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Eliciting Stakeholder Representations of a Marine Socio-Ecosystem: Participatory Modelling of Shellfish Aquaculture in the Normand-Breton Gulf, France

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Abstract: In data-poor situations, qualitative modelling (Puccia and Levins' "loop analysis") combined with participatory involvement of stakeholders is well suited to holistically represent the complexity of socio-ecosystems and to assess system stability and its responses to long-term perturbations. This paper presents the results of a qualitative modelling project that involved an interdisciplinary team across natural sciences, social sciences, and modelling. The project focused on analysing the sustainability of a socio-ecosystem with an intense activity of shellfish aquaculture in the Normand-Breton gulf, France. Our primary objective was to involve stakeholders into the participatory development of qualitative models describing the structure and functioning of this regional aquaculture system. Six area-specific workshops were held independently with different focus groups, namely shellfish producers, managers and other stakeholders, to elicit key components, interactions and pressures viewed as significant to socio-ecological dynamics. First, we identified differences and commonalities in system perceptions across areas and stakeholder groups. Despite discrepancies between focus groups, we successfully derived a synthetic representation that reconciles alternative views of the system. Second, we predicted system responses to various perturbation scenarios. Overall, the participatory qualitative modelling exercise identified key drivers of the system that have not received much attention from past research and management. In particular, the lack of social acceptability appears as a major constraint limiting the potential for shellfish aquaculture to expand in the region.

***Keywords**:* Qualitative modelling; participatory approach; socio-ecosystem; sustainability; shellfish aquaculture.

1 INTRODUCTION

The ecosystem approach to fisheries and aquaculture has become the main framework for public policies that regulate these sectors (Soto *et al*., 2007, Costa-Pierce, 2010). The approach focuses on the notion of sustainable development while specifying the need to preserve the goods and services provided by marine socio-ecosystems. This paradigm based on ecosystems is the basis for research that aims to examine the different ecological, economic and social dimensions at play in the dynamics of these socio-ecosystems. Modelling is increasingly used to better understand the nature of the relationships between the elements of these systems. It is used to both describe the key interactions that govern system dynamics, and explore potential system responses to ecological, economic or institutional changes. In shellfish socio-ecosystems, modelling can help explore the nature of interactions between (i) ecological processes, which can affect the amount of primary trophic resource available to aquaculture (Cugier *et al*., 2010); (ii) biological processes, allowing estimation of growth and production of cultured shellfish biomass (Cugier *et al.*, 2010, Gangnery *et al.*, 2015); and (iii) socio-economic processes associated with the individual and collective strategies of the actors engaged in the management of shellfish farms (Pérez Agúndez *et al.*, 2010, Mongruel *et al.*, 2011).

A diversity of approaches to modelling complex systems exist, and can be described according to their level of realism, precision, and generality. A given approach strikes a compromise between these dimensions and maximizes two while neglecting the third (Levins, 1966). While mechanistic models favour realism and precision, statistical models give priority to generality and precision to analyse correlations, while they do not seek to explain processes and causal effects between system components. Qualitative models favour generality and realism, to the detriment of precision. More specifically, qualitative models focus on the structure of socio-ecosystems, and the relationships between key processes structuring their dynamics (Dambacher, 2001). This allows representing variables relating to different dimensions (e.g. physical, biological, ecological, economic and social), which is an essential step in the elaboration of socio-ecosystem representations. Indeed building integrated models of socio-ecosystem is often a challenge, especially due to lack of data and information; heterogeneity of data (i.e. qualitative versus quantitative data, non-homogeneous frequencies of data collection, etc.); or biased information regarding some of the components under study. Therefore, qualitative modelling is able to integrate information from various disciplines, including the social, cultural and economic dimensions of socio-ecosystems, and helps understanding and analysing socio-ecosystem interactions.

