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How to model social-ecological systems? – A case study on the effects of a future offshore wind farm on the local society and ecosystem, and whether social compensation matters

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ABSTRACT

Models of social-ecological systems (SES) are acknowledged as an important tool to understand human-nature relations. However, many SES models fail to integrate adequate information from both the human and ecological subsystems. With an example model of a future Offshore Wind Farm development and its effects on both the ecosystem and local human population, we illustrate a method facilitating a "balanced" SES model, in terms of including information from both subsystems. We use qualitative mathematical modeling, which allows to quickly analyze the structure and dynamics of a system without including quantitative data, and therefore to compare alternative system structures based on different understandings of how the system works. By including similar number of system variables in the two subsystems, we balanced the complexity between them. Our analyses show that this complexity is important in order to predict indirect and sometimes counterintuitive effects. We also highlight some conceptually important questions concerning social compensations during developmental projects in general, and wind farms in particular. Our results suggest that the more project holders get involved in various manner in the local socio-ecological system, the more society will benefit as a whole. Increased involvement through e.g. new projects or job-opportunities around the windfarm has the capacity to offset the negative effects of the windfarm on the local community. These benefits are enhanced when there is an overall acceptance and appropriation of the project. We suggest this method as a tool to support the decision-making process and to facilitate discussions between stakeholders, especially among local communities.

1. Introduction

As pressures of anthropogenic activities on natural systems increase, so does the need to understand human-nature relationships. Under the paradigm of system thinking, Social-Ecological System (SES) models have been suggested and used as a tool to acknowledge and understand these relationships [1,2]. Often, depending on the questions addressed and the discipline of the user, they have taken the view of a natural system embedded into society, or vice versa [2–4]. For example, when exploring the effect of fishing on marine systems, the social subsystem is commonly reduced to only fishermen (e.g. Ref. [5,6]. Or as when Tiller et al. Tiller et al. [7] explored how the projected effects of climate change reaches the consciousness of fishermen and their adaptive capacity, the ecological subsystem consisted of algal blooms, fish and jellyfish in a

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number that was more than double the amount of social variables. Consequently, these models tend to be depicted in detail for one of the subsystems, while the other subsystem is represented by only a few variables, which are supposedly representing the structure, the basis for the dynamics of the subsystem. Although this can be useful in many studies, not giving enough attention to both subsystems one can fail to incorporate some of the possible dynamics resulting from interactions and feedbacks within and between subsystems, which can have consequences on the emergent properties of the SES [8,9]. There exist different frameworks, languages, and theories between different disciplines, and linking these subsystems also requires collaborations between them and integration of different concepts, methods and modeling views [4,10]. In addition, models commonly used in SES modeling such as Bayesian belief networks [11,12], structural equation modeling [13], coupled physical-ecological and bio-economical models [14–16] are often limited by the type of data that are available or possible to collect. A possible method that may bridge some of these barriers is qualitative mathematical modeling [17]. Qualitative models are general causal models used to understand complex systems [18]. They are not based on quantitative data, and system parameters are therefore not necessary to measure. They allow incorporating variables and processes that are difficult to measure by relying on the general shape of functions and their relationships between variables. Hence, qualitative models sacrifice precision, but offer generality and realism in return [19].

Human developments, Offshore Wind Farms (OWF) included, are important examples of when social and ecological systems are both directly affected. Both positive and negative effects of OWF development on the ecosystem have been reported [20,21]. Despite the positive resonance of OWFs and the seeming general support by the public, OWF developments are often receiving resistance and opposition locally [22,23]. This is often because of fear for potential negative impacts on the environment and marine life [24,25], on the sea landscape [29], on various recreational and work activities of the local population [24,26], or on the emotional attachment that people have to the place [27]. The attitude among the local community and stakeholders, and conflicts with developers or managers, can influence the effectiveness of a project, which costs time and money [23,25,28,29].

Project developers use different acceptance strategies to overcome the various conflicts that arise with human developments, such as participation and consultation with local communities, compensatory measures, local taxation or communication, as shown by Oiry [30] in the French context of marine renewable energy. The concept of compensatory measures for a territory suffering the negative impacts of a public utility development, as we considered in this work, can be defined as a set of measures implemented to achieve a balance between the negative and the positive local impacts of a project. Despite a confusion in the literature about the content of compensatory measures [31–33] it is possible to distinguish two main types of measures, depending on the issues sought: ecological compensation and social compensation measures. The aim of ecological compensation is to take physical management measures that benefit the impaired local ecosystems so that no net ecological loss happens once a project is set up [34]. This kind of compensatory measures is commonly implemented on a regulatory basis, as is the case in France, where it was developed in 1976 with the law on the protection of nature (n°76–629) and was reinforced in 2010 by the "Grenelle II" law. Social compensation measures, also referred as community benefits, target more anthropological local issues, such as the impacts - actual as well as perceived - of a project on a local population, its health, its living environment as well as leisure or economic activities. Community benefits are often designed on a voluntary basis and can either be monetary (financial compensation, direct or indirect through taxation, individual or community based) or support measures (funding of community facilities, job creation, etc.). It is expected that both ecological and social compensation measures improve the overall acceptance of a local infrastructure, thus anchoring the latter within the surrounding community [31]. How stakeholders will react to compensation and if it will increase their acceptance towards the project depend however on the stakeholder's own interests and social settings [35,36].

To integrate abstract notions such as acceptance, human attitudes, and changes in perception into SES is a challenge, to which qualitative mathematical modeling has the capacity to address. It further allows for a rapid analysis of the structure and dynamics of a system [37], and therefore to compare alternative system structures based on different understandings of how the system works, for example based on different stakeholder's views of the system. The response of the system to one or several perturbations can be further analyzed through press perturbation analysis [38]. Hence, this method seems very well suited for exploring different management action options [39,40], and investigate the impact of multiple anthropogenic stressors [5] on a system. The effects of the wind farm on the ecosystem have previously been analyzed with qualitative modeling [5], in combination with cumulative anthropogenic disturbances. Here, we are building on this work by Raoux et al. [5], and have constructed a qualitative model of a SES reflecting hypothetical causal links between human and ecological actors (and functions). We have integrated values and attitudes towards land and resource use as we consider they would be affected by a planned construction of an OWF in Courseulles-sur-Mer, France (eastern English Channel, Bay of Seine), which we are using as a case study. The innovative aspect of this paper is to complement the discussion of the links between compensatory measures and the local acceptance of an OWF by using a SES framework and focusing on social compensation. We aim at testing the qualitative modeling method on a more balanced SES, in terms of number of system variables in both the ecosystem and social subsystems, which are allowed to interact directly and indirectly within and between subsystems. We also show how this method can be used to compare different system structures (representing different hypotheses about the system structure) in terms of system stability and their response to perturbations. Qualitative models have frequently been applied to study biological systems, sometimes including social components, but this is the first time, according to us, it is intentionally used to formulate a "balanced" SES. We do not intend to give absolute answers on how this specific SES works. However, by using this case study we are conceptually addressing some important questions concerning social compensation and its effect on local population's perception and acceptance, motivated by human developmental projects in general, and wind farms in particular. We are specifically addressing *i)* how press perturbations (human-induced impacts) will propagate and affect actors in the SES as a whole, *ii)* if the structure of the system (through the examination of different compensation strategies) has an importance in how the system will respond to press perturbations. *iii)* We are also exploring if the perception and acceptance of the local population is important in how the system responds to multiple perturbations.

2. Methods

First, we defined multiple model structures representing the system under different potential social compensation schemes by the wind farm enterprise and analyzed the theoretical stability of these possible network-structures. Secondly, we made predictions on how the variables in the network are likely to respond (directly or indirectly) to press perturbations, representing cumulative human-caused impacts. The perturbation analyses results are then presented as heat plots showing the estimated probability of a positive or negative change.

