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Federico Cornacchia, Alberto Gabino Martínez-Hernández
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By **Federico Cornacchia** (Fondazione Eni Enrico Mattei)
Alberto Gabino Martínez-Hernández (Fondazione Eni Enrico Mattei)
Marco Bidoia (Fondazione Eni Enrico Mattei)
Carlo Giupponi (Fondazione Eni Enrico Mattei and Department of Economics, Ca' Foscari University of Venice)

Summary

As the impacts of climate change are expected to be increasingly disruptive, a growing share of the economic literature moved to modelling approaches to address the interconnectedness of social, economic, and environmental issues. Among them, System Dynamics (SD) stands out as a well-established modelling approach to analyse complex social-ecological systems. In order to benefit from such modelling exercises it is necessary to follow a structured process, bearing in mind that models should have as their ultimate ambition that of supporting decision-making processes. Yet, the connection with decision-making is addressed only in the last phases of the modelling process, with emphasis placed only on few particular sectors. Hence, a lack of a general framework that can be used as a reference to address climate change adaptation and which could provide insights to economic valuations to support decision-making processes for a different range of sectors emerges. Consistently, the present study aims to bridge the observed gap by employing a combined SES-DAPSIR framework to build a conceptual modelling process for simulating the behaviour of a generic socio-ecosystem, with a particular focus on climate change adaptation. It also illustrates how the proposed conceptual modelling process is concretely put into practice with an application for a coastal socio-ecosystem. This allows demonstrating how the proposed methodology constitute a potential common starting point for different targeted modelling exercises, resulting particularly useful when moving from analytical modelling to decision support.

Keywords: Climate change adaptation, system dynamics, decision-making, socio-ecosystem, SES-DAPSIR framework, conceptual modelling

JEL Classification: C63, Q54, Q57

Address for correspondence:
Federico Cornacchia
Researcher, Fondazione Eni Enrico Mattei (ADAPT@VE)
Palazzo Ca' Tron, Santa Croce 1957
30135 Venice, Italy
e-mail: federico.cornacchia@feem.it

Towards a modelling process for simulating socio-ecosystems with a focus on climate change adaptation

Federico Cornacchia[1], Alberto Gabino Martínez-Hernández[1], Marco Bidoia[1], Carlo Giupponi[1,2]

[1] Fondazione Eni Enrico Mattei, Climate Change Adaptation Program (ADAPT@VE), Venice
[2] Department of Economics, Ca' Foscari University of Venice

Abstract

As the impacts of climate change are expected to be increasingly disruptive, a growing share of the economic literature moved to modelling approaches to address the interconnectedness of social, economic, and environmental issues. Among them, System Dynamics (SD) stands out as a well-established modelling approach to analyse complex social-ecological systems. In order to benefit from such modelling exercises it is necessary to follow a structured process, bearing in mind that models should have as their ultimate ambition that of supporting decision-making processes. Yet, the connection with decision-making is addressed only in the last phases of the modelling process, with emphasis placed only on few particular sectors. Hence, a lack of a general framework that can be used as a reference to address climate change adaptation and which could provide insights to economic valuations to support decision-making processes for a different range of sectors emerges. Consistently, the present study aims to bridge the observed gap by employing a combined SES-DAPSIR framework to build a conceptual modelling process for simulating the behaviour of a generic socio-ecosystem, with a particular focus on climate change adaptation. It also illustrates how the proposed conceptual modelling process is concretely put into practice with an application for a coastal socio-ecosystem. This allows demonstrating how the proposed methodology constitute a potential common starting point for different targeted modelling exercises, resulting particularly useful when moving from analytical modelling to decision support.

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Addressforcorrespondence:

Federico Cornacchia

Fondazione Eni Enrico Mattei (ADAPT@VE)

Palazzo Ca' Tron, Santa Croce 1957

30135 Venice, Italy

E-mail: federico.cornacchia@feem.it

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Introduction

Theoretical background and problem statement

In recent years, a growing share of the economic literature moved to modelling approaches such as agent-based models (ABMs), GIS-based models, and systems dynamics (SD) models (Scrieciu et al., 2013). These types of modelling approaches can be seen as a bridge between natural and social scientists to address the interconnectedness of social, economic, and environmental issues. Among these methodologies, SD stands out as a well-established modelling approach to address a wide range of complex social-ecological issues.

Although modelling exercises inherently require a creative component, it is nevertheless necessary to follow a structured and disciplined process to conduct them (Sterman, 2000). Various proposals for the structuring of a modelling process exist in the literature, including Argent et al. (2016), Saeed (1992), Sterman (2000), Voinov (2008). As also emphasised by Farr et al. (2022), there is a variety of proposed modelling workflows, accompanied by an analogous diversity of tools that can be used in an integrated manner to conceptualise the structure of the considered systems and to proceed with the modelling exercise. Additionally, according to some authors (Currie et al., 2018; Voinov, 2008), models should always have as their ultimate ambition that of supporting decision-making processes, particularly system dynamics ones. For this reason, modelling processes and decision-making processes are closely related.

Concurrently, the impacts of climate change are expected to be disruptive. Planning and implementation have increased in many countries in relation to adaptation strategies to reduce vulnerability and exposure against climate change, with a particular emphasis on coastal and marine systems, and transformative and structural adaptation actions are needed to cope with high emissions scenarios (Cooley et al., 2022; IPCC, 2022). Yet, to date there are remarkably few systems dynamics models that follow a comprehensive modelling process which, from the early steps, focuses on the close link with decision-making processes.

This connection is addressed and remarked only in the last phases of modelling processes, such as in relation to the use of the resulting model to cope with complex issues (Voinov, 2008). Economic forecasts of climate change impacts with conventional economic approaches usually depart from a fairly abstract level of analysis, characterised by little or no strong connection with real-world data and overly ponderous assumptions (Keen, 2020). Moreover, following the work of Martínez-Hernández (2022), for the case of climate change adaptation in coastal areas, it is highlighted a lack of a clear link of decision-making processes in the first steps of the modelling flow in existing system dynamics modelling processes, with emphasis placed only on one or two particular sectors.

Therefore, a lack of a general framework that can be used as a reference to address climate change adaptation and which could provide insights to economic valuations to support decision-making processes for a different range of sectors emerges. Consistently, the present study aims to bridge the observed gap.

Purpose of the work

Based on the above, the purpose of this paper is manifold:

- **Objective 1.** Presenting a conceptual modelling process for characterising and simulating the behaviour of a generic socio-ecosystem, with a particular focus on climate change adaptation; This is achieved by structuring the modelling process in such a way as:

    - **Objective 1.1.** To emphasise the important relation between system dynamics modelling and decision-making processes. This is achieved by starting the modelling process from the explication of triggering factors grounded on state-of-the-art literature, as well as by reporting the most pressing environmental and socio-economic issues related to climate change.
    - **Objective 1.2.** To build a conceptual modelling framework that can be used as a reference method for addressing several climate change-related issues. This is enabled by building a 'repository' of key socio-ecosystem elements from which one can draw for carrying out different, more targeted, modelling exercises;

- **Objective 2.** Displaying how this proposed conceptual modelling process is concretely put into practice with an application for a coastal socio-ecosystem.

The following sections are intended to present in detail the proposed conceptual modelling process and how its construction was conducted. This was done through a system analysis exercise with an application for a coastal socio-ecosystem. Based on this, it will be possible to aim at the presentation of the presented approach as general guidelines for the analysis of socio-ecosystems. Hence, sections reporting the rationale behind each step are followed by sections illustrating the application of the modelling process to a coastal socio-ecosystem. A final section presents a discussion and some concluding remarks.

Methodology – Conceptual Modelling Process

In Figure 1, the proposed conceptual modelling process is depicted. The 'triggering factors' and 'general system conceptual model' steps are conceived as steps prior to the two initial steps generally proposed in the existing literature as 'goals and objectives' and 'conceptual model' or with a similar nomenclature (Voinov, 2008). Hence, the latter two steps were renamed as 'targeted goals and objectives' and 'targeted conceptual model' because their implementation is based on the two proposed preliminary steps.

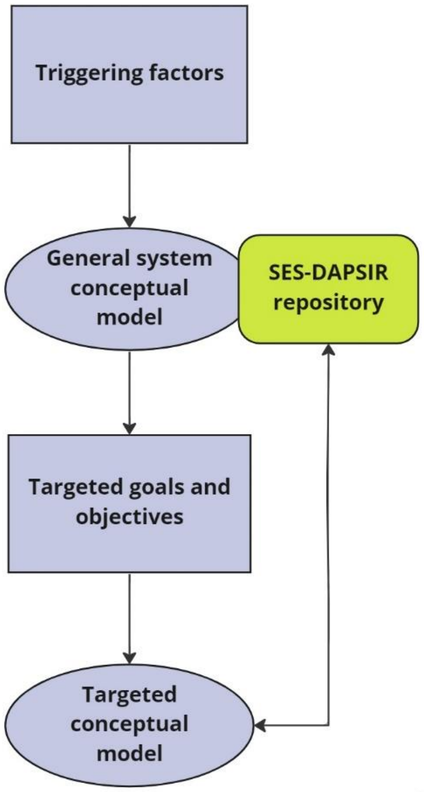

Figure 1. Steps designed for the development of a generic socio-ecosystem conceptual model.

In the following sections, the rationale behind the different steps comprising the proposed modelling process is provided.

Step 1 – Triggering Factors

With regard to objective 1.1, the present paper advocates the integration of trigger identification as the new initial step in the modelling process, conceived by integrating elements from Integrated Coastal Zone Management (ICZM) and Integrated Water Resources Management (IWRM) decision-making processes.

It is well known that for its establishment as a standalone discipline, despite some obvious commonalities, SD intentionally distanced itself from different viewpoints of management science (Forrester, 1961). However, it has already been pointed out in the past how some cautious re-engagement with such a field of work could prove fruitful for SD methodological flows (Lane, 1995). Accordingly, similar to the initial approach of system evaluation undertaken in management science, the need for a global consideration of factors was highlighted by Lane (1995) in its 'Folding Star Framework' for SD modelling. For instance, for the first step of this framework called 'Appreciation of the Situation', Lane suggested the grounding of the modelling process in an account of the natural, designed physical, and designed abstract systems including the interpretation of phenomena made by decision and policy-makers as well as aspects of the social context in which they are found[1]. This was suggested with the expectation that the SD model or other types of models would contribute to a better understanding of these systems and also to improve model validity from the early stages of conceptual modelling (Lane, 1995).

However, what is currently being done in management science is different from what is usually proposed as the first stage in SD modelling processes. For instance, the first step of the modelling process as proposed by Sterman (2000) (i.e., 'problem articulation') and Voinov (2008) (i.e., 'goals and objectives') already requires several specifications, such as:

- Specifying a detailed objective that goes through the definition of a specific problem to be addressed;
- The main features of the system (variables and key concepts) that need to be accounted for to achieve the stated objective;
- To whom the results want to be communicated in order to maximise the usefulness of the model's outputs; The time range and spatial boundaries to be considered.