An important feature of Ecosystem-Based Management is the need to involve stakeholders in management design and the supporting research, as well as in management decision-making (Long *et al.*, 2015). Indeed there has been a growing interest in involving stakeholders in research on marine socio-ecosystems and in the integration of stakeholder knowledge in scientific studies of these systems. In particular, involving stakeholders in the development of qualitative models, through participatory workshops for instance, ensures that their knowledge is included in developing these representations and that the models focus on key issues for stakeholders (Fulton *et al.*, 2015; Voinov *et al.*, 2016). Involving stakeholders early in discussions regarding the management of marine socio-ecosystems and in the ensuing decision processes can also increase support towards management systems that include decision-support approaches and tools.

In this study, we adopted qualitative modelling as a framework to (1) elicit information from stakeholders about the Normand-Breton socio-ecosystem associated with the shellfish aquaculture industry, (2) compare and reconcile the alternative representations of this system elaborated by different stakeholder groups, and (3) develop a holistic understanding of the system's dynamics, and specifically assess the consequences of selected scenarios of change.

2 MATERIAL AND METHODS

2.1 The Normand-Breton Gulf

The Normand-Breton gulf (NBG) is located in the Western Channel and extends from the west of the Bay of Saint Brieuc to the north of the Cotentin peninsula. The case study coastline is about 300 km for a total marine area of ca. 11 000 km^2. In this study, we focused mainly on the area from Cancale to Cherbourg, including the bay of Mont Saint Michel and the Western part of Cotentin. This case study belongs to two administrative regions, Brittany and Normandy. In this specific area, bivalve aquaculture largely dominates aquaculture and is usually located in sheltered and intertidal areas (bays, estuaries). Two species are mainly cultivated: the Pacific oyster *Crassostrea gigas* and the blue mussel *Mytilus edulis*, with annual productions around 19 000 and 29 000 tonnes, respectively (Gangnery *et al.*, 2011). In addition to shellfish aquaculture, numerous economic and social activities potentially compete for the use of coastal and marine space, such as fisheries (commercial and recreational harvesting several species of fish), tourism (including diverse nautical activities), agriculture (various crop and animal productions), sand gravel extraction and discarding of sediments dredged in commercial harbours, nuclear power plant, and urban development. Besides, one site (the bay of Mont Saint-Michel) has a recognised heritage value due to remarkable landscapes and living species resulting in different levels of cultural and environmental protections.

Different management issues have been identified in the area (AAMP, 2009). They include protection of key marine habitats; understanding and preserving coastal ecosystems in relation to ecosystem functions and land/sea interactions, maintaining seabirds and marine mammals' diversity; improving water quality and maintaining primary productivity of the coastal zones; and coping with invasive species which affect coastal biodiversity and productivity. Improving the coherence and transparency of decision-making process regarding coastal zone management; developing new uses in the coastal zone; and promoting sustainable activities, including aquaculture and fisheries, were also identified as important issues.

2.2 Qualitative Modelling

Qualitative modelling approach is based on the graphical representations of dynamic systems (Puccia and Levins 1985, Dambacher and Ramos-Jiliberto, 2007). This approach relies on the construction of graphs characterizing the relationships between the elements of a system, which are then analysed mathematically using interaction matrices. These analyses make it possible to explore the nature of the factors of equilibrium or imbalance that are likely to condition the dynamics of the system and therefore its sustainability.

A qualitative model can be represented as a sign-directed graph (Puccia and Levins, 1985) where key variables are shown as nodes, which are interconnected by interactions shown as oriented edges (→, or –o, for a positive or a negative interaction, respectively). A qualitative graph can then be mathematically written as an interaction or community matrix, which can be analysed to characterise system stability near equilibrium (Dambacher *et al.*, 2003b), and variable responses to long-term perturbations based on model feedback structure (Puccia and Levins, 1985; Dambacher *et al.*, 2002, 2003a, b). Specifically, the adjoint of the community matrix can be determined, analytically or numerically (Melbourne-Thomas *et al.*, 2012), to provide the signs of system responses to a perturbation, which are called, hereafter, press perturbation analyses. In this study, we adopted a numerical approach based on Monte-Carlo simulations to determine variable responses to perturbation scenarios (Marzloff *et al.*, 2016). In short, n=500 quantitative community matrices, which each respects qualitative network topology, are drawn randomly: interactions are drawn in]0,1] if positive; in [-1,0[if negative; or are equal to 0 if nil. Predicted responses to perturbations are reflected in the proportion of response signs (positive, negative or nil) derived for each variable under a given long-term perturbation scenario across the n adjoint matrices. Predicted variable responses to perturbation scenarios are computed using the red-grey-blue colour scaling described in Marzloff *et al.* (2016): if all predicted responses for a given variable are of the same sign across all n matrices, its response sign is fully-determined and shown in white if no effect, in dark blue if negative, or in dark red if positive. If the n randomly-drawn matrices predict different response signs then there is an ambiguity in the response sign due to the counteracting effect of the different feedback loops involved. Ambiguous responses are shown in faded colours as ambiguity increases (red or blue for positive and negative responses respectively), and appear in dark grey if less than 2/3 of the signs predicted are consistent.

