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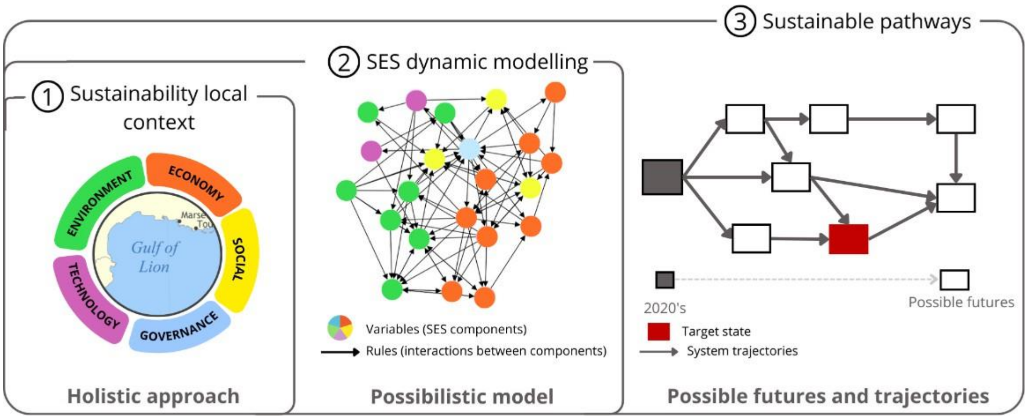
Pathways toward sustainability in Mediterranean marine social-ecological systems: the Gulf of Lion as a case study

Par : Miléna FERRET



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GLOSSARY & ABBREVIATIONS LIST

Abbreviations:
CFP: Common Fisheries Policy
CTL: Computation Tree Logic
EDEN: Ecological Discrete-Event Network
GFCM: General Fisheries Comission for the Mediterrranean
GoL: Gulf of Lion
MEY: Maximum Economic Yield
MSY: Maximum Sustainable Yield
SCC: Strongly Connected Component
SES: Social-ecological system(s)
SSF: Small-scale coastal fisheries
STG: State Transition Graph

EDEN glossary:
State: Set of variables with associated values (+, - or undefined *)

Transition: State change induced by a rule execution. Therefore, it is a change in one or more variables values

Rule: modelled process or action of the social-ecological system. A relationship stating that if a certain condition is met, then some state variable values must change (represents process in the social-ecological system)

Trajectory: Sequence of one or more transitions (succession state-transition-state), correspond to pathways to reach a state of interest in the dynamic

State-Transition Graph: a graph where nodes represent states and edges represent transitions. Starting from a set of initial states, the firing of actions defines the set of reachable states

Interaction network or graph: a graph representing the interconnexions between variables

SCC: Strongly Connected Components are sets of states that are mutually reachable

Hull: a set of SCCs, states, and the transitions connecting them

CTL: Computation Tree Logic is a temporal logic used to express temporal properties of a system's dynamics

Property: a set of logical operations qualifying either:
- a state of the system (*topological or state property*),
- or the system's dynamics (*dynamical property, expressed using CTL*)

1. INTRODUCTION

In the context of global change, intensifying anthropogenic pressures on marine ecosystems threaten both natural systems and the human activities that rely on them (Halpern et al., 2015; Díaz et al., 2019). Addressing these challenges requires for transformative changes in societies and, more broadly, in marine social-ecological systems (SES) to move towards sustainability (Juri et al., 2025; O'Brien et al., 2025). SES are complex, adaptive, and coevolutionary systems in which social and ecological components are deeply interdependent, interacting across multiple spatial and temporal scales (Ostrom, 2009). This integrative perspective recognizes humans as intrinsic parts of nature, emphasizing the continuous interplay between natural ecosystems and societal dynamics (Berkes and Folke, 1998) In marine fisheries SES, people both shape and are shaped by marine ecosystem processes (e.g., fishing activities), necessitating careful consideration of the synergies and trade-offs between ecological integrity and societal well-being to achieve sustainability (Chapin et al., 2010; Hilborn et al., 2015).