2.1. Study area

The eastern English Channel, where the Courseulles-sur-mer OWF will be built in the next years, is a shallow epi-continental sea located between France and UK. It covers about 35 000 km^2, and the water depth never exceeds 70 m in the trench running through the center of the Channel [3]. The eastern English Channel is also a heavily used area where many human activities take place such as transportation, fishing, dredge deposit, and sediment extraction, and is currently the hotspot of OWF development [41]. The planned OWF of Courseulles-sur-mer will cover an area of 50 km^2 and be located 10 km to the nearest shore. Because of its location, this will have an impact (either visual or on local activities because of restricted fishing inside and around the wind farm area) on a coastal area going from Saint Vaast la Hougue to Le Havre. The main activities by the local communities are fishing and shellfish aquaculture, tourism (notably the World War II Allied landing beaches), and naval industry. These economic activities represent more or less 10 000 direct employments [42].

2.2. Qualitative mathematical modeling and signed digraphs

A qualitative mathematical model is based on a qualitative representation of the relationships shared between system variables, which is represented as a signed directed graph (or signed digraph). Signed digraphs illustrate the positive or negative direct effects [0/+/−] between variables in a system (Fig. 1) and can also be represented in a matrix form as the community matrix (**A**). Graphically, a direct positive effect of for example a prey population on its predator population (births or growth through consumption of prey), or the trawl fishery on the fishery economical sector (jobs and money created through resource utilization), is depicted as a link ending with an arrow (→). A direct negative effect that for example a wind farm can have on the trawl fishery (reduced fishing activity), or a predator population has on its prey population (rate of mortality from predation), is represented by a link ending with a circle (−•). Links directly connecting a variable to itself are self-effects, which can for example represent density-dependent growth in a population (if negative), or self-enhancing growth (if positive). We used PowerPlay graphical editor (version 2.0 [43], to draw up our conceptual models and to derive the associated community matrix, where each element $\mathbf{A}_{ij}$ represents the sigh of the direct effect of variable j on variable i (composed of [0/+1/-1]). Examples and good practice guidelines on this process can be found in Puccia and Levins [44]. Once the structure of a system is defined, the feedback of the system can be analyzed to determine the qualitative conditions for stability and predicted response to perturbations (as explained in section 2.3. and 2.4., respectively).

2.2.1. Ecological subsystem

The ecological subsystem, from plankton to top predators, was taken directly from the qualitative model by Raoux et al. [5]. They considered several effects by the OWF. More precisely, the construction of turbines with their associated scour protection creates new habitats and shelters. This results in increased habitat heterogeneity and can lead to changes in abundance, biomass, and species richness and composition of benthos and fish [45,46]. Filter feeders such as mussels and amphipods tend to colonize and dominate the vertical structures of the turbines, benthic predators such as crabs commonly inhabit the base of the foundations and the scour protections [47,48], and fish including commercially fished species have been shown to aggregate around the foundations [49]. Known as the “reef effect”, it is considered as being the main environmental effect caused by the OWF construction [50] and can potentially affect the whole food web [51]. In addition, for navigation safety, fisheries are in some cases excluded or restricted within the wind

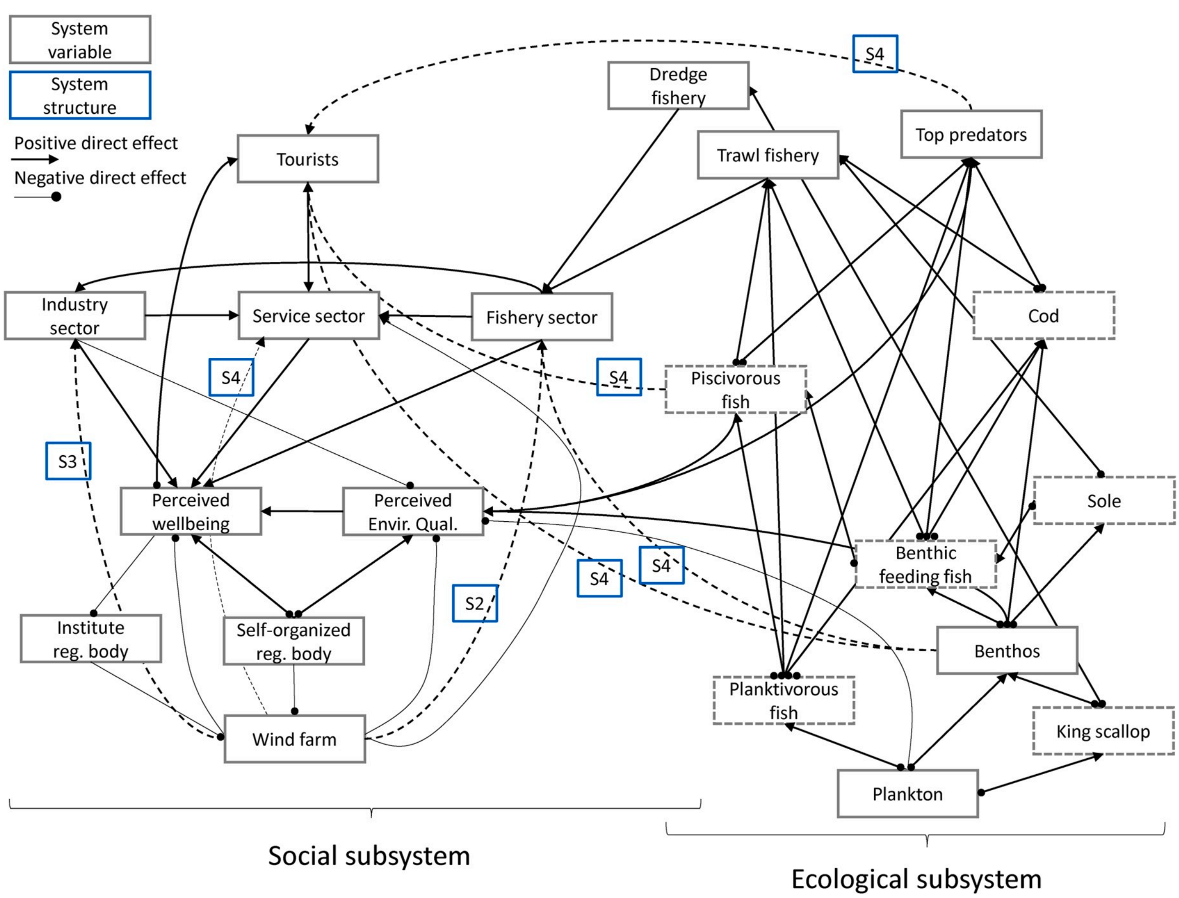

Fig. 1. Signed digraph of the social-ecological system in Courseulle-sur-Mer and the four different system structures (S1–S4). The base structure (S1) without compensation is shown with black solid arrows, and commercially fished species are indicated with boxes with dotted lines. The links added under the different compensation strategies (structure S2–S4) are shown with dotted arrows and the respective abbreviation S2–S4. All variables are assumed to have negative self-effects.

farm area. A possible exclusion of fishing activities inside the OWFs can act as a local marine protected area [52]. This "reserve effect" is likely to increase species abundances locally by reduced mortality rates of target species with potential spillover effects to adjacent area [52]. So far, empirical evidence of the reserve effect from existing OWF is limited, as it is difficult to separate this effect from the reef effect [51]. The possible direct effects by the reef and reserve effects were included as a press perturbation in this study, as explained in section 2.4.