The above involves the integration of a link between the output of the modelling process and the utility for decision-making processes only in the final step of the modelling process, i.e., when the model outputs are to be used.

Conversely, the development workflow of ICZM and IWRM see the centrality of the output's relevance to decision-making processes from the earliest steps. This involves, from a broader system perspective, the initial outlining of triggers, i.e., the factors that spark and motivate the whole process such as environmental and socio-economic issues and measures in place (e.g., adaptation measures) that impel action (Clark, 1991; Giupponi & Sgobbi, 2013; Thia-Eng, 1993). The incorporation of this step into the modelling process as the step that initiates the entire model development could enable to state the overarching motivations and reflections behind the need to create a model in a much broader system perspective than the usual focus on a single narrow problem.

Including 'triggering factors' as the first step in the modelling process allows discerning, with more hindsight, whether the modelling work is indeed necessary based on a general explication of problems and motivations (see Figure 1 above).

In this regard, concerning a possible application for climate change adaptation in coastal areas, reference can be made to the factors related to sea level rise (SLR) mentioned in the IPCC, including drivers, hazards, impacts of SLR and associated governance challenges (Oppenheimer et al., 2019). In relation to climate change in general and SLR in particular, it appears clear that there is not only one narrow problem that can be addressed and analysed as a closed system. As visible from Figure 2, multiple system factors (that could also be singularly and narrowly identified as problems) are interconnected in a sort of problem hierarchy, i.e., a cascade of factors (or problems) from drivers to responses and governance challenges. For instance, climate change induces global mean sea level (GMSL) rise which in turn, in combination with extreme sea level (ESL) events such as tides, storm surges and waves, creates coastal hazards. Coastal hazards result in impacts on ecosystem and human

[1] With this, Lane referred to the definitions provided by Checkland (1981): the ensemble of natural elements, i.e., 'natural systems'; the ensemble of man-made physical elements - such as infrastructure - and abstract elements - such as cultural artefacts - referred to as 'designed physical systems' and 'designed abstract systems'; and the study of the ensemble of human affairs, placed in the 'management and information systems'.

components, requiring responses in the form of policies and measures and from which relative governance challenges arise (Figure 2; Oppenheimer et al., 2019).

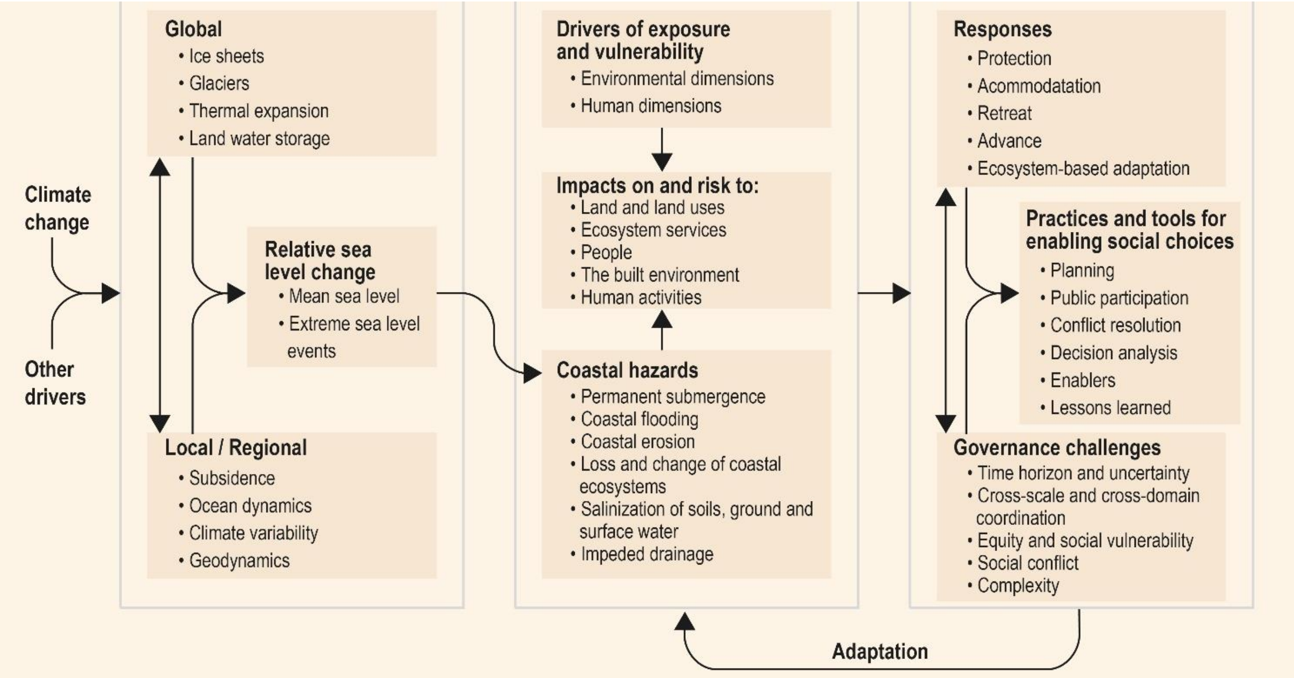

Figure 2. Schematic illustration of the interconnection of factors related to climate change, concerning low-lying islands and coastal areas, including drivers of SLR and ESL hazards, exposure, vulnerability, impacts and risk. Depicted are also responses and governance challenges (Oppenheimer et al., 2019).

Thus, the ensemble of factors related to climate change and the associated SLR depicted in Figure 2 are identified as the triggers that can guide and justify the initiation of a conceptual modelling process, which is absolutely necessary as a basis for possible different quantitative modelling exercises. Therefore, rather than starting by identifying a single factor as the sole and central focus of a modelling exercise, starting from a broader acknowledgment of a multiplicity of triggering factors can lay a more solid foundation to then move to a phase of conceptualization of key elements of a general system. The consideration of these elements would then allow tackling the very same multiplicity of triggering factors from the beginning to the end of a wider modelling exercise.

Step 2 – General System Conceptual Model

Once the set of triggers is made explicit, a second step of the modelling process named 'general system conceptual model' is proposed. This step is designed as an exercise of broad conceptualization of the whole system in which one or more specific triggers (i.e., problems) can be located and addressed. It is recognized that it is not possible to realistically conceptualise an entire system in its countless details. Hence, the aim is to consider a system as a whole and conceptualise it as comprehensively as possible, so as to obtain a general repository of elements referring to a generic system that can be used as a reference for more specific modelling exercises.

The conceptual model stage is often conducted in a participatory manner, whether with one's team members or external stakeholders, with the aim of capturing the understanding of the people involved in the modelling process regarding the structure and functioning of the system under consideration

(Argent et al., 2016). When dealing with judgments elicited by individuals (e.g., stakeholders, academic experts, etc.), it is also necessary to recognize in advance people's limited ability to process complex and multiple pieces of information. Having a conceptual model as a preliminary step enables reaching consensus among participants as it allows for the development of a common platform for mutual learning and understanding that can provide a solid foundation for a quantitative modelling exercise (Argent et al., 2016). In this regard, the use of conceptual models can help to interpret and frame concepts and processes, showing that they are not isolated but rather integrative components of a single picture (Catenacci & Giupponi, 2013).

However, there is no current standard for conducting conceptual modelling exercises. Some frameworks, such as the DPSIR, can be used for guidance but, in the end, it is recognised that a personalisation of the conceptual modelling process based on the specific needs of the study is applied (Argent et al., 2016; Voinov, 2008). For structuring this step, the present study includes a first attempt to integrate two distinct frameworks used for the interpretation of systems characterised by the interaction between humans and nature: the socio-ecosystem (SES) proposed by Giupponi (2022) and the DAPSIR, adapted from Elliott et al. (2017) and Judd & Lonsdale (2021).

The SES framework proposed by Giupponi (2022) was chosen as the background framework to conduct an initial participatory identification of key elements and processes of a generic coastal socio-ecosystem. The SES represents a particular type of multilevel system in which ecological and social elements engage in mutual interactions and feedback. The SES framework, presented in Figure 3, adopts a perspective tailored to an environment characterised by the interdependence and co-evolution of natural and anthropogenic elements, by applying the new concept of socio-ecosystem services (Giupponi, 2022).

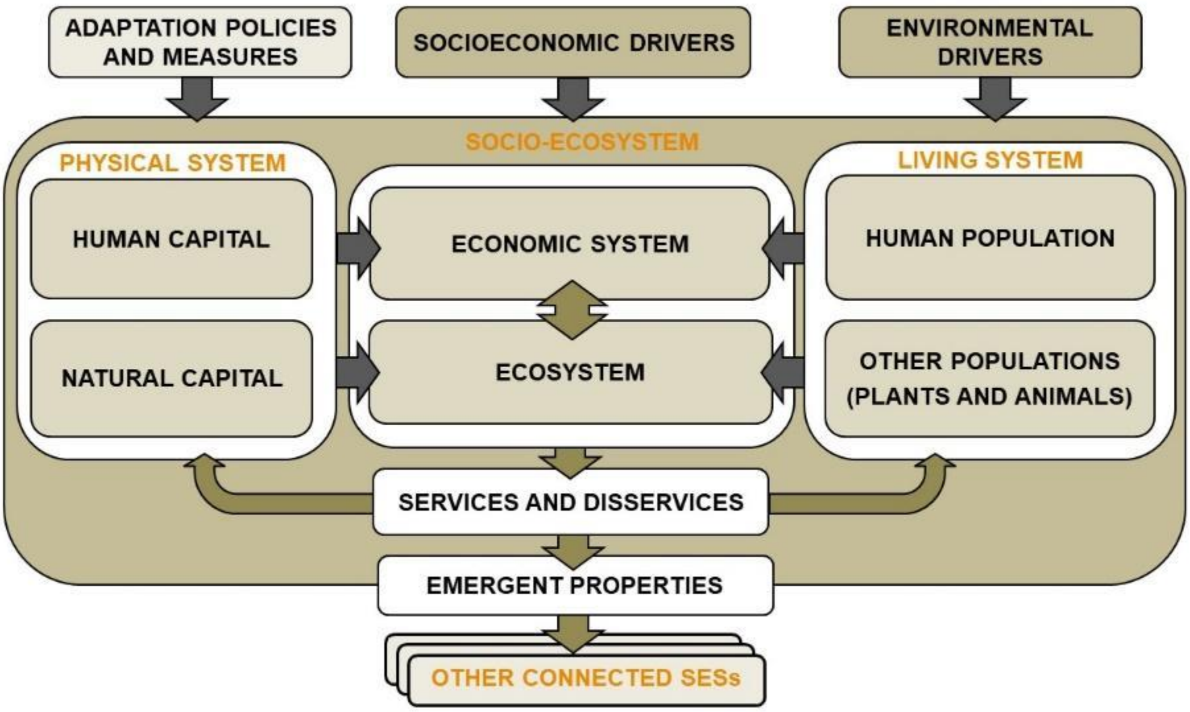

Figure 3. The socio-ecosystem (SES) and interactions among its main constituent modules (adapted from Giupponi, 2022).