Yet, defining and operationalizing sustainability in marine fishery SES remains a major challenge. As a socially constructed concept, sustainability is inherently multidimensional, context-dependent, and contested, with divergent interpretations among stakeholders (Boström, 2012; Hilborn et al., 2015; Stephenson et al., 2018). Sustainability science seeks to integrate diverse disciplines, methods, and epistemologies, but this ambition is hampered by the lack of coherent social–ecological framing (Wisz et al., 2020) and epistemological divides in how knowledge is valued and produced (Phillipson and Symes, 2013; Lee et al., 2019; Moon et al., 2021). The complex and dynamic interactions between the multiple social, economic and ecological components of SES further complicates the integrated understanding and practical application of sustainability in fisheries management (Mikkelsen et al., 2023). Achieving sustainability in fisheries SES requires accounting for their multidimensional character. Sustainability can be understood as a set of principles ensuring the responsible use of marine resources while minimizing environmental impacts and supporting the long-term well-being of coastal communities (Grati et al., 2025). This demands a comprehensive perspectives that incorporates ecological, economic, socio-cultural, governance, and technological dimensions (Singh et al., 2018; Stephenson et al., 2018; Nash et al., 2020) to capture interdependencies and identify viable sustainability pathways (Boström, 2012; Dahl, 2012; Garcia et al., 2014). Despite broad recognition of this need, most studies have addressed sustainability through a narrower lens.

Historically, fisheries management has been framed through ecological sustainability, focusing on single-species approaches and the reach of Maximum Sustainable Yields (MSY). Although central to international policies, the MSY concept has been criticized for its static foundations, estimation challenges, inability to prevent recruitment failure and limited capacity to account for the ecological, economic, and social complexities of fisheries (Martell and Froese, 2013; Tsikliras and Froese, 2019). Recent effort have extended MSY to multispecies contexts (MMSY) (Worm et al., 2009; Kolding et al., 2016) and promoted ecosystem-based approaches that incorporate interactions among species, habitats and human activities (Collie et al., 2016; Kroetz et al., 2019). These approaches aim to sustain the health, productivity and resilience of entire marine systems (Grati et al., 2025). However, despite significant progress on ecological and environmental aspects, the human dimension remains insufficiently addressed (Hornborg et al., 2019). When considered, it is often reduced to economic indicators, such as maximum economic yield (MEY) (Bennett et al., 2021b; Thébaud et al., 2023). While the MEY aims to provide a more holistic perspective by balancing lower effort with higher biomass compared to MSY to maximize the economic profit, it still has limitations and does not fully address the broader human dimension of sustainability (Grafton et al., 2007). Broader social aspects of sustainability, such as equity, well-being, or labor conditions, remain rarely addressed (Veldhuizen, 2017; Bennett et al., 2021a) and the joint consideration of the three pillar of sustainable development (environmental, economic, and social dimensions) has been even more limited in fisheries research and management (Garlock et al., 2022).

To overcome these limitations, multidimensional approaches have been developed, combining quantitative and qualitative methods (Lindkvist et al., 2022). Quantitative approaches, such as Bayesian networks, Structural Equation Models or network analysis help capture the complex interactions and feedbacks linking ecological, social, and institutional components (Parsons et al., 2021). These approaches allow researchers to quantify relationships, explore system responses, reveal patterns of governance and collaboration, and simulate long-term scenarios to investigate potential sustainability pathways (Kroetz et al., 2019; Alexander et al., 2020; Nomura et al., 2022). While powerful, quantitative approaches often fall short of capturing the complexity and nuanced dynamics of SES because they often require extensive data, may oversimplify human behavior, and struggle to fully capture the context-specific (Fulton et al., 2011; Yates et al., 2018; Elsawah et al., 2020).

Given these limitations, qualitative modelling offers a promising alternative. By incorporating multiple non-linear feedbacks, direct and indirect drivers, interconnections among system components, and both scientific and local knowledge, qualitative models enable a more holistic understanding of complex systems (van Vliet et al., 2010; Schwermer et al., 2021; Szymkowiak and Rhodes-Reese, 2021). These models are well-suited to data-poor contexts and to capturing cultural, social, and economic dimensions of SES (Dambacher et al., 2003). They do not aim for exhaustiveness but rather focuses on representing the key structural relationships in a SES. The inherent simplification in qualitative modelling also facilitates dialogue among stakeholders (e.g., researchers, fishers or decision-makers), enabling their meaningful involvement in the modelling process (Chevallier et al., 2025). Applications of qualitative modelling approaches to marine SES are increasing and have been applied to explore how system components respond to perturbations (e.g. livelihood maintenance in a fishing community (Barber et al., 2015)) or for aquaculture development (Gourguet et al., 2021), or to management changes (Harvey et al., 2016; Mancini et al., 2016; Thermes et al., 2024). These approaches provide valuable insights into how interactions shape system feedbacks and drive complex dynamics, but they primarily focus on system responses to external shocks, overlooking a more comprehensive representation of the full range of possible system states and trajectories.