2.2.2. Social subsystem

Based on literature information (scientific and grey literature), reports of public debates, and discussions with experts, associations and industrials, the social subsystem was defined focusing on what different compensation measures can do to the local population, and how social compensation affects the response of the SES to human-induced impacts (press perturbations). The social subsystem was structured around its economic, political and socio-cultural functions. In this framework, we consider that the "wind farm" (NB: quote marks denote variables names as given in Fig. 1 and explained in Table 1) operation may have impacts on the local population's social [53] and cultural capitals [54]. Hence, our goal was to assess how the OWF will affect what the local population values, and thereby their life quality (i.e., the local population's "perceived wellbeing"; [55]. The "perceived wellbeing" is directly impacted by the economic activities in the territory ("industry sector", "service sector" and "fishery sector"), the political dynamics ("Institutional" and "self-organized regulatory bodies" (SORB)), as well as by how they perceive the environmental quality ("perceived environmental quality"). The "perceived environmental quality", in turn, is directly impacted by activities and changes in the environment. For example, big industrial development, the wind farms included [56,57], is often associated with concerns about its impacts on the environment at large [58], either justified or not. Consequently, the direct negative effect of the "industry sector" and "wind farm" is on the "perceived environmental quality". Further, this part of the Normandy coastline, which is both a Natura 2000 zone and a potential UNESCO site of the WWII allied landing beaches [59], has an important patrimonial and recreational value to both the local and external ("tourist") population. Tourism is therefore important to the local economy through increased activity and job opportunities (positive effect by "tourist" on "service sector"), which indirectly increases the "perceived wellbeing". Meanwhile, high levels of tourism can affect the local population's socio-cultural values and decrease their quality of life [60]; therefore, the direct effect of "tourists" on "perceived wellbeing" was considered negative.

Table 1
Description of variables in the social-ecological model.

Nr	Variable name	Definition
Social Network		
1	Wind farm	(Eolien offshore du Calvados). The physical structure (e.g., as affecting the fisheries) and the enterprise running the wind farm (e.g., effected by the regulatory bodies).
2	Self-organized reg. body	Self-organized regulatory body (SORB). The activity of environmental and cultural associations and collectives, which are formed to lobby for the benefit of the local population.
3	Institute reg. body	Institute regulatory body (IRB). The activity of governmental or city institutions to take regulatory action for the wellbeing of the population.
4	Perceived wellbeing	The wellbeing of the local population as based on spiritual, cultural and economic values.
5	Perceived Envir. Qual.	Perceived environmental quality. How the local population perceive the environmental quality (different degrees of good or bad).
6	Fishery sector	The local fishery sector, in terms of job opportunities and work activity.
7	Industry sector	The local industry sector, in terms of job opportunities and work activity.
8	Service sector	The local service sector including tourism, in terms of job opportunities and work activity.
9	Tourists	Tourists, in terms of number of tourists.
10	Dredge fishery	The local dredge fishery in terms of job opportunities and activity.
11	Trawl fishery	The local trawl fishery in terms of job opportunities and activity.
Ecological Network		
12	Plankton	Phyto- and zooplankton
13	Planktivorous fish	Planktivorous fish
14	Piscivorous fish	Piscivorous fish
15	Top predators	Four marine mammals, two seabird, two cephalopod groups
16	King Scallop	King Scallop
17	Benthos	Hard and soft bottom species of epibenthos and benthos
18	Benthic feeding fish	Benthic feeding fish
19	Sole	Sole
20	Cod	Cod
External Driving Nodes (press perturbations)		
21	Fishing restrictions	Consequences of safety measures around the offshore wind farm on the social system.
22	Reef effect	Reef effect due to offshore wind farm construction.
23	Reserve effect	Consequences of the safety measures around the offshore wind farm on the ecosystem.
24	Climate warming	Global change, here considered as increased sea temperature.
25	Switch in perception	Acceptance by local population of the wind farm development.

The offshore "wind farm" is expected to impact the social system through: i) concerns about the negative impacts of the wind farm structure on the environment ("perceived environmental quality") [24,25], and ii) a reduced "perceived wellbeing" (spiritual and cultural) due to the eyesore in the sea created by the wind farm structure [33,61]. The wind farm is also expected to negatively affect the social subsystem through fishing restrictions in the wind farm area [62]. However, this aspect was not included in the base structure but as a perturbation scenario (section 2.4). Furthermore, the local population influences the activity of the wind farm through "institute regulatory bodies" (IRB, governmental institutes) and "self-organized regulatory bodies" (associations or NGOs) that are acting in the interest of the local population's wellbeing, or for different environmental or cultural interest [30]. This regulatory mechanism in the model works in two steps. Consider for example a reduced "perceived environmental quality" due to the concern of the wind farms impact on the environment. Conceptually, this would translate to an increased willingness by associations ("self--organized regulatory bodies") to put legal pressure on the "wind farm" enterprise due to the environmental concerns, meaning it will cost the wind farm enterprise time and money to take actions to address the environmental concern. Practically, in the model this situation is equivalent to a decrease in the "perceived environmental quality" variable, which also reduces the direct negative effect on the "self--organized regulatory bodies" by the "perceived environmental quality", resulting in an increase in the variable "self-organized regulatory bodies". In the next step, because of the increase in the variable "self--organized regulatory bodies" and the direct negative effect on the "wind farm" enterprise, the overall result is a reduction in "wind farm" activity. This decrease in the "wind farm" is in turn weakening the negative direct effect on the "perceived environmental quality" variable, and the regulatory cycle between the local population and the wind farm enterprise is completed (Fig. 1, Table A1).

2.2.3. Alternative system structure and compensation strategies

We constructed four alternative views of the SES in form of different structures (S1–S4) to depict the effects of three different sets of social compensation measures. The links, all positive, for each structure were added cumulatively, and the structure therefore depicts different levels of connectance within the system. The different system structures of the SES were (Fig. 1, Table A1):

Structure 1 (S1): without any compensation.

Structure 2 (S2): with monetary compensation, which is money paid to compensate for loss of activity. We considered compensation to the fishery sector only, which was represented by a link from the "wind farm" to the "fishery sector".

Structure 3 (S3): with hiring of local enterprises (we consider to the industry sector only) for service and maintenance work of the wind farm, opposed to hiring external enterprises. This was represented by a link between "wind farm" and "industry sector".

Structure 4 (S4): with investments in local projects to benefit from ecosystem services. We considered these investments firstly as a direct link between the "wind farm" enterprise and the "service sector", allowing enterprises to develop new business around ecosystem services. Secondly, this direct link was added in combination with links from different variables in the ecosystem to the "tourists" or "fishery sector". More specifically, the expected increase of epibenthos and benthos communities (*i.e.*, mussels, amphipods, and crabs) around the wind farm foundations are attractive for divers or for new fisheries, and development of diving companies (link between "benthos" and "tourists") or new fisheries (link between "benthos" and "fishery sector") may be profitable. Similarly, top predator sightseeing or recreational offshore fishing (links between "top predators" or "piscivorous fish" to "tourists") are other potential tourist developments.

2.2.4. *Linking the subsystems*

We considered two major types of links between the ecological and social subsystems. Firstly, fishery activities, in form of "trawl" and "dredge fishing", have direct negative effects on the respective fished species in the ecological system. Secondly, nature's contributions to people (ecosystem services) are the benefits humans obtain from the ecosystem [63–66]. Since they reflect direct social-ecological interactions, they are suitable links from the ecological to the social system and have previously been suggested to connect social and ecological networks [67,68]. We considered some possible ecosystem services by their direct positive or negative impact on the "perceived environmental quality" (nr. 32–35 Table A1 e.g., spotting marine mammals may increase the perception of a good environmental quality while a more turbid water due to increased plankton may give an impression of less good environmental quality), which in turn impacts the "perceived wellbeing" of the local population (Fig. 1). Lastly, impacts caused by human activities were only included as press (constant) perturbations to the system (see section 2.4. below). Because of the typical nature of human impacts on the ecosystem, press or pulse perturbation have been suggested as suitable linkages from a SES [67].