In any socio-ecosystem, we have the co-presence of natural and anthropic elements, with their structural elements, which constitute natural capital on the one hand and human capital on the other. Functional interactions occur between the elements of the living world (humans and all other biotic components of ecosystems), and from their interactions the supply and demand for goods and services is determined. The complex relationships between the various supplier and recipient elements determine as a result the functioning of the socio-ecosystem, both in positive (e.g., supply of goods and services and preservation activities) and negative (e.g., impacts of human activities on natural components) terms (Giupponi, 2022).

In an attempt to clearly capture this complexity, the SES framework considers the fundamental elements that make up a socio-ecosystem. An outer frame identifies the boundaries of the socio-ecosystem, within which are the two main subgroups of the physical elements (on the left) and the elements of the living world (on the right). From this physical perspective, the SES considers the terrestrial and aquatic environmental elements, defined as 'natural capital', and the elements of urbanised areas (e.g., infrastructures), here defined as 'human capital'. These elements are considered in their interactions with biological elements, both human and natural, identified here as the SES modules 'human population' and 'other populations (plants and animals)'. The internal interconnections between elements of the natural world and elements of the anthropic world result in socio-ecosystem services or disservices. The latter take place through interactions between ecosystem processes and functions ('ecosystem' module) and economic system dynamics ('economic system' module). These complex interactions can generate emergent properties of the system, i.e., hardly predictable outcomes of the interaction between the ensemble of elements (Giupponi, 2022).

At the same time, outside the system frame, the modules 'adaptation policies and measures', 'socioeconomic drivers', and 'environmental drivers' account for the necessary consideration of the effects of possible adaptation measures and important economic (e.g., macroeconomic trends), social (e.g., political crises), and environmental variables (e.g., extreme events, mean sea level rise) external to the socio-ecosystem (i.e., external forcing) on the internal elements. Outside the boundaries of the system there is also the module 'other connected SESs' indicating the existence of other socio-ecosystems that may be related to the considered one. Lastly, it should be noted that all connections between SES modules are bi-directional in nature, pointing to the possible establishment of feedback loops that can stabilise the system or, conversely, make it unstable (Giupponi, 2022).

In order to facilitate the transition from a general identification of key components of a coastal socio-ecosystem within the SES to the steps of identifying causal linkages between them, the DAPSIR framework was utilised. The DAPSIR was used here as a tool for facilitating the reading of the interconnections between the SES components from a causal perspective.

The logic behind the DAPSIR framework as proposed by Judd & Lonsdale (2021) is that anthropogenic Drivers require human Activities to be satisfied. The pursuit of these activities induces Pressures on natural systems that in turn lead to changes in the State of natural capital. These changes influence human well-being through Impacts on ecosystem services (and consequently on human welfare). Finally, these impacts require Responses in the form of measures.

This framework was initially designed in response to a need for a problem-structuring framework that would allow for a system-wide analysis of the complex socio-ecological interactions in the marine environment. In addition, it was designed to clearly depict the causal chain from anthropogenic drivers and activities to impacts on the environment, society and the necessary responses, in a way that is also understandable to a wide range of policy-makers and stakeholders (Elliott et al., 2017; Judd & Lonsdale, 2021).

Given that the SES concept is being considered in the present study, the causal reasoning behind the DAPSIR framework is reinterpreted consistently with the SES, in the following way: anthropogenic Drivers in combination with environmental Drivers affect human Activities. The pursuit of these activities induces Pressures on the considered SES that in turn lead to changes in its State. These changes influence human well-being (welfare) through Impacts on socio-ecosystem services and economic features. Finally, these impacts require Responses (in the form of measures). Figure 4 shows the DAPISR framework as reinterpreted in this study. Particularly, it should be emphasised that in the DAPSIR as reinterpreted in the present study, the Drivers are not only anthropogenic but also environmental, and the component 'State' refers not only to the state of the natural capital but is understood as the condition of both natural and anthropogenic elements (for more details on the adopted DAPSIR definitions see Table 1).

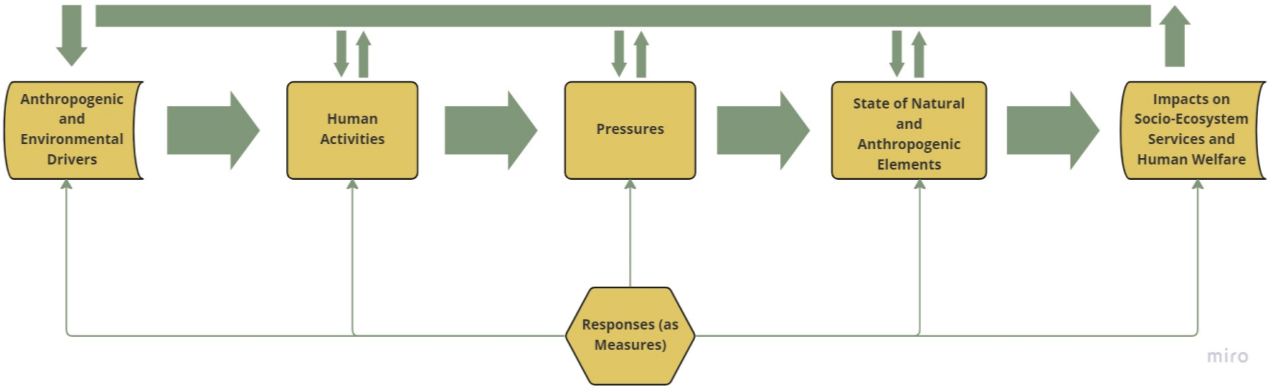

Figure 4. DAPSIR framework as reinterpreted in this study in view of the nexus with the SES framework.

However, being the DAPSIR initially designed based on a rather unidirectional flow from human drivers and activities to impacts on natural capital, the original definitions of its components do not accurately reflect the more interactive nature of the SES. Therefore, the definition of each DAPSIR component was revised in order to show how the DAPSIR can be a suitable lens through which to interpret the SES in terms of causal relationships. Moreover, as it can be seen at the top of Figure 4, the set of arrows going in and out of each box were added to represent the possible feedback interactions that can take place between DAPSIR components. For transparency and consistency, the definitions of the DAPSIR components adopted in the present study in order to facilitate the creation of a nexus with the SES are presented in Table 1.

Table 1. Adopted definitions of the DAPSIR components.

DAPSIR component	Definition
Drivers	Drawing on Maslow's hierarchy of human needs, it is possible to argue that the main socio-economic drivers are related to basic human needs, such as the need for food, energy, space, movement of goods, security or recreation (Elliott et al., 2017; Maslow, 1943, 1981). These needs define individual and social motivations for certain activities and shape an entire set of socio-economic drivers. In addition to these drives, important environmental drivers affecting socio-economic activities can be identified.

Activities	Human activities pursued within the socio-ecosystem and undertaken as a consequence of the drivers in order to meet society's needs (Judd & Lonsdale, 2021). Some examples are agriculture, aquaculture, shipping, extraction of living resources such as fish and shellfish harvesting.
Pressures	Pressures exerted by undertaken activities on the socio-ecosystem (Judd & Lonsdale, 2021). Some examples are land reclamation, introduction or spread of non-indigenous species, pollution.
State	State and/or condition (and related dynamics of change) of the elements belonging to the following SES modules: Natural Capital, Other Populations (Plants and Animals), Human Capital, Human Populations.
Impacts	Intended as the impacts on socio-ecosystem services and economic features driven by changes in the state.
Responses	Policy or social responses, intended as management measures (in place or potential) that are or can be implemented to prevent or minimise the causes of state changes or, where impacts have occurred, to mitigate their effects (Judd & Lonsdale, 2021).

Overall, the 'general system conceptual model' step was designed to allow the creation of a repository of main macro-categories of elements – and sub-elements - framed in a combined SES-DAPSIR frameworks, causally linked to each other. During the 'targeted conceptual model' step (see STEP 4), this enables to select only specific subsets of such macro-categories and their sub-elements and only a specific subset of interlinkages to be studied in the model, based on the objectives of the particular modelling exercise stated in the 'targeted goals and objectives' step. This is based on the fact that some of the elements become relevant only in certain geographic contexts and/or for certain purposes. Therefore, the identified macro-categories of elements are useful to provide a broad repository of main concepts and elements related to a generic socio-ecosystem.

Implementation of the General System Conceptual Model step

Using the aforementioned frameworks as general underpinnings from which to start, the 'general system conceptual model' step was conducted, choosing an application to a coastal SES as an illustrative example, through the following sub-steps:

- **SUB-STEP 2.1.** A *creative modelling workshop* (CMW) involving several experts was first organised. The workshop consisted of a brainstorming exercise focused on identifying the main elements of a generic coastal socio-ecosystem, working on the SES as a background framework. Therefore, the main question that guided the brainstorming exercise was the following: "What are the key elements of a coastal SES that can be observed and measured?". A structured format was chosen for conducting the brainstorming exercise, i.e., the workshop facilitator established a rotation enabling each participant to contribute with ideas. Two rotations were undertaken and, in each rotation, each participant was given a fixed amount of time to talk freely and propose elements to be assigned to the different modules of the SES framework. The second rotation was designed to allow the expression of new ideas and concepts generated after hearing the intervention of other experts in the previous rotation. After the two rotations, an open discussion was conducted to intervene, if necessary, in the refinement of proposed elements or to add last-minute elements by mutual agreement. The gathering and allocation of proposed elements to the SES modules was done using a conceptual mapping software. The results of the assignment of elements to the SES modules during the brainstorming exercise are shown in Figure 5.