2.3 Stakeholders' Workshops

A pilot approach to participatory qualitative modelling was adopted in this interdisciplinary study, which aimed to elicit multiple representations of the NBG shellfish aquaculture socio-ecosystem by different groups of stakeholders, in separate workshops. The workshops were organised in the two administrative regions (bay of Mont Saint-Michel, Brittany and Western part of Cotentin, Normandy), with homogeneous focus groups of stakeholders of limited size (< 10 participants). In each region, three groups of stakeholders were identified: (i) "shellfish producers" including shellfish (mussel and oyster) farmers and their representatives (Regional Committee of Shellfish farming, trade unions), (ii) "managers" including (local) environmental and maritime administrations, NBG delegation of French Agency for Biodiversity, elected officials, water agencies, and coastal conservatory; and (iii) "other stakeholders" with representatives from other uses of the gulf (professional and recreational fishermen) and environmental non-governmental Organizations (NGOs).

In total, six workshops were held independently in March 2017 to elicit key components, interactions and pressures viewed as significant to socio-ecological dynamics in the gulf. The workshops addressed three main questions: (i) what are the current issues faced by the shellfish production sector? (ii) what are the important interactions between ecosystem, shellfish production activity and other uses of the ecosystem in relation to these issues? and (iii) what are the levers of action for the shellfish aquaculture sector? Prior to these six workshops, a workshop involving scientific experts of the system under study was also organized to address the same questions.

The formalism of the qualitative model approach described in section 2.2 was presented to stakeholders so as to collaboratively develop representations of the socio-ecosystem of the Normand-Breton gulf based on collective inputs elicited during each workshop. Workshop participants were asked to first list all variables of interest, and then specify key interactions between these variables, step-by-step, by drawing a qualitative representation on a whiteboard. Six conceptual models (i.e. sign-directed graphs) that represented the vision of the different groups of stakeholders of the socio-ecosystem were thus built, in addition to an expert-based representation.

2.4 Synthetic Analyses

A synthetic representation (or sign-directed graph) was then developed with the variables appearing in at least three of the six stakeholder workshop models, i.e. the variables mentioned in at least half of the focus groups. Analysis of the system responses to various perturbations - i.e. press perturbation analyses – was performed on this synthetic model. This synthetic representation and the analysis of the model responses were validated by stakeholders during a debriefing meeting held in June 2017. This meeting gathered in one place the participants in the six workshops organised in March 2017.

3 RESULTS

The six different sign-directed graphs, called hereafter models, of the socio-ecosystem from the six participatory workshops were analysed and compared. Terminology to describe the variables was harmonised following all workshops in order to make all models comparable, and variables were grouped in three broad dimensions: Environmental, Economic and Social.

3.1 Stakeholder’s Representations of the Socio-Ecosystem

The characteristics of the models built during each participatory workshop are summarized in Table 1.

Table 1. Characteristics of the models built in the six participatory workshops. “B” stands for the workshops organised in Brittany and “N” for the ones in Normandy.