2.3. *Qualitative stability analyses*

If a qualitative mathematical model is to be a viable representation of a real and existing system, it is important to determine its scope for stability, such that model variables can persist despite a disturbance, and whether it can exhibit familiar or predictable behavior. Assessing model stability is based on the analysis of feedback cycles in the system and is examined through two Routh-Hurwitz criteria [69]. The first criterion considers the balance between positive and negative feedback cycles and requires that the system is dominated by negative feedback cycles at all levels of the system. This can be determined by the maximum weighted feedback (*wFn*), which is a measure of the net to the total amount of feedback at the highest level of the system. When tending towards −1, it indicates that a system is likely to converge towards its previous equilibrium state following a perturbation. If close to +1 it indicates that the system is likely to diverge from its equilibrium after a perturbation. When close to zero, the system is near a state of neutral stability and has a nearly equal chance of being stable or unstable. The second criterion is based on the balance between short and long feedback cycles and requires that long feedback cycles at higher levels in a system do not overwhelm shorter feedback cycles at lower levels. Here the shortest cycles are comprised of a variable's self-effect and the longest are those that with a cyclical path that includes only once all variables of the system. The sign of a Hurwitz determinant (wDn) determine criterion II, which should be positive in sign if a model is stable. Model structures can be categorized *a priori* according to their vulnerability to failing criterion I (giving class I models) or criterion II (giving class II models). When class I models are unstable it is due to excessive positive feedback at the highest level of the system (i.e., for longest-length feedback cycles), which typically causes runaway growth or decay in a particular variable or subsystem of variables, preventing the system's return to a former state of equilibrium. Class II models become unstable when there is excessive feedback at higher levels in the system (or insufficient lower-level feedback), which causes the system to oscillate uncontrollably. Further theoretical background and details about these stability metrics can be found in Dambacher et al. [69]. In order to calculate the scope for stability for our four alternative model structures (S1–S4, Fig. 1), we used a program developed by Dambacher et al. [37] (esapubs.org/archive/ecol/E083/022) for qualitative analyses of the community matrix and calculations of the stability matrices (*wFn*, *wDn*). The analyses were done in Maple version 2017.3 [70], as based on the community matrices made in the graphical editor program PowerPlay.

2.4. *Press perturbation analyses*

Perturbation analyses predict the likely change of direction that population variables will take in response to a perturbation. A press (sustained) perturbation is caused by a permanent change to one or more system parameters resulting in a shift in the equilibrium level of system variables. This analysis is based on the sign of pathways of interactions as going from input variable to response variable and can be analyzed qualitatively through the inverse of the community matrix [37]. When all effects (all pathways of interactions) are of the same sign, there will be a complete sign determinacy in the response prediction. When there are both positive and negative effects, however, the predicted response is ambiguous. The relative balance of positive vs. negative effects in a response prediction can be used in numerical simulations to assign a probability for sign determinacy. We used this approach and the program developed by Dambacher et al. [37](esapubs.org/archive/ecol/E083/022) in Maple to analyze the sign response and the associated level of probability of sign determinacy for 10 different press perturbation scenarios. The individual perturbations are from Raoux et al. [5]. The different scenarios had five main perturbations (Fig. 2):

Fishing restrictions (Perturbation 1, P1): The consequences of safety measures around the OWF on the social system, in terms of reduced fishing opportunities for the "trawl" and "dredge fishery".

Reef effect (P2): Representing the consequence of the OWF on the ecosystem through the "reef effect", *i.e.* the hard substrate of the wind farm is expected to increase habitats and shelters for benthic ("benthos") organisms thus supporting their growth in terms of both abundance and biomass.

Reserve effect (P3): The consequences of safety measures around the OWF on the ecosystem, causing a decrease in fishing pressure (and a potential increase in abundance) on the main commercial species, *i.e.* planktivorous fish ("PLF"), benthic feeding fish ("BFF"), piscivorous fish ("PIF"), Sole ("SOL"), and "Cod".

Climate warming (P4): The consequences of global change, and warming in particular, on ecosystems in terms of changed species distribution (and a reduction) of King scallop, Sole, and Atlantic cod due to warming [5].

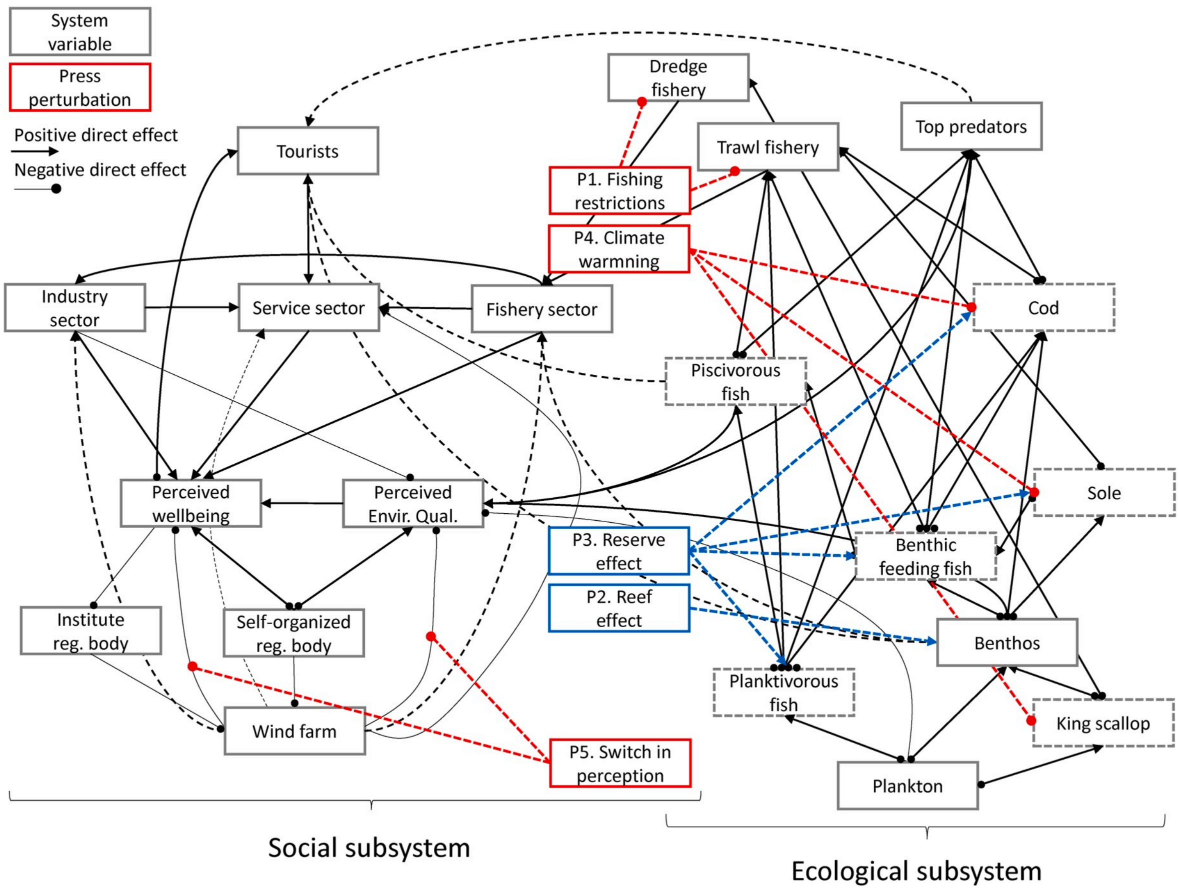

Fig. 2. Signed digraph of the social-ecological system in Courseulle-sur-Mer and the five press perturbation scenarios (P1–P5). The changes represented by each press perturbation scenario are shown as an additional variable box with positive (blue) or negative (red) link/s to a certain variable/s in the system. The links show the effect posed by the perturbation. All variables except the press perturbations are assumed to have negative self-effects. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Switch in perception (P5): The potential consequence of a change in perception of the local population towards the wind farm enterprise, making the local population regard the wind farm's activities as positive. Stakeholders acceptance towards a project depends on many factors and is of course unique to each individual [71]. Here we are not defining what would cause a switch in perception by the local population, but rather how each press perturbation scenario would be influenced by a change in perception towards acceptance.