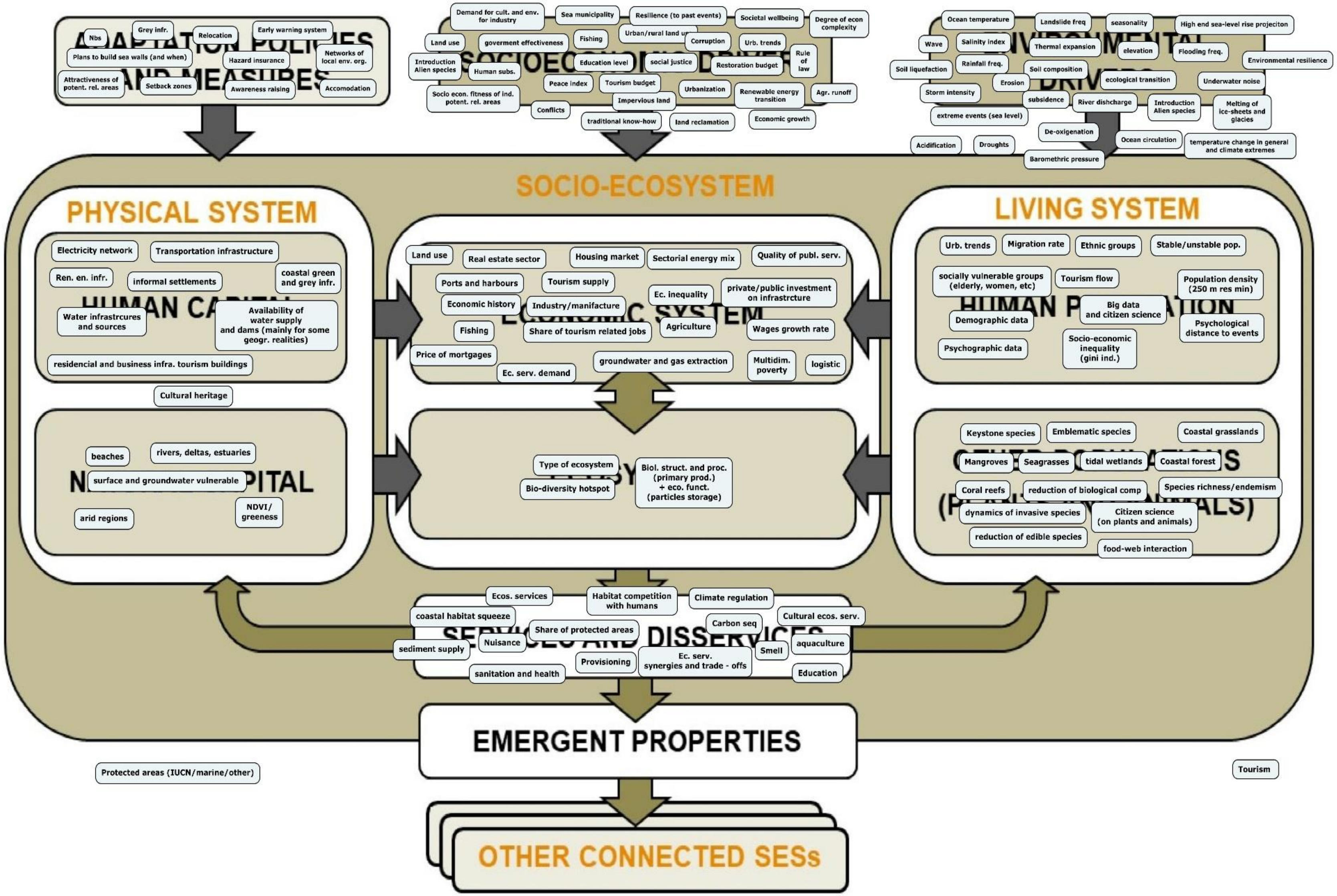

Figure 5. Overview of the main elements of a coastal socio-ecosystem proposed by experts involved in brainstorming workshops and allocated to the SES modules. Given that the main objective of the workshop was to collect as many proposals as possible concerning the main elements of a coastal socio-ecosystem, the visual form of the result was considered of secondary importance.

- **SUB-STEP 2.2.** *Cleaning, Consolidation, and Clustering* of gathered elements. In this step, the elements gathered during the first brainstorming workshop underwent an initial round of comparison and cleaning, in an effort to eliminate any redundancies, overlaps, and identify possible aggregations in order to create a narrower set of key concepts. This sub-step was conducted by focusing on the gathered elements both individually and as a whole, while maintaining the building blocks that comprise the SES as background framework. The results of this step were named 'Shared Conceptual Model 1st Release'.
- **SUB-STEP 2.3.** In this step, the methodology designed for integrating the SES framework and the DAPSIR framework was implemented. Considering that the DAPSIR framework is not immediately consistent with the SES framework, the procedure chosen for this step was based on the goal of building and strengthening such a nexus. Thus, the process of building the conceptual model was centred on a SES view in the background, subsequently mainstreamed into the DAPSIR framework for initial identification of causal links between elements. This operation was carried out employing a determinate coding convention[2].

  As next phase, the *elements that were assigned to the SES modules were interpreted from a DAPSIR perspective, assigning them to different DAPSIR components*. The output of this step was named 'Shared Conceptual Model 2nd Release' and its visual overview is presented in Figure 6.

[2] The content of 'shared_conceptual_model_release_1' was first subjected to a colour-coding phase. Different colour codes have been assigned to different modules of the SES framework. This allowed assigning a colour to the different elements of the system based on the SES module to which they were assigned, enabling the visualisation of the nexus with the SES framework when the elements are then inserted in the DAPSIR framework. Colour-codes were assigned as follows: Adaptation policies & measures (pink); Socio-economic drivers (blue); Environmental drivers (red); Natural capital (purple); Human capital (grey); Human populations (orange); Other populations (plants & animals) (light-blue); Economic system (yellow); Ecosystem (brown); Services and disservices (green).

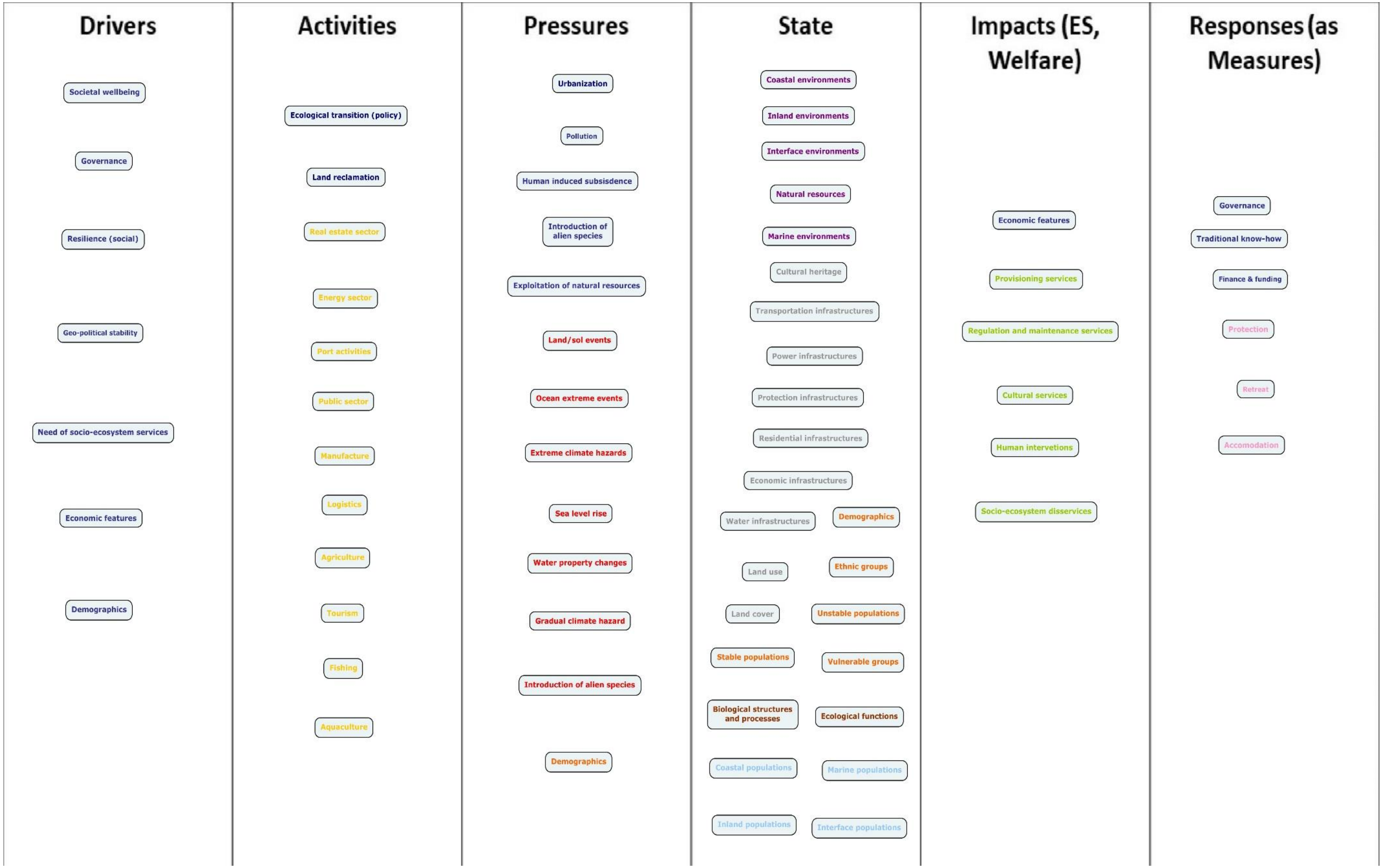

Figure 6. Result of the allocation of the elements previously assigned to the SES modules (and colour-coded according to them) to the components of the DAPSIR framework.

➢ **SUB-STEP 2.4**. In this step, the experts who participated in the first workshop were again involved in the context of a *second workshop*. Prior to the workshop, the conceptual model draft contained in ‘Shared Conceptual Model 2nd Release’ was shared with the participants. During the workshop, the following sub-steps were conducted:

- *Open discussion*. The possibility of proposing and discussing alternative allocations of certain elements to the components of the DAPSIR framework was provided. Some changes to the distribution of elements as presented in 'Shared Conceptual Model 2nd Release' were made based on mutual agreement. If deemed necessary, it was also given the opportunity to suggest some changes to the coding assigned to the elements during STEP 2.3.

- *Drawing causal linkages*. An exercise of identifying unidirectional causal linkages, necessarily drawn between an individual element of one DAPSIR component and another individual element within the next DAPSIR component, was conducted by the expert group.

- *Drawing feedback loops*. As the last phase, an exercise of identification of feedback loops between individual elements distributed along the DAPSIR components is conducted by the expert group.

To collect causal linkages and feedback loops proposals from the experts, the setting as in the first workshop was adopted. The output of the second workshop is depicted in Figure 7.