Participatory workshop	Entry variable of the model	Number of variables			Number of variables involved in feedbacks	Variables most involved in feedbacks
		Environmental	Economic	Social		
B / shellfish producers	stock density	14	5	7	17	plankton, production biomass
B / managers	stock density	7	8	9	20	social acceptability, undersized organic waste, economic return
B / other stakeholders	area of concessions	0	3	15	14	social acceptability, image of the bay, area of concessions
N / shellfish	stock density	12	9	6	20	plankton

producers						
N / managers	stock density	8	7	7	11	production biomass
N / other stakeholders	stock density	15	2	4	12	production biomass

The entry variable of the model corresponds to the first variable chosen by the stakeholders to start building the model (Table 1). While these entry variables were identical (i.e. oyster or mussel stock density indifferently[1]) for almost all the models except one, the total number of variables varies from 18 to 27 variables across models, and the number of variables involved in feedbacks ranges from 11 to 20 variables. The model from the focus group of "other stakeholders" in Brittany was the one that differed the most from the others. This model had a different entry variable and did not include environmental variables. Except for this model, the three environmental, economic and social dimensions were represented in all models, which is a crucial point for integrated modelling.

3.2 Synthetic Representation of the Socio-Ecosystem

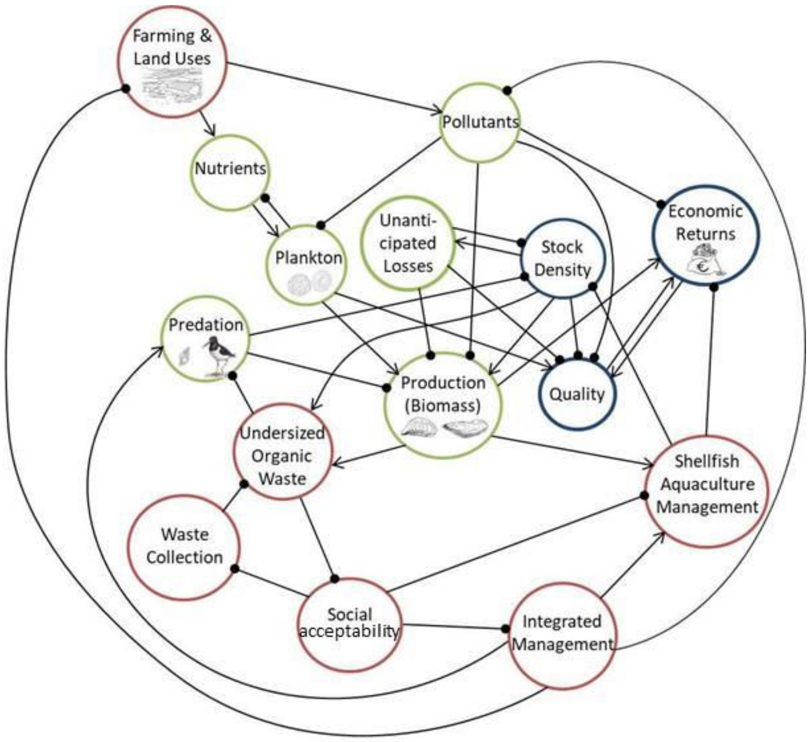

Figure 1. Synthetic sign-directed graph of the NGB socio-ecosystem, with environmental variables in green; economic variables in blue and social variables in red.
→ indicates positive interaction, ——• indicates negative interaction

Fig. 1 represents the synthetic model (or sign-directed graph) of the socio-ecosystem built with variables from at least half of the workshop models. Variables interact with other variables both from the same dominant feature but also from other dimensions (Fig. 1). This demonstrates the relevance of working at the scale of a socio-ecosystem, in which ecological, economic, and social aspects lead to particularly complex dynamics. While environmental and social dimensions were the most represented, with 6 variables in each of these two dimensions, the economic dimension was less detailed with only 3 variables. The economic variables related to shellfish quality, stock density and economic returns. This last variable, in the vast majority of the models where it appears, had no impact on the socio-ecosystem; it only receives links, which means that, in this representation, it is not an element that directly influences shellfish aquaculture management or production (biomass). This may seem counterintuitive insofar as the economic results of the activity necessarily influence medium and long-term production strategies. However, within short-term production cycles, companies can only implement marginal changes after seeding. Hence, the economic dimensions of the models considered are only short-term in scope. In the synthetic model, production is influenced by two negative feedback loops: 1) production - shellfish aquaculture management - stock density – production; 2) production - undersized waste - social acceptability - shellfish aquaculture management - stock density - production). The first feedback loop relates to the existing management regime aimed at controlling stock density, which affects the productivity and quality of shellfish. Undersized waste relates to undersized mussels that are stored on the shoreline