Perturbation P1–P4 were taken from Raoux et al. [5]. Raoux and co-authors discussed in detail how the different cumulative impacts affected the food-web. Here we use these perturbations mainly to illustrate how the social system may respond to positive (P2, P3) vs. negative (P1, P4) perturbations, either on a few (P1, P2) or several (P3, P4) impact-variables, which are located at different ecosystem levels.

3. Results

3.1. Stability analyses

The alternative model structures (S1–S4) were all classified as class I models, with a low to moderate scope for stability as indicated by the low maximum weighted feedback (*wFn* in Table 2, [69]).

3.2. Press perturbation

The variables in the social subsystem were predicted to respond overall negatively with high probability to the different press perturbation scenarios (as much as 89% of variables in social subsystem with negative sign, if not considering "IRB" and "SORB" because of their regulatory behavior) (Fig. 3A–E, Fig. 4B and C, Table A2). However, with increasing means of compensation (S3 and S4) the predicted responses in the social subsystem was more positive (Fig. 4B). More specifically, the social subsystem responded more positively to press perturbations leading to increases to variables in the ecological subsystem (reef and reserve effect, P2 and P3 respectively, Fig. 3). These positive effects where further enhanced when there was an acceptance of the wind farm (P5, and scenario P1P2P3P5 in particular). When press perturbations were entered as negative links (e.g., fishery restriction P1 and climate warming P4), the social subsystem was predicted to respond

Table 2
Summary results of sign stability analyses for the five model structures (S1–S4). Maximum *wFn* is the maximum feedback in the system, and *wDn* is the weighted determinant. Network structures are presented in Fig. 1 and table A1 and A2.

Model structure	Details of model structure	Classification of model	*Maximum wFn*	*wDn*
S1	With wind farm	Class I	−0.019	$6.3 * 10^{-36}$
S2	Compensation: Monetary	Class I	−0.0061	$1.2 * 10^{-36}$
S3	Compensation: Engagement of local enterprises	Class I	−0.0027	$3.9 * 10^{-37}$
S4	Compensation: Investment in local enterprises	Class I	−0.0014	$1.3*10^{-37}$

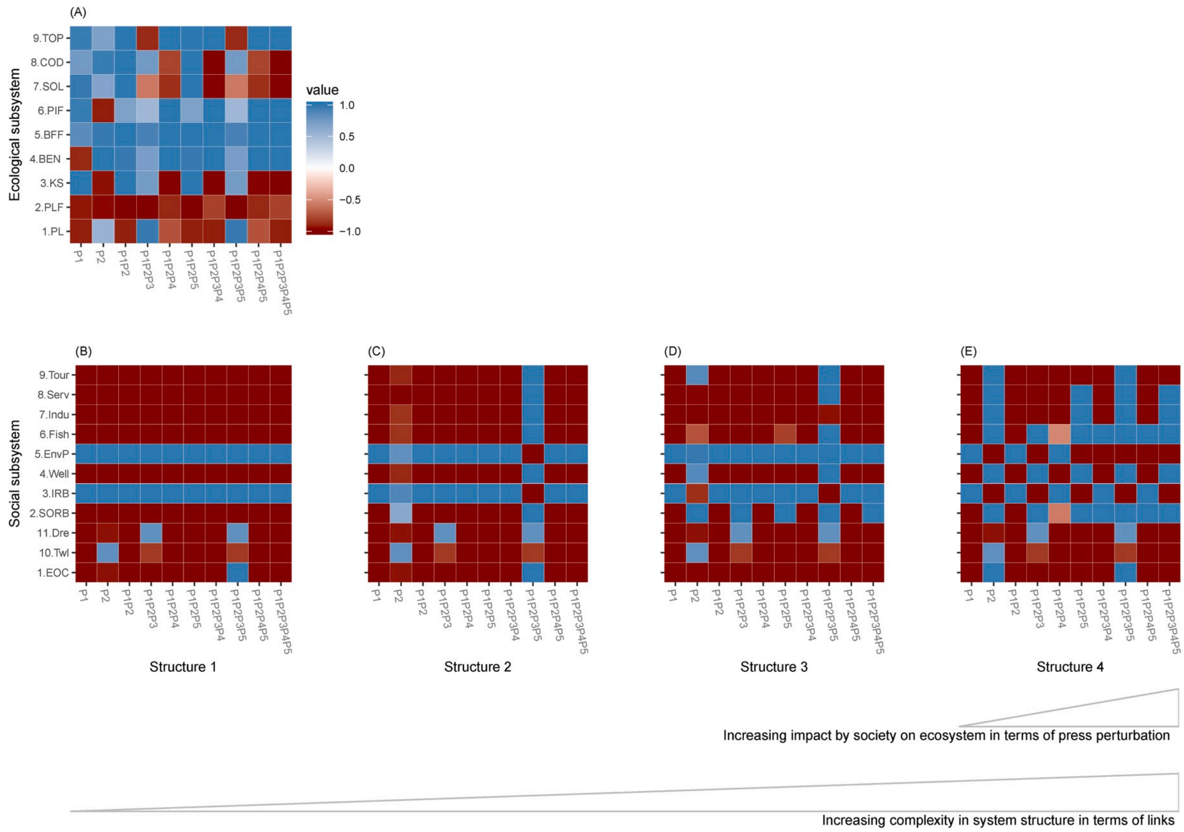

Fig. 3. "Heatplot" showing the estimated probability of a positive (blue color) or negative (red color) change of the (A) ecological and the (B–E) social variables as a response to different press perturbation scenarios (P1–P4). (B) Structure 1 depicting the social-ecological system without any compensation, (C) structure 2 including a monetary compensation to the "fishery sector", (D) structure 3 including compensation in form of employment of the "industry sector", and (E) structure 4 including compensation in form of investments into development of new enterprises for the "service sector" to take advantage of ecosystem services. Probabilities of no changes (zero) were not found in the analyses. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

more negatively.

The predicted response to the press perturbation scenarios of the variables in the ecological subsystem were identical for the five network structures (SI–S4), since all effects by society on the ecosystem were analyzed as press perturbations. The variables in the ecological subsystem generally responded positively to the different press perturbations (Figs. 3A and 4A). on the contrary to the social subsystem, but as expected, the ecological subsystem responded positively to a fishery restriction (P1). The biggest positive response by the ecological subsystem was under combined fishery restriction and reef effect (P1P2). Another interesting property of the subsystem is that any of the climate warming scenarios (P4) had a negative impact, each of them leading to the lowest possible proportion of variables with a positive change (Fig. 4A).

For some scenarios, unexpected changes were predicted in the SES. Under the reserve effect scenario (P3, in for example scenario P1P2P3P5) that methodologically was realized through a positive input to "planktivorous fish" (PLF), "benthic feeding fish" (BFF), "piscivorous fish" (PIF), "Cod" and "Sole", some of these positively impacted variables (PLF and "sole") still responded negatively (Fig. 3E). Here the positive input was outweighed by a predicted increase in their predators (PIF, Cod and BEN; Figs. 3E and 2). These effects also propagated to the "top predators" (which were predicted to decrease) and to "plankton" (which were predicted to increase), and also into the social subsystem causing a predicted decline in "perceived environmental quality". Further detailed responses for each specific variable and for each network structure and compensation scenario can be found in Fig. 3 and Table A2.