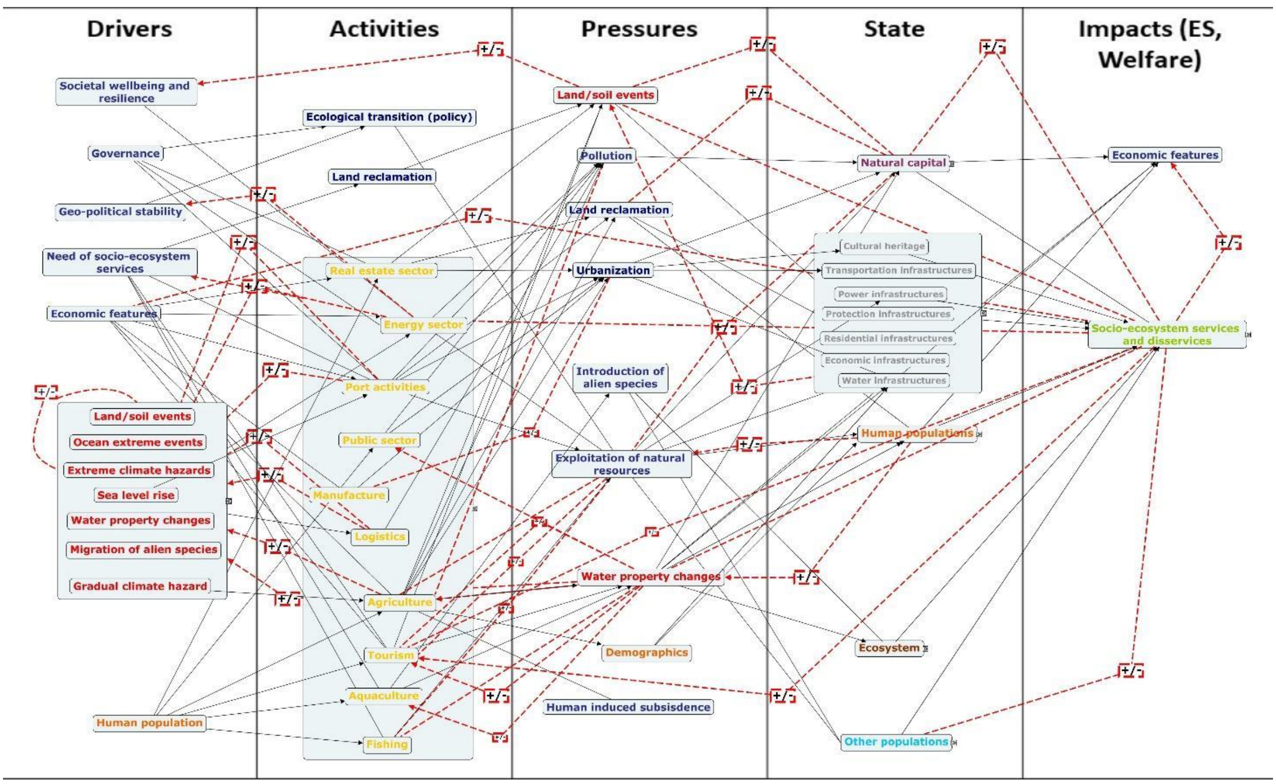

Figure 7. Identified causal linkages (black arrows) and feedback loops (red arrows) between the SES elements distributed across the DAPSIR components[3].

- **SUB-STEP 2.5**. *Refining and consolidating the output of the second workshop.* In this step, the names and positions of the elements distributed across the DAPSIR components were further refined. In addition, where possible, the elements were grouped in larger macro-categories. When reasonable, these macro-categories were grouped according to the nomenclature of the SES categories and modules. This was accompanied by a systematisation of the identified linkages and feedbacks, checking whether the identified links and feedbacks between individual elements could be extended to the entire macro-categories. Lastly, definitions of the macro-categories were provided accounting for SES definitions and literature[4]. The outcome of the steps just described is depicted in Figure 8.

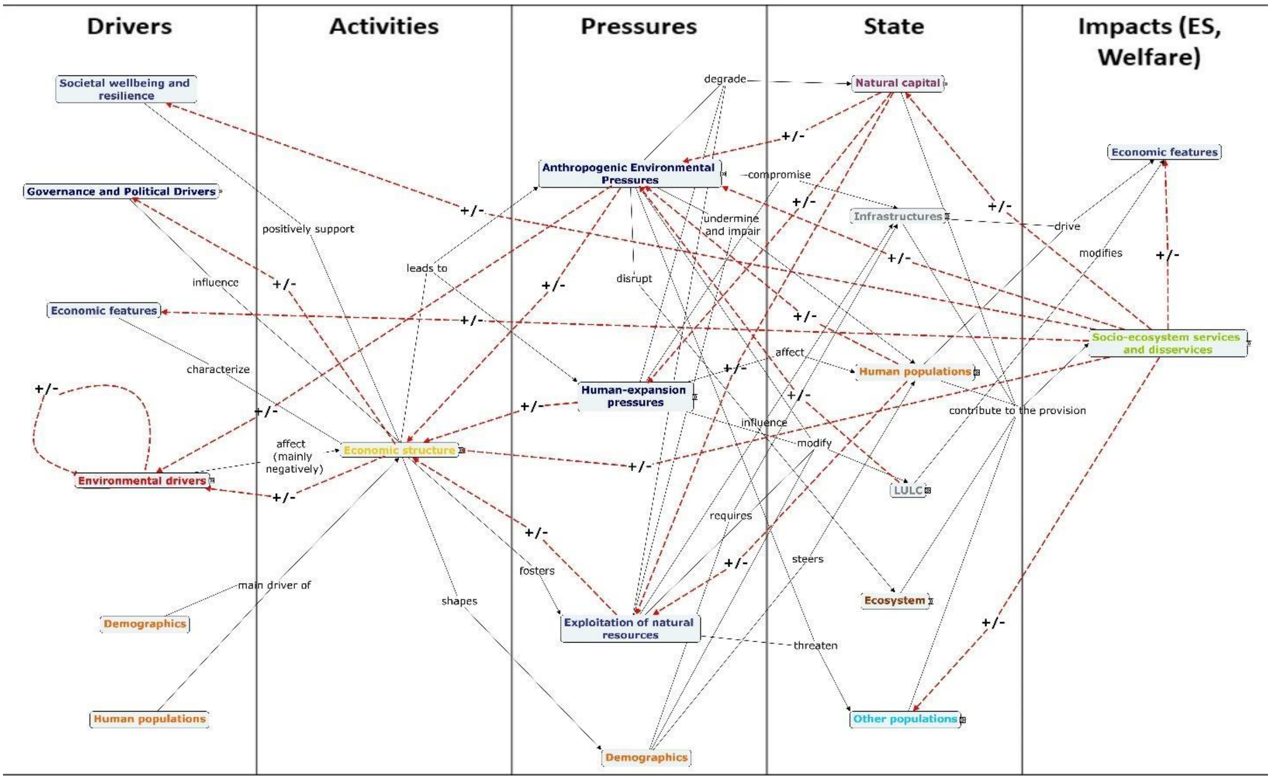

Figure 8. Overview of the developed general system conceptual model. Here, causal linkages and feedbacks between macro-categories of SES elements resulting from refining and consolidating the output of the second workshop are presented on a DAPSIR background.

[3] The Response component of the DAPSIR was omitted. This allowed focusing on the internal dynamics of the system rather than on the responses in terms of policies.

[4] The subdivision of identified SES elements in macro-categories (with relative definitions) and their sub-elements can be found in the Appendix, together with an indication of the DAPSIR components to which they have been allocated.

Step 3 – Targeted Goals and Objectives

After the development of a general system conceptual model, the identification of targeted goals and objectives follows. In this regard, based on what has been developed in terms of main elements of a coastal SES and their relationships, the members of the modelling team were asked to prepare proposals for targeted goals and objectives that could be addressed via targeted modelling exercises.

Following the collection of the team's proposals, the feasibility of the proposed targeted objectives was examined and only a subset of them was selected and presented in an overall team's plan, together with a team's common objective and the potential modelling tools to be used. Particularly for the work of the involved team, the common goal was the development of a spatial dynamic model of a SES and its main agents. Several targeted objectives - individual and non-individual, and focused on different geographical areas can also contribute to the common goal (e.g., economic valuation of ecosystem services employing dynamic modelling approaches, analysis of case studies on implementation of NbS as adaptation strategies employing GIS-based and system dynamic approaches).

Step 4 – Targeted Conceptual Model

Once the targeted goals and objectives are defined, the 'targeted conceptual model' step follows. Considering that one or more targeted objectives can be identified, this translates into the possibility of developing one or different targeted conceptual models, each in relation to a stated targeted objective. Starting from the developed general system conceptual model (previously presented in Figure 8), only macro-categories of elements and specific causal links and/or feedbacks between them that are deemed relevant in relation to the targeted objective of the modelling exercise can be extracted.

Compared to the general system conceptual model, a targeted conceptual model constitutes a more focused qualitative description of the system based on a particular targeted objective. Based on the latter and according to Voinov (2008), for the delineation of a targeted conceptual model it is necessary to proceed to the identification of the three main dimensions of structure, space, and time in a way that best addresses the targeted objective.

In terms of the structural dimension of the system, when developing a targeted conceptual model, it is crucial to first define system boundaries. Defined boundaries make it possible to distinguish the system under consideration from the external world, both in time and space, facilitating the identification of materials and information entering and leaving the system; elements and/or processes that are internal to the system (endogenous); and elements external to the system (exogenous).

In practice, to identify the structural dimension of the system it could be particularly useful to filter the macro-categories of concepts, linkages, and feedback which are of the greatest relevance in relation to a targeted objective. To provide an example of the implementation of this step, the following objective was formulated:

Extending a SD conceptual model developed by Hossain et al. (2020) to address ecosystem-based adaptation in tropical areas, with the theoretical aim of modelling the coastal protection ecosystem service provided by mangrove forests and estimating its economic value.

Hossain et al. (2020), constructed a conceptual system dynamics model for the southwestern coastal SES of Bangladesh by encompassing multiple livelihoods (fisheries, shrimp farming and forestry, and agriculture) and identifying several feedback loops involving ecological components (such as mangroves and water) and socio-economic components (such as subsidies and shrimp farming activity; Figure 9).

