sole prices (Figure 7), sole catch and regional Value added in the region of Haute-Normandie measured between 1994 and 2011. The regression from Equation (12) is statistically significant: the P values are 3.4*10^{-16} for \text{Total Catch}^t, 5.0*10^{-35} for \( VA^{t-1} \) and 1.0*10^{-12} for the constant respectively. \( R^2 = 0.53 \) and \( R^2 \) adjusted = 0.52.

\(^7\) The result of Equation (11) 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 I-O table of the reference year 2007.
2.4 How the economic system (I-O) is embedded within the ecosystem modeling (SD)?

Powersim is able to synchronize a SD model with various datasets such as Excel. We use that property to connect the differential equation-based SD model built on Powersim with the matrix of our I-O table built on Excel. This allows us to model an ecological system on Powersim and an economic system on Excel. Both components, the economic and the ecological system, make up the global SD model. Those two components are tightly interconnected one to another as emphasized in Figure 1 with small bold arrows. The architecture of the ecosystem model is based on the System Dynamics (SD) principles while the one of the I-O model has been adapted to be able to interact with the SD model in an automatized way. That is, the I-O model provides the SD model economic outputs and receive feed-back inputs from the SD model, and all that on a year by year basis.

Figure 2 details each of these interconnections and show the part of the “Economic component (on Excel)” that is connected to the “Surrounding ecosystem model (on Powersim)”. The arrows that go out of the box representing the Surrounding ecosystem and enter into the box representing the Economic component are feedback loops. They allow the model to simulate the changes caused by the economic system on the ecosystem and the feedback impact of these changes on the economic system. Let’s illustrate one of the five feedback loops from Figure 2. The “Extension of economic activities on natural nurseries” is the primary causes of the economic-induced “Destruction rate” responsible for the decrease of nursery areas in the ecosystem. This modifies the “Sole stock internal of the Seine” estuary and changes the “Catchable stock” which is the part of the “Sole stock internal of the Seine” that can be caught according to “Fishing quota” policy. This has an effect on the amount of sole fish that can be “Caught in the internal area” since it is prohibited for fishermen to exceed the “Catchable stock”. Thereby, it limits the “Final domestic demand for sole fish” in the “Economic component” of the “Global system”. This is the first feedback impact. The second feedback impact results from the impact of the amount of sole fish “Caught in the internal area” on prices. According to the law of supply and demand, a decrease in the amount of sole fish “Caught in the internal area” induces a rise in the price of sole fish (verified and quantified by Equation (12)).

There is one important key to make possible the integration of the I-O sub-model to the surrounding ecosystem model that is based on SD equations. It is the dynamisation of four variables. Without that, the integration would not be possible given that SD modeling is inherently dynamic, that is, the results given by SD models in year $t$ are systematically calculated as a
function of the results in year $t-1$. As shown in Eq. 2 and 5 in Cordier et al. (2014), as well as in Eq. 6 and 12 from this paper, the variable that are endogenised in a dynamic way are the household consumption, companies’ investments, Sole stock internal to the Seine and the price of sole fish:

- Two dynamic vector of companies’ investments and household consumption: profits and incomes earned in year $t-1$ influence respectively investments (Eq. 5 in Cordier et al., 2014)) and household consumptions in year $t$ (Eq. 2 in Cordier et al., 2014).

- Sole stock internal to the Seine: a cohort structure (age 1 through age 10) is applied to capture the dynamics of the sole stock internal to the Seine. One thing worth mentioning is that age 1 population is determined by the nursery area rather than the total sole population (Eq. 6). Age 1 in year $t-1$ becomes age 2 in year $t$ after natural mortality and catch taken into account (Eq. 5).

- One scalar of the price of fish in year $t$: it is calculated by the model as a function of sole catch and regional income (regional value added) in year $t-1$ (Eq. 12).

The integration of I-O into SD modeling allows also to palliate the linear property of ecosystem variables modeled in the I-O version developed in Cordier et al. (2014, p.94). In their paper, the Figure 5a of the temporal evolution of the population of soles originating from the Seine estuary is purely linear.
Figure 2. Interconnections between the Economic component (on Excel) and the Surrounding ecosystem (on Powersim) within the global system (SD model). Note: the variables that are endogenised in a dynamic way are those connected to an incoming arrow with “\(t - 1\)” (Investments, Final consumption of all other services and products, Final domestic demand for sole fish, Sole Price and Sole stock internal of the Seine). It means that their value depends on the results given by the model in previous year.
3 Results

The I-O/SD model is run year by year, that is, the model gives a result at each time period \((t)\) of 1 year. The starting year, named the reference year \((t_0)\), is the average on the period 2002-2011 for ecosystem variables and the year 2007 for economic variables. The last period is 2020.