4. Discussion

4.1. Why a balanced social-ecological system view?

Qualitative modeling enables users to ask general but realistic questions about networks of interacting variables [19], thus allowing to test different hypotheses concerning system's functioning. These alternative views can illustrate different hypothetical compensation strategies, which are reflected by various model structures. Or, they can represent alternative views or hypotheses about how the system functions based on different stakeholders' or researchers' knowledge and views [5,40]. The objective with our work was not to give absolute answers about what will happen around the Courseulles-sur-Mer's wind farm development if some specific kinds of compensation are utilized or not. Rather, our main aim was to illustrate one tool that can be used to build up and analyze the SES by exploring its potential dynamics in our model system, and giving examples of the type of questions that can be addressed using this tool. Human decisions and actions inevitably affect the SES and will lead to changes in the system that can be hard to predict. The press perturbation analyses allow exploring these types of changes, one by one, or their cumulative effect. The results (in terms of the probability in direction of change of a variable) suggest what is likely to happen to the different variables given different strategies and scenarios. For example, in our model system the fishery restriction had an overall negative effect on the society. This negative effect had an important top-down control on the social subsystem, as it persisted under many of the other human induced changes (perturbations) even if they were positive. Only under multiple compensations (i.e., strong

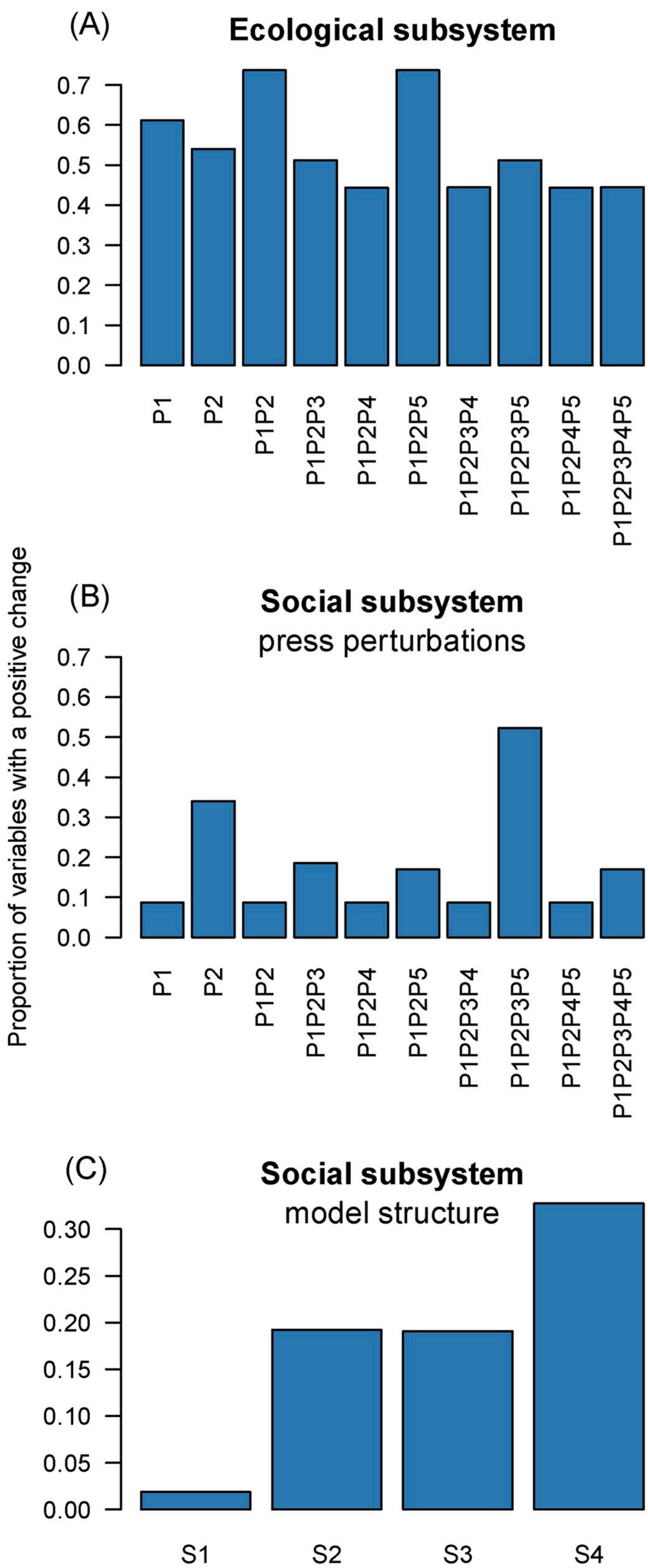

Fig. 4. The proportion of variables in the social and ecological subsystems showing a positive response in relation to the (A and B) press perturbation scenarios, and (C) model structure, which represents different compensation by the wind farm enterprise. The "Institute Regulatory Body" and "Self Organized Regulatory Body" were not included in the calculation because of their regulatory behavior and a positive response in these variables does not represent a positive change to the society (see section 2.2.2 for a description of their regulatory behavior).

connection to the ecosystem) was this top-down control overtaken (Fig. 3). Hence, this is not a conclusion in absolute terms; the point of interest is that added complexity (and increased connectedness) to a system can alter the final output. Thus, this illustrates a tool that can be useful in discussions with managers, politicians or the public [5,17,40].

One of our main objectives was to construct and analyze a balanced SES in terms of the information integrated in the social and ecological subsystems (i.e., system variables). However, this does not necessarily mean that the two subsystems will equally affect the dynamics of the system, or that the variables of the two subsystems will be affected in comparable ways by press perturbations. This will depend in a large degree on the topology within the subsystems, and the interaction (links) between the two subsystems. The importance of a balanced SES view that we want to highlight here is the potential effects of letting complexity in both subsystems (which comes through the direct and indirect interactions between system variables) to contribute to the dynamics of the system.

In the following text we are focusing the discussion around the social subsystem and how it is affected by the ecological subsystem, and less on the ecological subsystem alone since it has been discussed in detail previously [5]. With our example we also wanted to show the importance of including a certain degree of complexity in both subsystems in order to catch the dynamics between variables, and indirect and sometimes unexpected effects. In our example, increased complexity (in terms of links, i.e. connectance) within and between subsystems affected how the social subsystem was predicted to respond to different press perturbation scenarios (Fig. 3). In addition, unexpected indirect changes were observed only when depicting a more complex structure under multiple perturbation scenarios (as in the positive effect on the "dredge fishery" in some perturbation scenarios despite being reduced due to fishery restrictions P1P2P3 and P1P2P3P5; or in the reserve effect P1P2P3P5, which intuitively would increase the "perceived environmental quality"). Still, some of the impacted fish species (PLF and "Sole") were predicted to respond negatively, as they reacted to an increase in their predators' that had benefited from an increase in other prey (Figs. 2 and 3E). These effects propagated to the "top predators" (which were predicted to decrease) and "plankton" (which were predicted to increase) and further into the social subsystem thus causing the predicted negative effect on the "perceived environmental quality". Including interactions between multiple variables in both subsystems allowed these indirect effects to emerge. Emergent properties of a system are by definition not possible to predict without considering the system as a whole [72] and is one of the main reasons for considering a greater degree of complexity [73]. The key to ecosystem-based management for example is to consider how nature is affected by human decisions and actions, and how humans respond to changes in the ecosystem [74]. Consideration of a more developed SES is a core requirement of holistic and effective management [2,75].

Another asset of the method used here is that the user can integrate variables and processes that would possess different data types in a quantitative model (e.g., energy flows in ecosystems, money in an economical system). This is often one of the challenges when fusing a SES [76]. Because tedious data collections are not needed, a model and a general understanding of a system can be built up relatively quickly [77]. Instead, the important process in the analysis consists in building and understanding the structure of the system, which can be reached through data, expert knowledge, interviews, workshops, and discussions. Further, alternative models can be analyzed in order to test uncertainty about the system structure, using qualitative modeling. An additional step would be to couple it to a Bayesian belief networks, a useful tool when exploring different scenarios. Moreover, the consistency between the same SES based on different methods can be formally tested using the Bayesian belief network [5,38]. However, qualitative modeling has also drawbacks. Firstly, by not being quantitative. Our predictions for system response to a perturbation is only directional (i.e., increase or decrease), but society will also want to know how much their world will change. Furthermore, qualitative models also lack precise detail of their time and space dimensions. Clearly, the processes within and between the social and ecological subsystems are taking place at different geographical and temporal time scales, and how a press perturbation is propagating within the system will depend on these relative differences. In our work we considered a geographical limited area (defined in section 2.1) while the temporal scale is intrinsically set by the processes and factors affecting the growth and decay of the system's components and variables. By generalizing over time and space, however, it is possible to get an overall time integrated view of the dynamic of a system.