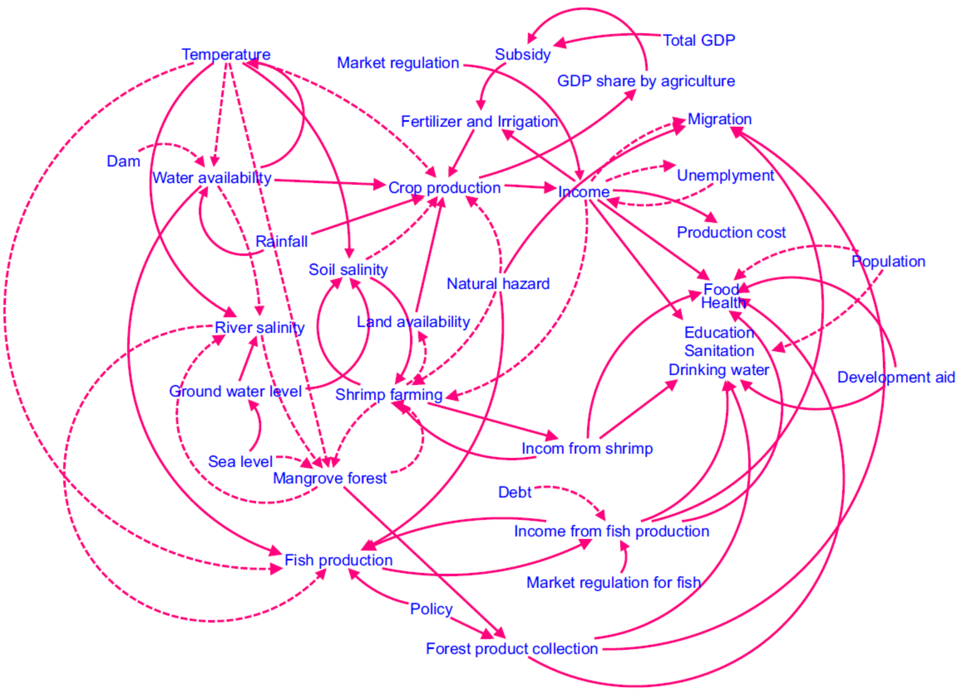

Figure 9. System dynamics conceptual model for the SES of a Bangladesh delta (Hossain et al., 2020).

However, although activities such as shrimp farming and related impacts in tropical areas have often been subject to modelling exercises, this has rarely been supplemented with modelling of (economic) impacts on the provision of coastal protection service by mangroves, especially employing system dynamics approaches.

The importance of considering the ecosystem service of coastal protection by mangroves through quantitative modelling exercises has been emphasised by different authors (Blankespoor et al., 2017; Dasgupta et al., 2019). In fact, healthy mangrove forests have been shown to be economically valuable as they can avoid large costs for construction and maintenance of artificial coastal protection barriers, especially in view of sea-level rise (Dasgupta et al., 2019).

Accordingly, the formulated objective reflects the intention of extending the conceptual system dynamics model developed by Hossain et al. (2020) by integrating components able to represent the provisioning dynamics of coastal protection service by mangroves, and how these change in relation to other considered factors such as shrimp farming, sea level rise, and salinity.

In order to integrate elements related to the dynamics typical of the provision of coastal protection service provided by mangroves, as illustrated by works such as Blankespoor et al. (2017) and Dasgupta et al. (2019), to the conceptual model of Hossain et al. (2020), the constructed general system conceptual model can be adopted. Therefore, the elements of the conceptual model by Hossain et al. (2020) were first brought into the general system conceptual model (Figure 10).

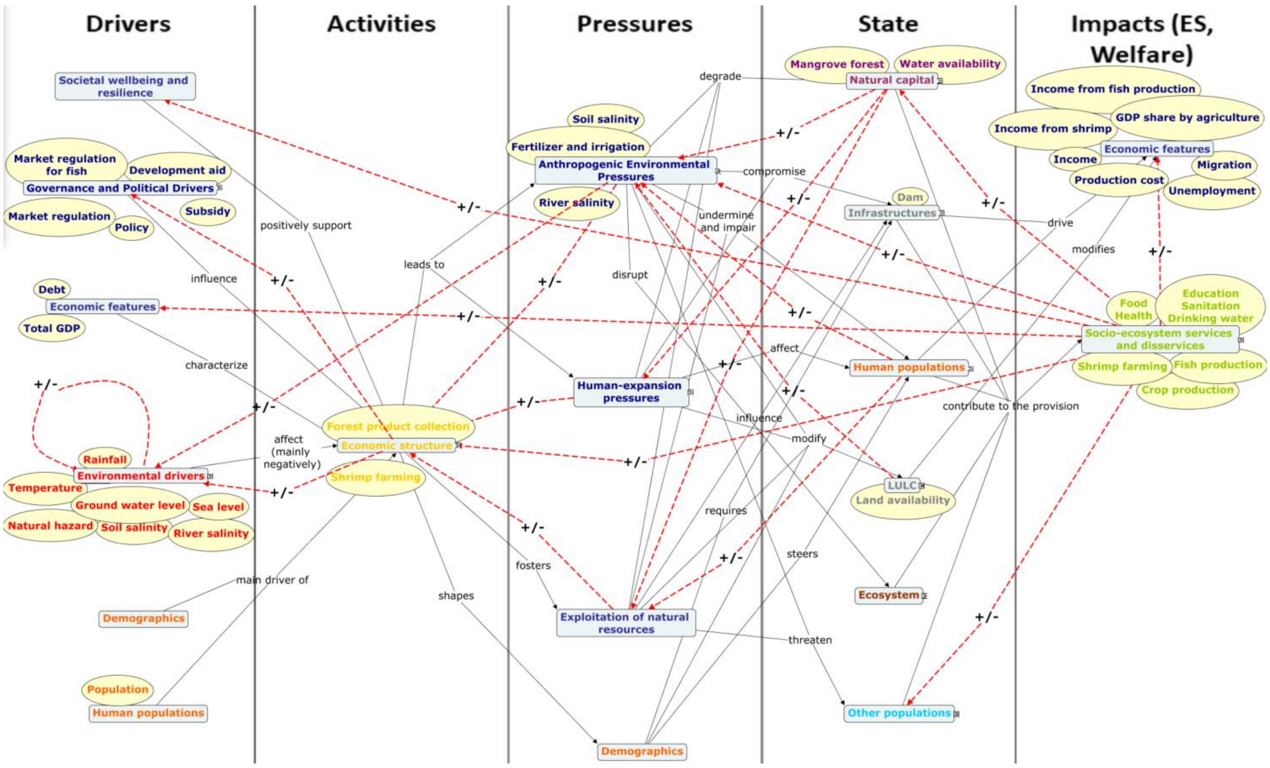

Figure 10. Visualisation of the elements of the Hossain et al. (2020) conceptual model in the general system conceptual model frame.

Through this illustrative exercise, it can be made evident how the employment of the proposed general system conceptual model as an analysis lens can facilitate, in cases of considering already existing models, the identification of previously missing elements relevant to the dynamics of interest. The insertion of the elements of the conceptual model of Hossain et al. (2020) in the general system conceptual model makes it possible to show that in Hossain's conceptualization of the SES, some elements that are fundamental to the consideration of others in terms of system dynamics are missing, or at least, not clearly made explicit. For instance, the element 'fish production' has been used in a way that appears to represent simultaneously a fishery activity and an ecosystem service. The same has been done for the crop production element. However, in terms of systems dynamics, especially when the goal is to quantify the provisioning of the ecosystem services, it is important to appropriately distinguish between the human-led activity, the natural component that contributes together with the active role of humans to the provision of the ecosystem service, and the final ecosystem service.

Consequently, elements such as 'fish' and 'mangroves' were added in relation to the macro-category 'other populations' in order to make the ecological components more explicit; ‘Shrimp biomass extracted from aquaculture’ and ‘crab, honey, and fish fry’ were added to make the actual final provisioning ecosystem services transparent; ‘Fisheries’ and ‘agriculture’ were added to better articulate human-led activities for the extraction of natural resources. Furthermore, to reflect the stated objective, the element 'coastal protection service' was included in relation to the category of socio-ecosystem services and disservices and the element 'mangrove forests' was interpreted as an infrastructure, precisely a green infrastructure used in climate change adaptation plans (Figure 11; Blankespoor et al., 2017).

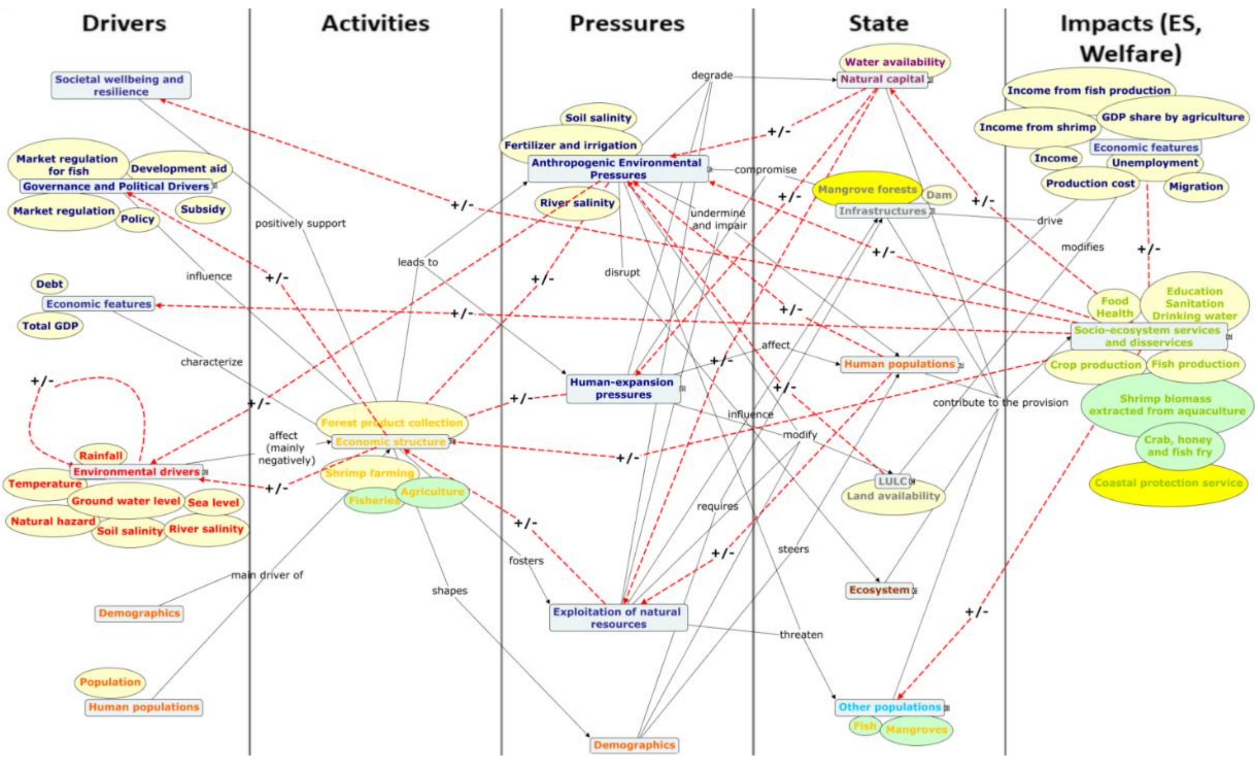

Figure 11. Exemplification of the addition of elements to the conceptual model so as to make all the factors that comprise a chain of causality from drivers to the provision of ecosystem services more evident. The elements of ‘fish’, ‘mangroves’, ‘shrimp biomass extracted from aquaculture’, ‘crab, honey, and fish fry’, ‘Fisheries’, and ‘agriculture’ were integrated as well as ‘mangrove forests’ and related ‘coastal protection service’. The last two elements were added in order to better reflect the stated objective.