[1] All models considered oyster and mussel production indifferently.

and become organic waste, thus affecting the social acceptability of the sector. This waste only concerns mussel rearing and is related to the local production technique using wooden poles. Mussel growth on poles is highly heterogeneous and when mussels are harvested, all individuals present on the pole are retrieved. Smallest individuals are not marketable and are stored on the shoreline involving visual and olfactory pollution. Interestingly, social acceptability, in this model, directly negatively impacted three components but is negatively impacted only by the undersized organic waste. The representation of the socio-ecosystem did not focus only on marine interactions but also on land/sea interactions. The link between land and sea was indeed highlighted by the variable "farming and land uses" which provides nutrients useful for the growth of plankton, but also pollutants that have a negative impact on production.

3.3 Press Perturbation Analyses

Using the synthetic model (Fig. 1), we estimated the consequences of selected perturbation scenarios, focusing on the key issues identified with stakeholders in the workshops. These were related to (i) long-term improvement in waste collection, (ii) increase in integrated management and increase in aquaculture practices management, as well as (iii) increase in social acceptability. The predicted responses of variables to the various scenarios are presented in Fig. 2 using the red-grey-blue colour scaling described in section 2.2.

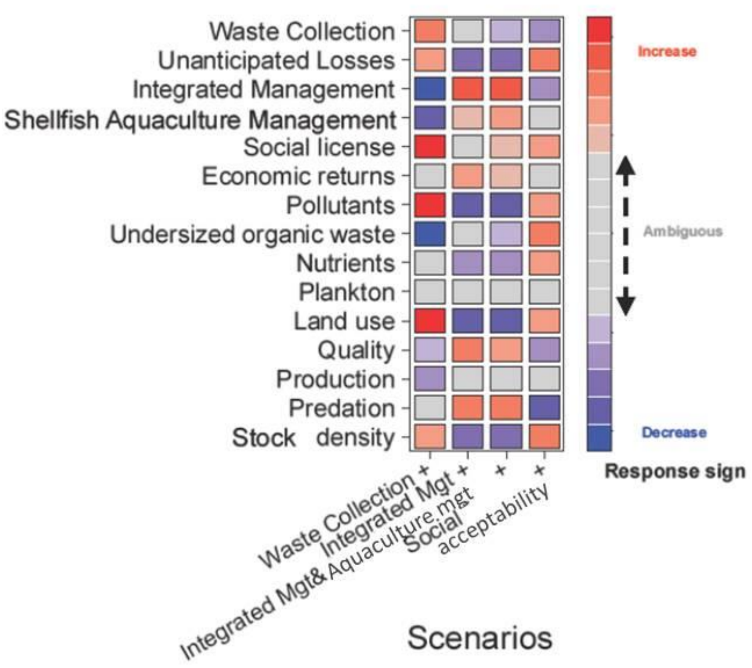

Figure 2. Predicted qualitative responses of variables to various perturbation scenarios (i.e. increase in: waste collection, integrated management, integrated management and shellfish aquaculture practices management, and social acceptability) according to the synthetic model (Fig1.). Right: Coloured squares represent the sign of response of each variable (y-axis) to a given scenario (x-axis): white for neutral; grey for ambiguous; red for positive; blue for negative. When responses are positive or negative, the degree of shading increases with prediction uncertainty.

Waste collection was predicted to improve the social acceptability of shellfish aquaculture (dark red, Fig. 2), which indirectly releases regulation via the social acceptability/ integrated management/ shellfish aquaculture practices management feedback loop and counter-intuitively allows for pollution and intensive land uses to develop. Pollution and intensive land uses in turn were likely to negatively affect overall shellfish production, both quantitatively and qualitatively, with uncertain consequences on economic returns.

Enforcement of integrated management measures (combined or not with increase in aquaculture practices management) facilitated higher economic returns due to an increase in production quality (as a result of a combination of decreased pollution, reduction in intensive land uses, and lower stock density) over quantity.