4.2. Does social compensation matter?

Our results show that the way social compensation strategies are implemented (monetary, involvement of local enterprises, investment in projects linked to ecosystem services) has an important influence on how the system is likely to respond to various external pressures (press perturbations). We show that the more the wind farm developer creates links with the local population (in terms of social compensation), the more likely are the different actors in the social subsystem to respond positively (Fig. 4B). However, we also revealed differences in the likelihood of positive responses: the marginal effect of S2, compared to S1, seems modest whereas the marginal impact of S3 is null and the marginal effect of S4 is high (Fig. 4B). Our basic system structure assumes a negative perception of the OWF development (*i.e.*, negative link from wind farm to perceived wellbeing and perceived environmental quality). We also assume that the compensations have a direct positive impact in terms of increased incomes. (Table A2), but without directly affecting the perception and acceptance of the wind farm. Research indicates that there is generally a positive view of renewable energy as such [78,79], although when being directly affected by an OWF project people tend to be more skeptical [61]. There are clear divisions in how people perceive an OWF [79], as well as there are divisions in how they respond to compensation [32].

Previous research show that compensation's influence on the acceptance of a project seems to depend on for example the type of compensation, the size of the compensation, perceived risks of the development, previous experiences of similar developmental projects, and whether it is a community vs. individual compensation, among others [36,79–82]. For example, monetary compensation is often associated with a "bribe effect", which refers to the stakeholders feeling bought out of a problem and has shown inefficient to increase the acceptance of a project [80,83,84]. Rather, investments in local projects benefiting the common good [80], environmental conservation or restoration projects [36] seem to be more valued and have a more positive influence on the local community. Because of the complex nature of compensation and perception, we included a switch in perception towards acceptance as a press perturbation (a constant change) analyzed for all system structures. This implies that we are not specifically defining when or why the society shows acceptance towards the wind farm, rather how an acceptance towards the wind farm may affect the system in combination with different compensation strategies. The results showed, as expected, that an acceptance towards the wind farm tended to enhance any positive effect on society (reef or reserve effect scenarios). Acceptance combined with comprehensive social compensation were clearly predicting the more important positive effect on society. The results also showed that the climate-warming scenario reduces significantly, if not completely, the influence of social compensation on the overall resilience of the system. This situation is interesting and rather counterintuitive, suggesting that the social acceptance towards OWF is likely to decrease over time, as the climate becomes warmer. Such a reasoning urges developers and local communities to implement rapidly renewable energy facilities if they want to benefit from the potential advantages of social compensation. This point is undoubtedly linked to the SES specification used in this paper, but it is worth considering in future research as it plays as an additional argument towards a prompt need to fight collectively against global warming.

Social acceptance is a term that is widely used by stakeholders in the practical policy literature when it comes to development project [85], although it is suffering from unclear definitions [86,87]. However, behind the compensation tool used by industrials and decision-makers to overcome conflicts and increase acceptance [31], which is often presented as a way to include population in the development process, is hidden the fact that the result of the negotiation is already set [30]. In a SES approach, we suggest considering the process of compensation not as a strategic tool to gain the acceptance of population, as it would be considered in political science for instance, but as a tool to enhance the resilience of the overall system for which it is possible to forecast the perturbation (an industrial project). In this respect, the different types of compensation measures could be evaluated by their capacity to lead the system back to a stable stage after the inclusion of the wind farm. For the developmental project to be included, it will need to create bonds with other parts of the system. This is what would be considered as appropriation, when new use of the object is created beyond its original destination [88]. Clearly, in our basic model structures (S1, S2) where the restricted fishing had a strong top-down effect on the rest of society, the predicated response by society was mainly negative (Fig. 3B and C). The more the wind farm integrated into the system (S3, S4), however, the more positive responded the society. There are several examples of appropriation of wind farm projects that have been experimented, especially in Northern Europe [89] where local population become stakeholder of the energy plant, thus benefiting from the profit of the development. This suggests that the systemic approach taken here allows exploring a much wider diversity of options in the field of compensation.

5. Conclusions

Our modeled SES is an illustrative example on the importance of modeling a more-or-less balanced SES including similar complexity in both subsystems in order to catch indirect and unexpected changes in the SES. Our case study on social compensation by a wind farm enterprise indicated that investment into the wellbeing of the local population by developers is important for increasing the positive effects and therefore the benefits of the society as a whole. It predicted that the acceptance of the developmental project further enhances these benefits. However, there is currently lack of knowledge on how local populations perceive OWF projects and how they respond to compensation, particularly on French territory. Therefore, in order not only to give hypothetical answers on how society could respond to a wind farm project, this knowledge gap needs to be covered, suggestively by anthropological field studies. As a final remark, we believe that while it is the role of environmental and ecological scientists to inform the public about potential positive and negative effects of OWFs and renewable energy in general, it is in the hands of social scientists to inform managers and policymakers, and to argue to developers and industry, the social and economic benefits to their project of a full participation in local communities.

Declaration of competing interest

We declare we have no competing interests.

CRediT authorship contribution statement

Matilda Haraldsson: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing - original draft. **Aurore Raoux:** Conceptualization, Methodology, Writing - review & editing. **Fabien Riera:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Julien Hay:** Conceptualization, Validation, Writing - review & editing. **Jeffrey M. Dambacher:** Conceptualization, Methodology, Software, Formal analysis, Validation, Formal analysis, Writing - review & editing. **Nathalie Niquil:** Conceptualization, Methodology, Funding acquisition, Writing - review & editing.

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Appendix

Table A1
Description of links between variables in the social-ecological model. The ecological subsystem is taken from Raoux et al. [5], which is an aggregated ecosystem derived from an ecopath model [41]. See their work for details about the variables and links in the ecological subsystem.