From the general system conceptual model, it is also evident how ecosystem processes and functions underpinning the provision of ecosystem services, contained in the macro-category 'ecosystem', are a crucial element when it comes to ES modelling. Likewise, through the support of the general system conceptual model, it is possible to assess what other elements, linkages, and/or feedbacks are relevant or not to the objective of the modelling exercise. Indeed, in Figure 12 the result of a possible elimination of some irrelevant elements/macro-categories, linkages, and feedback in relation to the stated objective was provided in order to obtain a cleaner targeted conceptual model.

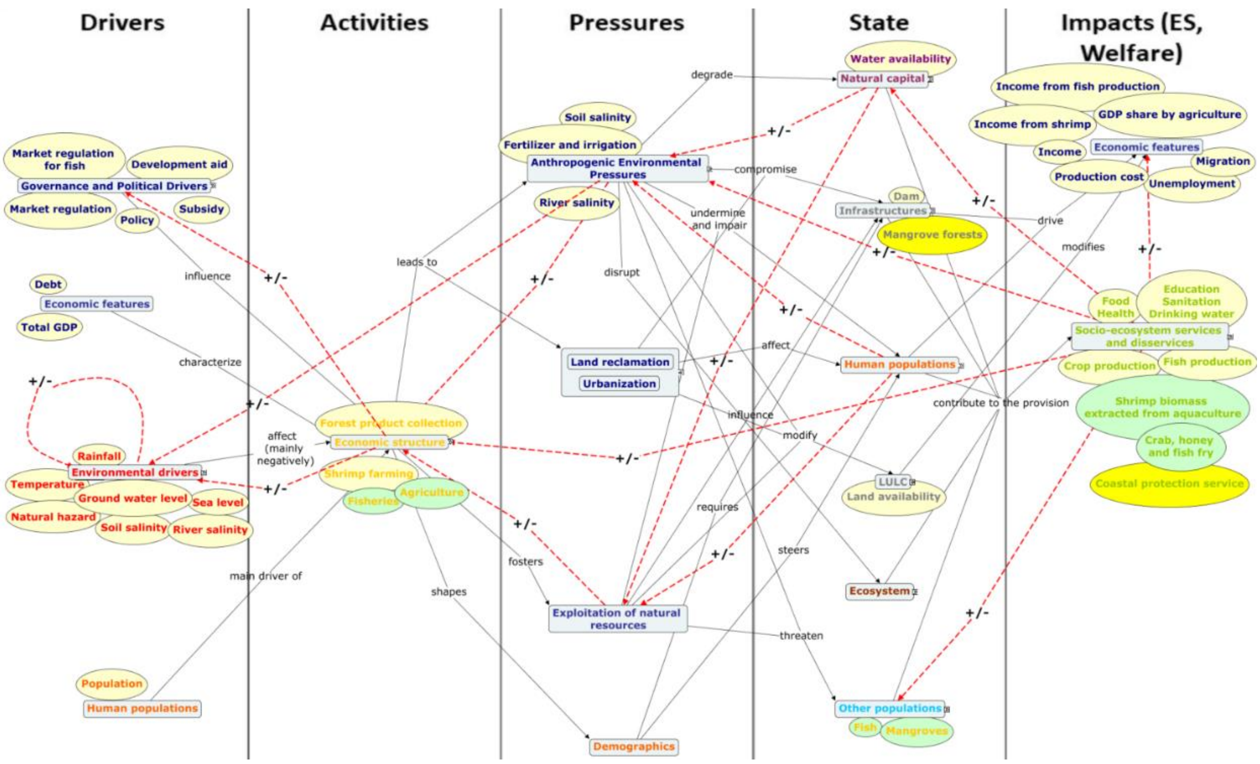

Figure 12. A possible configuration of targeted conceptual model resulting by expanding the conceptual model of Hossain et al. (2020), integrating elements for modelling the ecosystem service of coastal protection by mangroves, and removing elements, linkages, and feedback not relevant in relation to the stated objective.

Furthermore, consistently with Voinov and Sterman's guidance regarding the definition of system boundaries, the differentiation between endogenous and exogenous elements was also already implemented within the exercise of creating a targeted conceptual model (Sterman, 2000; Voinov, 2008). Accordingly, the implementation of the proposed conceptual modelling process allows all those SES elements included in the Drivers column of DAPSIR to be identified as exogenous drivers (Figure 14). All the remaining elements can be considered as endogenous.

In terms of specifying the spatial dimension, the study area is localised in the south-west coast of Bangladesh. This is an area of approximately 25,000 km², with a total population of 14 million and home of the world's largest mangrove forest, the 'Sundarban' (Hossain et al., 2020). Lastly, concerning the time dimension of the considered system, it can be reasonably assumed that the system is evolving dynamically because it does not reach an immediate equilibrium. In fact, due to the time-dependency of some variables and their interactions, it is needed to explicitly simulate the evolution of the system through time.

Discussion and Concluding remarks

In most cases, building a conceptual model is the first concrete step in developing a model (Voinov, 2008). In the present work, the objective was to initiate the creation of a conceptual model of a generic SES, which can be referred to in the context of different studies as a starting point for the identification of more specific objectives and related targeted conceptual models. Hossain & Szabo (2017) already pointed out how conceptual tools such as DPSIR could be applied to interpret the dynamics of socio-ecological systems. Accordingly, the present study responded to this need by proposing a general lens to interpret the dynamics of SESs.

The general system conceptual model was overall designed to allow creating a set of main macro-categories of elements framed in a combined SES-DAPSIR framework causally linked to each other. This can enable to 'fish out' only a specific subset of macro-categories and to study only a specific set of their sub-elements, based on the needs of the particular modelling exercise to be conducted. This is due to the fact that some of the elements could be relevant only in certain geographic contexts and/or for certain purposes. The identified macro-categories of elements are useful to provide a broad repository of main elements related to a generic socio-ecosystem. In order to address a dynamic simulation process, it was deemed appropriate to build a combined SES-DAPSIR framework, by which a formalisation in terms of causality was constructed. The primary reason for this is that such a causality forms the basis of a modelling process since the connections that link one SES element to another can become functions of a model. Hence, the proposed general system conceptual model and the related repository of key socio-ecosystem elements can constitute a potential common starting point for different targeted modelling exercises.

It was demonstrated how the proposed methodology allows analysing and further developing existing models. The proposed conceptual model can interface with an existing model, facilitating the identification of missing elements and elements that need to be reformulated. Against this background, the proposed methodology appears particularly useful when moving from the analytical modelling part to the decision support part. Its employment enables the user to assess how a model considers different elements of a system and, if they are not considered, how they can be integrated, while having a reference conceptual model that is solid and transparent in terms of interpretation of SES elements and their interconnections. Existing models, and the experiences behind these models, make it possible not to start from scratch when undertaking modelling exercises but, in order to benefit from these experiences, they must be understood. The more accessible the models and works of other authors are, the more one needs to be able to interpret them if the aim is to reuse and build on their insights. The proposed methodology can serve as an interpretation key. Hence, the strength of the presented conceptual modelling methodology is the establishment of a framework that can be followed for various (qualitative or quantitative) modelling exercises of coastal and non-coastal SES with a focus on climate change adaptation.

Furthermore, the proposed framework can also be used in (qualitative or quantitative) modelling exercises of a socio-ecosystems without a focus on climate change adaptation. In this case, it will be possible to identify relevant triggering factors useful to 'customise' a SES-DAPSIR repository, from which to start for the identification of targeted objectives and the realization of targeted conceptual models. Clearly, an iterative nature of the presented general system conceptual model and the associated repository of SES elements is envisaged. As also specified by Voinov (2008), the iterative nature of the modelling process comes into play, in that, a more detailed analysis of the information necessary to develop a targeted conceptual model may already require a redefinition of the stated targeted objectives as well as a potential refinement and consolidation of the repository. However, the iterative process is not to be seen as a limitation of the presented framework. Rather, by proceeding in the future with conducting differentiated modelling exercises, an iterative approach will be the key to make the general system conceptual model more robust, with an increasingly accurate repository of main SES elements.

This structured conceptual modelling process may be better suited to make the transition to the steps of stock and flow diagrams and quantitative modelling more transparent and robust. Ideally, such a structured conceptual model could not only provide a basis for the application of System Dynamics modelling but represent a potential starting point for the application of several modelling approaches such as Bayesian Belief Networks, agent-based modelling, and GIS-based modelling.

Bibliography

Argent, R. M., Sojda, R. S., Guipponi, C., McIntosh, B., Voinov, A. A., & Maier, H. R. (2016). Best practices for conceptual modelling in environmental planning and management. *Environmental Modelling & Software*, *80,* 113–121. https://doi.org/10.1016/J.ENVSOFT.2016.02.023

Blankespoor, B., Dasgupta, S., & Lange, G. M. (2017). Mangroves as a protection from storm surges in a changing climate. Ambio, 46(4), 478–491. https://doi.org/10.1007/S13280-016-0838-X/FIGURES/2

Catenacci, M., & Giupponi, C. (2013). Integrated assessment of sea-level rise adaptation strategies using a Bayesian decision network approach. *Environmental Modelling and Software*, *44*, 87–100. https://doi.org/10.1016/J.ENVSOFT.2012.10.010

Checkland, P. B. (1981). Systems Thinking, Systems Practice. Chichester: Wiley.

Clark, J. R. (1991). *The Status of integrated coastal zone management: a global assessment*. Coastal Area Management and Planning Network, Rosenstiel School of Marine and Atmospheric Science, University of Miami. https://doi.org/10.3/JQUERY-UI.JS

Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. S.-M. (2022). 2022: Ocean and Coastal Ecosystems and their Services. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. In Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, (p. 236). Cambridge University Press. In Press.

Currie, D. J., Smith, C., & Jagals, P. (2018). The application of system dynamics modelling to environmental health decision-making and policy - A scoping review. *BMC Public Health*, *18*(1), 1–11. https://doi.org/10.1186/S12889-018-5318-8/TABLES/5

Dasgupta, S., Islam, M. S., Huq, M., Khan, Z. H., & Hasib, M. R. (2019). Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. PLOS ONE, 14(3), e0214079. https://doi.org/10.1371/JOURNAL.PONE.0214079

Elliott, M., Burdon, D., Atkins, J. P., Borja, A., Cormier, R., de Jonge, V. N., & Turner, R. K. (2017). "And DPSIR begat DAPSI(W)R(M)!" - A unifying framework for marine environmental management. *Marine Pollution Bulletin*, *118*(1–2), 27–40. https://doi.org/10.1016/J.MARPOLBUL.2017.03.049

Farr, W. W., Allen, S. D., Tomoaia-Cotisel, A., & Hovmand, P. S. (2022). Documenting the modeling process with a standardized data structure described and implemented in DynamicVu. *System Dynamics Review*, *38*(3), 264–291. https://doi.org/10.1002/SDR.1716

Giupponi, C. (2022). *Venezia e i cambiamenti climatici - Quale futuro per la città e la sua laguna?* Rizzoli.