Among qualitative models, the Ecological-Discrete Event Network (EDEN) framework (Gaucherel and Pommereau, 2019) is particularly relevant for studying the full spectrum of sustainability in marine fisheries SES. EDEN allows for integrated modelling of ecological and human-related variables within a single whole-system model. It relies on a qualitative, rule-based, discrete-event formalism to explore all possible system trajectories through possibilistic transitions, thereby identifying all potential states resulting from successive rule applications (Gaucherel et al., 2021). Its possibilistic, not probabilistic or deterministic, nature makes EDEN particularly well suited for holistic exploration of long-term SES dynamics and for assessing the reachability of sustainable states (Gaucherel and Pommereau, 2019). While still emerging, this approach has only applied in terrestrial SES to assess the multifunctionnality of a mountain SES (Mao et al., 2021) or to identify recovery trajectories of volcanic region after eruption (Cosme et al., 2023) or investigate sustainable pathways of agricultural systems (Cosme et al., 2024; De Lapparent et al., 2025).

The present study develops the first application of this modelling framework to a marine fishing SES, and addressed a central question: is it possible to achieve sustainability across ecological, economic, and social dimensions within such marine fisheries SES? If so, what trajectories can lead to sustainability? If not, what trade-offs and compromises must be considered? To investigate these aspects we applied the EDEN framework to the Gulf of Lion (GoL) in the northwestern Mediterranean Sea. The GoL is a biodiversity hotspot and highly productive marine system where fishing activities play a central socio-economic role but face chronic overexploitation (FAO, 2024), environmental pressures, climate change (Panzeri et al., 2024a) and competing maritime uses (Depellegrin et al., 2019). It exemplifies a complex social-ecological system facing ecological, economic, and governance challenges, with a growing regional consensus on the need to transition toward long-term sustainability, in line with the UN 2030 Agenda for Sustainable Development (United Nations, 2015), the GFCM (General Fisheries Comission for the Mediterrranean) 2030 Strategy (FAO, 2021), and the French National Strategy for the Sea (Ministère de la Transition écologique, 2024), making it an archetypal case study for exploring sustainability pathways.
Our objectives are threefold: (i) to characterize the GoL SES across multiple sustainability dimensions and their interlinkages; (ii) to define a target state of sustainability that minimizes environmental impacts while maximizing societal well-being and nature’s contributions; and (iii) to explore the reachability, persistence of this target and the trajectories that may lead toward or away from it.

2. MATERIAL AND METHODS

The following sections present the study framework (Figure 1) the context and complexity of the Gulf of Lion (GoL) marine Social-Ecological System (SES), the Ecological-Discrete Event Network (EDEN) modelling approach and its application to the GoL, and the methodology used to assess sustainability trajectories.

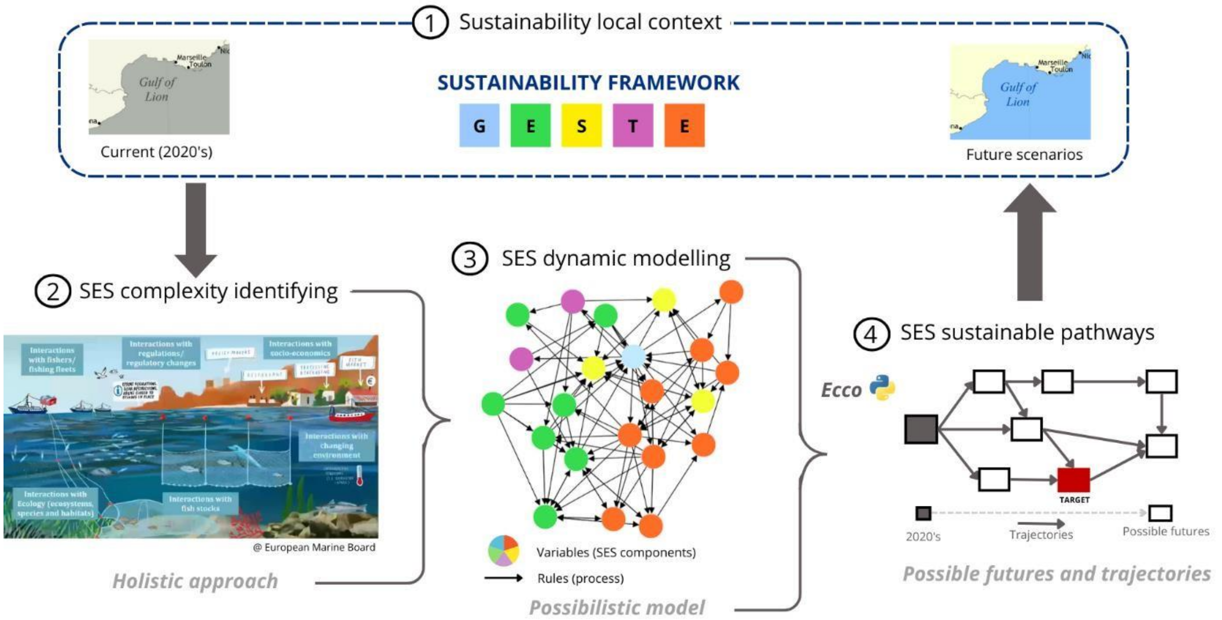

Figure 1: General framework for studying sustainability trajectories in the marine social-ecological system of the Gulf of Lion in the Mediterranean Sea.