Two scenarios are simulated with the model over the period 2007-2020: a first scenario without restoration and a second one with restoration activities. In the second scenario, restoration activities start in 2007 and end in 2017. They consist in restoring a total of 23.7 km² in the following planning: 2.16 km² of nurseries with high density of juvenile sole fish (> 45 individuals/km²) are restored each year during 11 years. The choice of that level of restoration is based on stakeholder wishes: local stakeholders (scientists, fishermen, industry representatives, policy-makers, etc.) 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). And yet, our model suggests that the effect of the natural evolution of nursery areas (which follows a natural destruction path) together with restoration activities might result in a total area of nursery with high fish density of 127.9 km² in 2020 (Figure 4b). This is the level achieved in 1978. The cost of the restoration \((\Psi^t\) in equations from Section 2.2) amounts to M€2007 59.72 per year. It is calculated based on the unitary cost of restoration of intertidal nurseries\(^8\), which is M€2007 27.7 per km² restored\(^9\) (Port Autonome du Havre, 2000), and the annual average area restored in our restoration scenarios (2.16 km²/year).

Figure 3(a) shows that without restoration of nursery natural habitats, the size of the population of sole fish originating from the Seine estuary might decrease by 5.5% between 2007 and 2020. This is due to the current trend in the evolution of nursery areas in the Seine estuary (Figure 4(a)) estimated based on past data and expert consultations (see “Destruction rate” in Figure 1 and 2). Figure 3(b) suggests that the restoration of 2.16 km² per year between 2007 and 2017 would result in a growth by 10.1% of the size of the population of sole fish originating from the Seine estuary between 2007 and 2020. This is the net effect of the restoration policy and the natural- and human-induced destruction rate (Figure 4(b)) – the destruction trend keeps on in nursery areas that are not restored.

---

\(^8\) Intertidal nurseries are located in the littoral zone that is above water at low tide and under water at high tide.

\(^9\) M€2007 means Million Euros to be spent between 2007 and 2017 for restoration activities but expressed in prices of the year 2007 (like all prices in this paper).
**Figure 3.** Evolution 2007-2020 of the population of soles (in number of individuals) originating from the Seine estuary given by the I-O/SD model (a) without nursery restoration and (b) with restoration of 23.7 km² (2.16 km²/year of nursery restored between 2007 and 2017).

**Figure 4.** Evolution 2007-2020 of the total surface of nursery areas (in km²) with high density of juvenile sole fish (> 45 individuals/km²) in the Seine estuary (a) without nursery restoration and (b) with restoration of 23.7km² (2.16 km²/year of nursery restored between 2007 and 2017).
Regarding the catch of soles by fishermen, we would expect the model to show an increase compared to the situation without restoration since restoration of marine habitats allows the Seine estuary to shelter a greater population of sole. In fact, the increase of catch is probably postponed after 2020\(^{10}\), that is, after the restoration period is ended and household incomes (and thus household consumption) are no longer impacted by restoration costs. Meanwhile, Figure 5 shows that the catch is slightly reduced compared to the scenario without restoration. That can be explained by the slowing down of income evolution due to restoration costs. This is because we assume in the model that economic would agree to 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 reductions decrease the income of households (shareholders and employees), which explain that households reduce their purchase of fish products during the period of nursery restoration compared to a situation without restoration. As a result, fishing companies adapt progressively to this temporary change in consumer behavior and reduce the amount of sole they catch as in Figure 5 – a fishing company may adapt through reductions in the number of boats, of employees on board, of working time, etc.

The macro-economic impact on regional GDP of the Seine estuary is shown in Figure 6. GDP increases from the 2007 base value of 100.0 to 120.7 without restoration and 119.0 if restoration activities are carried out.

Figure 7 shows the validation of the I-O/SD model regarding its ability to estimate the price of sole fish.

\(^{10}\) This cannot be seen on the graph from Figure 5. We decided to stop simulation in 2020 because the reference year of the I-O model is 2007. It might not be robust to run simulation on a longer run.
Figure 5. Catch of soles in the Eastern channel (zone VIIId) by fishermen from the Seine estuary as estimated by the I-O/SD model. Note: the Eastern channel (zone VIIId) is both the internal part together with the external part of the Seine estuary (as named in Figures 1 and 2).