Counter-intuitively, as described above, improvement in social acceptability released the need for regulation (e.g. via waste collection, integrated management and/or changes in aquaculture practices management) and allowed for pollution and intensive land uses to develop. As a consequence, the shellfish aquaculture sector did not prioritise quality over quantity, which could result in higher organic waste (and hence only a marginal long-term increase in social acceptability).

4 DISCUSSION

We applied an experimental protocol to the construction of alternative representations of the NBG shellfish aquaculture socio-ecosystem by various focus groups of stakeholders. The representations and discussions during the workshops highlighted current issues faced by stakeholders, such as undersized organic waste left on the foreshore; easements (i.e. the space occupied by shellfish farms); quality of water; social acceptability and the need for dialogues between stakeholders. It is interesting to note that these concerns did not map with the issue raised in the scientific expert group workshop, as in most scientific studies of the system which tend to focus their assessment of aquaculture sustainability on the impacts of invasive species or on high oyster mortalities (Girard and Pérez Agúndez, 2014). Compared to previous studies, the wider scope of our findings was made possible through the use of a modelling approach based on participatory implementation of qualitative modelling, identification of scenarios from the workshop outcomes and analysis of system responses to press perturbations according to these scenarios. An abundant literature shows that the use of models and scenarios to address social issues and to explore possible solutions is particularly well adapted to the participation of multiple actors (see Jakeman *et al.*, 2008 for example).
One result of particular interest is the emphasis which emerged of the need to address social processes, with the guidance of the main actors of the system. One of the strongest issues raised by local residents and environmental non-governmental organizations (NGOs) in the bay of Mont-Saint-Michel relates to the undersized organic waste produced by mussel farmers. This concern indirectly addresses other social issues linked to the management of waste, the environmental impact of shellfish aquaculture or the mitigation of conflicts between coastal users. Such issues constitute important factors that condition the social acceptability of aquaculture by the local communities. As a consequence, any wish of farmers to develop shellfish aquaculture in new areas is rejected by local stakeholders and decision makers would attempt to avoid social conflicts by stopping aquaculture expansion. Social acceptability therefore appears as one of the major key variable in the model. However, it is represented as a black box linked to several other variables, which would likely mask different perceptions by the stakeholders. One of the main challenges with respect to the dynamics and the sustainability of this socio-ecological system is therefore to unravel this social acceptability "black box". This challenge is often recognised in other systems but rarely the core of integrated modelling approaches (Byron *et al.*, 2011).

We set up alternative models to reflect the different perceptions of issues, key interactions and intervention options. Consensus generally occurred within each stakeholder group but alternative models emerged from the separate workshops. They were confronted in the final meeting with all stakeholders. No final consensus on a single representation was obtained but the synthetic model captured some essential components of the system. However this model was not presented as the ultimate representation of the system and the other representations were introduced and described as legitimate systems. Besides, another source of ambiguity arose from the analysis of the synthetic model which did not predict a clear response of the system to perturbations. Ambiguity can therefore be handled in several ways. Sharing different representations would raise public awareness of issues at stake. In addition, the use of different models would provide a set of potential system responses to perturbations to stakeholders and decision makers (Hosack *et al.*, 2008).

Our study is a first step which allows identifying key variables of a socio-ecosystem that can then help building an integrated quantitative and operational model. It points to where future research effort should focus, for instance on social acceptability measurement. Model analysis did not predict a clear response of the system for some issues and outlined the need for more quantitative approaches. The complementarity between modelling approaches results from model features and limitations regarding generality, realism and precision (Dambacher, 2001). The interest of complementary models with different levels of complexity has also been emphasized by Fulton *et al.* (2015).To demonstrate this point, Fulton *et al.* (2015) used different model types and showed how the combination of model outcomes helps addressing complex issues, informing policy makers and making both modellers and stakeholders attitudes evolve. Such a strategy would certainly apply to our case, and benefit from other models previously developed to address specific issues in the Normand-Breton gulf shellfish socio-ecosystem (Cugier *et al.*, 2010).

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