Nr	From	To	Sign	Definition
Social Network				
1	Wind farm	Perceived wellbeing	–	The "eyesore" in the sea landscape caused by the wind farm structure reduce the spiritual value of the sea landscape and the perceived wellbeing.
2	Wind farm	Perceived environmental quality	–	Concerns about potential negative impacts on the environment by the wind farm activities and structure.
3	Self-organized regulatory body	Perceived wellbeing	+	Activities by associations and collectives, in form of lobbying for the sake of the local populations interests, increase the wellbeing of the local population.
4	Self-organized regulatory body	Perceived environmental quality	+	Activities by associations and collectives, in form of lobbying for the sake of the environmental conservation, increase the perceived environmental quality. This can sometimes be by associations informing and creating awareness of what value the nature has to offer.
5	Self-organized regulatory body	Wind farm	–	Associations and collectives put pressure on the wind farm enterprise through e.g. opposition of the project and legal procedures, which inhibit their efficiency and cost the enterprise time and money.
6	Perceived wellbeing	Tourists	+	The attraction of a place to tourists is partly linked to the perceived wellbeing of the local population. A local community with strong wellbeing (good ambience, economically stable, beautiful scenery etc.) attracts tourists, or vice versa.
7	Perceived wellbeing	Self-organized regulatory body	–	The stronger the perceived wellbeing, the less pressure by the local population on associations and collectives to lobby for the local community's interests (negative feedback link).
8	Perceived wellbeing	Institute regulatory body	–	The stronger wellbeing will decrease the objective of the institutes to take action (negative feedback link).
9	Perceived environmental quality	Perceived wellbeing	+	The perceived wellbeing is affected by the perceived environmental quality.
10	Perceived environmental quality	Self-organized regulatory body	–	A good perceived environmental quality, the less pressure from the local population on associations and collectives to lobby for the conservation of the environment (negative feedback link).
11	Fishery sector	Perceived wellbeing	+	Activities and jobs in the local fishery sector is connected to the local economy, which affects the perceived wellbeing.
12	Fishery sector	Industry sector	+	Activities in the local fishery sector creates jobs and incomes for local industries (fish food processing, entertainment of boats and gear, etc.).
13	Fishery sector	Service sector	+	Activities in the local fishery sector creates jobs and incomes for local service sector (fish market, food and restaurant branches etc.).
14	Industry sector	Perceived wellbeing	+	Activities and jobs in the local industry sector is connected to the local economy, which affects the perceived wellbeing.
15	Industry sector	Service sector	+	Activities in the local industry sector creates jobs and incomes for local service sector (food and restaurant branches, lodging etc.).
16	Industry sector	Perceived environmental quality	–	Too much industrial development is associated with a decreased environmental quality. Both by the occupied space the industries take, and potentially because of their activities.
17	Service sector	Perceived wellbeing	+	Activities and jobs in the local service sector is connected to the local economy, which affects the perceived wellbeing.
18	Institute regulatory body	Wind farm	–	Institutions have a regulatory impact on the activity of the wind farm, which depends on the status of the local population's wellbeing.
19	Tourists	Service sector	+	Tourists increase the jobs and income in the service sector.
20	Tourists	Perceived wellbeing	–	Too many tourists have negative effect on the local populations wellbeing (feeling of crowdedness, less peaceful etc.).
Links associated to compensations				
21	Wind farm	Fishery sector	+	Monetary compensation to the fisheries to compensate for losses.
22	Wind farm	Industry sector	+	'Indirect' compensation by involving and hiring local industries for work around the wind farm, opposed to hiring external companies. This may also involve training of local industries so they can handle the techniques specific to the wind farm.
23	Wind farm	Service sector	+	'Indirect' compensation by investments in local enterprises to startup companies, which in turn can take advantage of potential ecosystem services such as recreational fishing or diving (see links 24–27).
24	Piscivorous fish	Tourists	+	Accessibility to do recreational fishing can increase tourism. We consider recreational fishing to be mainly on piscivorous fishes.
25	Top predators	Tourists	+	Accessibility to see top predators can increase tourism.
26	Benthos	Tourists	+	The benthic community around the wind farm is an attractive diving spot for tourists (and locals) and can attract tourists.
27	Benthos	Fishery sector	+	New fishery industries on the benthic organisms (e.g., lobsters, cabs), which are expected to increase around the wind farm, can be developed.
Links between Social and Ecological Network				

(*continued on next page*)

Table A1 (*continued*)

Nr	From	To	Sign	Definition
Social Network				
28	Wind farm	Dredge fishery	–	Reduced dredging because of restricted fishing in wind farm area.
29	Wind farm	Trawl fishery	–	Reduced trawling because of restricted fishing in wind farm area.
30	Dredge fishery	Fishery sector	+	Fishery sectoring (in form of dredging) activity increases fishermen's economy.
31	Trawl fishery	Fishery sector	+	Fishery sectoring (in form of trawling) activity increases fishermen's economy.
32	Plankton	Perceived environmental quality	–	Phytoplankton can affect the water quality. High densities cause of phytoplankton causes a more turbid water that can be seen as less clean and attractive, which decreases the perception of a good environmental quality.
33	Piscivorous fish	Perceived environmental quality	+	Possibility for recreational fishing increases the perception of a good environmental quality.
34	Top predators	Perceived environmental quality	+	Spotting marine mammals increases the perception of a good environmental quality.
35	Benthos	Perceived environmental quality	+	Possibility to dive and see benthic communities increases the perception of a good environmental quality.

All links in the ecological system are predator-prey relationships and are not described in detail. See Raoux et al.[5] for details.

Table A2
Probability of a positive or negative change in response to a given press perturbation scenario for the four system structures and the ecosystem structure, as analyzed using the program developed by Dambacher et al. [37] (esapubs.org/archive/ecol/E083/022) in Maple.

Press perturbation scenario	P1	P2	P1P2	P1P2P3	P1P2P4	P1P2P5	P1P2P3P4	P1P2P3P5	P1P2P4P5	P1P2P3P4P5
Structure S1										
EOC	−1	−0.94	−1	−1	−1	−1	−1	1	−1	−1
SORB	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
IRB	1	1	1	1	1	1	1	1	1	1
Well	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
EnvP	1	1	1	1	1	1	1	1	1	1
Fish	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
Indu	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
Serv	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
Tour	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
Structure S2										
EOC	−1	−0.94	−1	−1	−1	−1	−1	1	−1	−1
SORB	−1	0.64	−1	−1	−1	−1	−1	1	−1	−1
IRB	1	0.89	1	1	1	1	1	−1	1	1
Well	−1	−0.89	−1	−1	−1	−1	−1	1	−1	−1
EnvP	1	0.83	1	1	1	1	1	−1	1	1
Fish	−1	−0.85	−1	−1	−1	−1	−1	1	−1	−1
Indu	−1	−0.85	−1	−1	−1	−1	−1	1	−1	−1
Serv	−1	−1	−1	−1	−1	−1	−1	1	−1	−1
Tour	−1	−0.89	−1	−1	−1	−1	−1	1	−1	−1
Structure S3										
EOC	−1	−0.98	−1	−1	−1	−1	−1	−1	−1	−1
SORB	−1	1	−1	1	−1	1	−1	1	−1	1
IRB	1	−0.86	1	1	1	1	1	−1	1	1
Well	−1	0.86	−1	−1	−1	−1	−1	1	−1	−1
EnvP	1	0.98	1	1	1	1	1	1	1	1
Fish	−1	−0.73	−1	−1	−1	−0.8	−1	1	−1	−1
Indu	−1	−1	−1	−1	−1	−1	−1	−0.95	−1	−1
Serv	−1	−0.99	−1	−1	−1	−1	−1	1	−1	−1
Tour	−1	0.86	−1	−1	−1	−1	−1	1	−1	−1
Structure S4										
EOC	−1	1	−1	−1	−1	−1	−1	1	−1	−1
SORB	−1	1	−1	1	−0.57	1	1	1	1	1
IRB	1	−1	1	−1	1	−1	1	−1	1	−1
Well	−1	1	−1	1	−1	1	−1	1	−1	1
EnvP	1	−1	1	−1	1	−1	−1	−1	−1	−1
Fish	−1	1	−0.98	1	−0.52	1	1	1	1	1
Indu	−1	1	−1	−1	−1	1	−1	1	−1	1
Serv	−1	1	−1	−1	−1	1	−1	1	−1	1
Tour	−1	1	−1	−1	−1	−1	−1	1	−1	−1
Ecological subsystem										
Twl	−1	0.83	−1	−0.83	−1	−1	−1	−0.83	−1	−1
Dre	−1	−0.94	−1	0.82	−1	−1	−1	0.82	−1	−1
PL	−0.92	0.55	−0.91	0.97	−0.73	−0.91	−0.92	0.97	−0.73	−0.92
PLF	−0.93	−0.96	−1	−1	−0.89	−1	−0.8	−1	−0.89	−0.8
PIF	0.96	−0.92	0.7	0.52	1	0.7	1	0.52	1	1
TOP	0.96	0.7	0.99	−0.88	1	0.99	1	−0.88	1	1
KS	1	−0.94	0.99	0.73	−0.98	0.99	−1	0.73	−0.98	−1
BEN	−0.89	1	0.97	0.72	1	0.97	1	0.72	1	1
BFF	0.85	0.97	1	0.92	0.99	1	1	0.92	0.99	1
SOL	0.98	0.68	0.99	−0.58	−0.86	0.99	−0.99	−0.58	−0.86	−0.99
COD	0.75	0.96	0.99	0.75	−0.79	0.99	−1	0.75	−0.79	−1

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2020.104031.

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