Figure 6. Gross Domestic Product of the Seine estuary (region Haute-Normandie) with and without restoration of nurseries as given by the I-O/SD model.
Figure 7. Price of sole fish per kilogram observed (in statistics from Agrimer, 2014) and calculated by the I-O/SD model (with the regression equation shown on the graph).

\[
Price^t = e^{-4.488086793 \times (VA^{t-1})^{0.777322352} \times (Total\ Catch)^{-0.130727997}}
\]

\[R^2 = 0.52\]
4 Discussion and conclusion

In this paper, we model an ecological-economics system based on two approaches: SD modeling based on Powersim for the ecological system and I-O modeling based on Microsoft Excel for the economic system. The reasons for coupling both approaches are threefold: first, the non-convexity of ecological systems is important to reflect in an ecological economic model and can be simulated with differential equations in the SD equations; second, an I-O table can capture detailed direct and indirect impacts of economic activities on pollutant emissions or natural resource depletions; third, in most developed countries, I-O tables are sufficiently well maintained such that our modeling approach could be transferred to other case studies.

Although there has been little academic research using an I-O/SD model, in businesses where practical solutions are required there are SD models which can be synchronized with other programs, including decision support programs and databases (e.g. Oracle, SAP, Excel, GIS, etc.). There may be both theoretical and technical reasons for the lack of development of our approach in academic literature. First, while a static I-O adopts constant technical coefficients and constant returns to scale using linear equations, SD emphasizes the nonlinearity of the dynamics using differential equations. Nonlinear relationships are fundamental in the dynamics of systems in the view of system dynamicists (e.g., Sterman, 2000). Second, while I-O is based on matrix architecture, SD is based on causal diagram architecture.

Despite these differences between I-O and SD and a need for a compromising attitude from both approaches, we believe that we can benefit from an I-O/SD model that can better capture the complexity of an ecological economic system. Another advantage of integrating I-O within a SD model is that in the latter, all causal links are shown explicitly. This reduces the possibility that important links would be forgotten in the description of the ecological economic system. Moreover, in the coupled model, I-O is freed from its dependency on “hard data” (Sterman, 2000) because the SD architecture and method opens the possibility for experts with proper knowledge and experience to estimate the parameters of mathematical relationships for which data do not exist yet. We did that for the estimation of destruction rate of nursery areas which is based on past observed data and expert consultations (top left of Figure 2).

One of the disadvantages of I-O equations is that it employs constant technical coefficients, and thus could be inaccurate if we wanted to simulate a time period longer than 10 years (or even 15 years, as in Wydra, 2011). Over a period of 10 years, productive relationships may change and economic structures may evolve substantially (Markaki et al., 2013, p. 269). To give an idea of this, the static version of the regional I-O model used in this paper gives error margins that range between -27% and +21% (depending on the
variable considered) over an 8 year period\textsuperscript{11}. In order to expand this period of
time to 20 years while keeping error percentages low, the regional I-O model
has been partially dynamised: companies’ investments are made dynamic and
final household demand also as well as the price of sole fish products. In order
to still further reduce that error percentage, technical coefficients should also
be dynamised. This would allow the time horizon of the simulation to be
expanded to a longer period (e.g. a 35 year period, as in Hamilton (1997)).

Although our model still needs some improvements, it brings insight
to the consideration of feedback loops in the modeling of interactions between
the economic system and the ecosystem. This is an original contribution given
that most papers in ecological-economics modeling omit feedback impacts on
the economic system generated by changes caused to ecosystems by this
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). Many papers do also consider feedback impacts
within the ecosystem, for example the feedback between phytoplankton and
upper Ocean Circulation (Nakamoto et al., 2007) or the feedback between the
Antarctic glaciation and the carbon cycle (Zachos and Kump, 2005).
However, only few papers take into account feedback between both, the
economic system and the ecosystem, for example the feedback impact
between agriculture and human genes (O’Brien and Laland, 2012) or bio-
economic feedback between ranch farming and the conditions of the
vegetation cover (Domptail and Nuppenau, 2010).

Acknowledgments

We would like to thank Olivier Le Pape, Benoit Archambault and Etienne
Rivot from Agrocampus Ouest (UMR ESE) as well as Thomas Poitelon from
Université de Versailles-Saint-Quentin-en-Yvelines (CEARC). This study has
been funded by the Sumitomo Foundation, the Asahi Glass Foundation, the
Yamada Fund for Scientific Research, and the Grants-in-Aid for Scientific
Research.

References

Conference proceedings of the System Dynamics Society.

\textsuperscript{11} Error margins are obtained after combining a sensitivity analysis (that takes into
account random errors) and retrovalidation (that takes into account systematic errors).