Giupponi, C., & Sgobbi, A. (2013). Decision Support Systems for Water Resources Management in Developing Countries: Learning from Experiences in Africa. *Water 2013, Vol. 5, Pages 798-818*, *5*(2), 798–818. https://doi.org/10.3390/W5020798

Hossain, M. S., & Szabo, S. (2017). Understanding the social-ecological system of wetlands. *Wetland Science: Perspectives From South Asia*, 285–300. https://doi.org/10.1007/978-81-322-3715-0_15

Hossain, M. S., Ramirez, J., Szabo, S., Eigenbrod, F., Johnson, F. A., Speranza, C. I., & Dearing, J. A. (2020). Participatory modelling for conceptualizing social-ecological system dynamics in the Bangladesh delta. *Regional Environmental Change*, *20*(1), 1–14. https://doi.org/10.1007/S10113-020-01599-5/TABLES/3

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Judd, A., & Lonsdale, J. A. (2021). Applying systems thinking: The Ecosystem Approach and Natural Capital Approach – Convergent or divergent concepts in marine management? *Marine Policy*, *129*, 104517. https://doi.org/10.1016/J.MARPOL.2021.104517

Keen, S. (2020). The appallingly bad neoclassical economics of climate change. *Https://Doi.Org/10.1080/14747731.2020.1807856*, *18*(7), 1149–1177. https://doi.org/10.1080/14747731.2020.1807856

Lane, D. C. (1995). *The folding star: a comparative reframing and extension of validity concepts in system dynamics* (T. Shimada & K. Saeed, Eds.). Gakushuin University. https://proceedings.systemdynamics.org/1995/proceed/papersvol1/laned111.pdf

Lane, D. C. (2006). It works in practice but does it work in theory? Comment on the paper by Vriens and Achterbergh. *Systems Research and Behavioral Science*, *23*(4), 565–571. https://go.gale.com/ps/i.do?p=AONE&sw=w&issn=10927026&v=2.1&it=r&id=GALE%7CA153911543&sid=googleScholar&linkaccess=fulltext

Martínez-Hernández, A. G. (2022). System Dynamics Modelling and Climate Change Adaptation in Coastal Areas: A Literature Review. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.4184371

Maslow, A. H. (1943). A theory of human motivation. *Psychological Review*, *50*(4), 370–396. https://doi.org/10.1037/H0054346

Maslow, A. H. (1981). *Motivation and personality* (Second). Harper and Row.

Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. CifuentesJara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321-445. https://doi.org/10.1017/9781009157964.006.

Saeed, K. (1992). Slicing a complex problem for system dynamics modeling. *System Dynamics Review*, *8*(3), 251–261. https://doi.org/10.1002/SDR.4260080305

Sterman, J. D. (2000). *Business Dynamics, System Thinking and Modeling for a Complex World*. Jeffrey J. Shelsfud.

Thia-Eng, C. (1993). Essential elements of integrated coastal zone management. *Ocean & Coastal Management*, *21*(1–3), 81–108. https://doi.org/10.1016/0964-5691(93)90021-P

Voinov, A. (2008). *Systems Science and Modeling for Ecological Economics*. Elsevier.

APPENDIX

Macro-categories of concepts under SES framework

Legend (D): Drivers (A): Activities (P): Pressures (S): State (I): Impacts (R): Responses Macro-categories of concepts are in *italic*

- **Adaptation policies & measures (SES Module) (COLOR)**

  - Protection (R/Measure)

  - Retreat (R/Measure)

  - Accommodation (R/Measure)

- **Socio-economic drivers (SES Module) (COLOR)**

- ***Governance and political drivers***, i.e., all the forces related to national and international institutional settings and relationships (which could be able to exert a certain influence on activities)

  - Governance (D) (R)

  - Geopolitical stability (D)

- ***Anthropogenic environmental pressures***, i.e., pressures on the environment directly related from human activities

  - Introduction of alien species (from shipping etc.) (P)
  - Anthropogenic land/soil events (P)

  - Anthropogenic water properties changes (P)

  - Pollution (e.g., microplastic, chemicals from industry discharge and water/soil pollution in general etc.) (P)

- ***Human-expansion pressures***, i.e., involves those pressures that arise from the population growth and expansion

  - Land reclamation (A)

- Urbanization (P)

- ***Societal well-being*** (i.e., state in which basic human needs are met and people are able to coexist peacefully in communities with opportunities for advancement[5]) and societal resilience (i.e., the capacity of people and communities to deal with external stresses and shocks[6]) (D)

  - Need of socio-ecosystem services (from industries, people etc.)

- ***Exploitation of natural resources***, i.e., the use of natural resources to sustain the social and material needs of a given community as well as to foster economic growth (P)

- ***Economic features***, i.e., intrinsic and exogenous characteristics of the economic system analyzed, which at the end determines the form of the economic activity. The boundaries and specificity of this concept change widely according to the scale and granularity of the model: from the characterization of the economic behavior and needs of the single individual to macroeconomic settings such as unemployment and inflation, for instance (when those are assumed exogenous in the targeted conceptual model) (D) (I)

  - Need of socio-ecosystem services (from industries, people etc.)

- **Environmental drivers (SES Module) (COLOR)**

- ***Environmental drivers***, i.e., changes in the baseline natural conditions which are in turn able to modify the current state of the entire socio-ecosystem. Those alterations can have or not an anthropogenic origin and are assumed to be generally disruptive. The variables associate with this concept, as in the case of economic features, are assumed to be exogenous: hence, their conceptual boundaries could vary according to the scale and granularity of the model
  - Ocean Extreme Events (D)
  - Extreme Climate hazards (D)
  - SLR (D)
  - Gradual Climate hazard (D)
  - Introduction of alien species (D)
  - Natural land/soil events (D)
  - Natural water properties changes (D)

[5] Retrieved from: https://www.usip.org/sites/default/files/GP_170-203_Social_Well-Being.pdf. The importance of this concept comes back frequently in IPCC reports.
[6] From Kwok et al., 2016 (https://doi.org/10.1016/j.ijdrr.2016.08.013).

Socio-ecosystem (Providers/physical system)

- **Natural capital (SES Module) (COLOR)**

- ***Natural capital***, i.e., the inanimate assets in the environment/natural systems, namely the natural physical elements (terrestrial and aquatic) of the system being considered
  - Coastal environments (S)
  - Marine environments (S)
  - Inland environments (S)
  - Interface environments (S)
  - Natural resources (S)

- **Human capital (SES Module) (COLOR)**

- ***Infrastructures***, i.e., constructed capital (human-made physical elements) consisting of manufactured goods, such as roads, power plants (including machinery), real estate, cultural heritage houses (e.g., churches), dams, etc.[7]
  - Cultural heritage (S)
  - Transportation infrastructures (S)
  - Power infrastructures (S)
  - Protection infrastructures (S)
  - Residential infrastructures (S)
  - Economic infrastructures (S)
  - Water infrastructures (S)

- ***LULC***, i.e., composition and physical characteristics (e.g., impermeable surfaces) or human-related activities (e.g. residential, commercial, transport) of landscape features on the earth's surface[8]
  - Land Use (S)
  - Land cover (S)

Socio-ecosystem (Beneficiaries/living system)

- **Human populations (SES Module) (COLOR)**

- ***Human populations***, i.e., the set(s) of individuals which could be thought as human actors of the system. They are assumed to interact with each other and with the other components of the system in order to generate goods and services through economic activities. On top of

[7] Giupponi, C. (2022). Venezia e i cambiamenti climatici - Quale futuro per la città e la sua laguna? Rizzoli; Jones et al., 2016 (https://doi.org/10.1016/j.landusepol.2015.12.014).
[8] Adapted from Cai et al., 2019 (https://doi.org/10.3390/s19143120) and Cihlar, 2000 (https://doi.org/10.1080/014311600210092).

that, they could be categorized under different classes and according to different features, depending on the modelling exercise. As a consequence, their behavior as individuals, but also the macro-scale dynamics related to the different population groups (i.e. demographics, etc.) is both affected to and affects the system[9]

- Ethnic groups (S) (D)
- Stable population (S) (D)
- Unstable population (S) (D)
- Vulnerable groups (socially and/or economically) (S) (D)

- ***Demographics***, i.e., the different categorizations of human populations and the information collected about them such as their size, growth, ages, and education[10] (P) (D)

- **Other populations (plants & animals) (SES Module) (COLOR)**

- ***Other populations***, i.e., natural biological populations[11]
  - Coastal populations (fish etc.) (S)
  - Coastal vegetation (coastal grassland, coastal forest, mangroves etc.) (S)
  - Marine populations (S)
  - Inland populations (S)
  - Inland vegetation (S)
  - Interface populations (S)

▪ **Economic system (SES Module) (COLOR)**

- ***Economic structure***, i.e., main sectorial activities, which includes primary, secondary and tertiary activities
  - Real estate sector (A)
  - Energy sector (A)
  - Port activities (A)
  - Manufacture (A)
  - Public sector (A)
  - Logistics (A)
  - Agriculture (A)
  - Tourism (A)
  - Aquaculture (A)

[9] This is the reason behind classifying this concept both under state and drivers.
[10] From https://dictionary.cambridge.org/dictionary/english/demographic.
[11] Giupponi, C. (2022). Venezia e i cambiamenti climatici - Quale futuro per la città e la sua laguna? Rizzoli.

- Fishing (A)

- **Ecosystem (SES Module) (COLOR)**

- ***Ecosystem***, i.e., biological structures and processes and ecological functions that arise from interactions/relationships between natural populations (other populations) and natural capital[12]
  - Biological structure and processes (ex.: primary production) (S)
  - Ecological functions (particles storage) (S)

- **Services and disservices (SES Module) (COLOR)**

- ***Socio-ecosystem services and disservices***, i.e., services that emerge from positive (or negative) interactions between ecosystems and society, benefiting (or negatively affecting) both and the entire socio-economic and ecological system. The concept of socio-ecosystem services, unlike the classical definition of ecosystem services, recognizes the role of human beings in determining in a positive sense, but also in a negative sense (disservices), the evolution of the planet, including its physical and biological components[12]

  - Socio-ecosystem disservices **(I)**

  - Provisioning services **(I)**

  - Regulation and maintenance services **(I)**

  - Cultural services **(I)**

  - Human interventions **(I)**

- **Emergent properties (SES Module)**

- Maladaptation

- Coastal habitats squeeze

[12] Giupponi, C. (2022). Venezia e i cambiamenti climatici - Quale futuro per la città e la sua laguna? Rizzoli.

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Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02 403 36934

E-mail: letter@feem.it
www.feem.it

Fondazione Eni Enrico Mattei