2.1 Case study: the marine social-ecological system of the Gulf of Lion

The Mediterranean Sea, covering less than 1% of the global ocean surface yet hosting about 10% of its marine biodiversity (ca. 17,000 species), is recognized as a hotspot of biodiversity and endemism (Coll et al., 2010). At its northwestern limit, the Gulf of Lion (GoL) hosts diverse habitats (e.g., *Posidonia oceanica* seagrass meadows) supporting rich benthic communities and several endemic or at-risk species, including seabirds, marine turtles, mammals, and elasmobranchs (Coll et al., 2012; Gili et al., 2013). Its high productivity, fuelled by annual coastal upwelling and nutrient inputs from the Rhône River, provides essential nurseries and spawning grounds for commercially important species (Raimbault and Durrieu de Madron, 2003; Giannoulaki et al., 2013). This makes the GoL a key area of the blue economy, fisheries play a central role (Plan Bleu, 2023).

Fisheries in the GoL are multi-gear (bottom and pelagic trawls, purse seines, gillnets and longlines) and multispecies (European hake, red mullet, anchovy, sardine, etc) (Ifremer, 2024b). Since the mid-1950s, Gulf of Lion fishing fleets have evolved from small traditional vessels operating in coastal areas to more technically developed boats fishing further offshore. However, since the early 2000s, the number of both French trawlers and small-scale fishing vessels has declined (Farrugio, 2013). French fishers are predominant in the GoL (87% of total catch volume (GFCM, 2025)), and the fishing fleet is subdivided into two main segments: the small-scale coastal fisheries and the “offshore” fisheries. Small-scale coastal fisheries make up most of the fleet (ca. 900 vessels, 79%, see Appendix S1), operating within three nautical miles using vessels under 12m with diverse fishing gears, despite their size, they account for a large share of landings (ca. 32 960 tons, 45.5% of total weight). The offshore fleet is dominated by demersal trawlers (40 vessels, 5%), which represent a little part of the fleet but contribute for 48% of landings (34 900 tons), alongside others fleet types such as tuna seiners (Prellezo et al., 2024; Zanzi et al., 2025). Fisheries are managed under the European Union (EU) Common Fisheries Policy (CFP) and may be organized in two types of bodies: Producer Organizations (POs), which promote CFP compliance and economic management, and “Prud’homies”, traditional local bodies that emphasize territorial resource management and community organization.

Although fisheries remain a socially, economically, and culturally significant activity shaping Mediterranean coastal dynamics (FAO, 2023), they face persistent challenges to ensure the long-term well-being of coastal communities.

Commercial stocks are chronically overexploited, with many assessed demersal stocks fully or overexploited (FAO, 2024). Despite some improvements, the Mediterranean Sea remains the FAO fishing area with the highest percentage (58%) of stocks fished at unsustainable levels (FAO, 2023). Several demersal stocks continue to experience very high fishing mortality rates, such as European hake, which is fished at rates up to 3.27 times higher than MSY in the western Mediterranean Sea (Mannini et al., 2025). These high exploitation levels, combined with insufficient gear selectivity (Lucchetti et al., 2021), cause cascading impacts on marine food webs (Colloca et al., 2017) and benthic habitats (Bastari et al., 2022; De la Torriente Diez et al., 2022), thereby limiting ecological recovery. The overall deteriorated state of marine resources contributes to declining trend in commercial catches (FAO, 2023) and weak economic performance (Colloca et al., 2013; Erauskin-Extramiana et al., 2024). This is reflected both in the dependency of certain fleets, particularly bottom trawlers, on subsidies to offset high production costs such as fuel costs (Cheilari et al., 2013; Guillen and Maynou, 2016), and in the limited intergenerational renewal of the sector, as the profession is characterized by an aging workforce and remains unattractive to new entrants due to difficult working conditions (Carif-Oref Occitanie, 2023). Beyond fisheries, additional human activities such as maritime transport, coastal activities, and increasing coastal urbanization exert further pressures on marine environments through pollution and habitat degradation (Coll et al., 2012; Katsanevakis et al., 2015). These pressures are exacerbated by climate change, to which the Mediterranean Sea is particularly vulnerable due to its semi-enclosed nature (MedECC, 2020; IPCC, 2022). Climate-driven changes, including seawater warming, deoxygenation, altered plankton productivity and biological invasions) are expected to reshape marine communities and population dynamics (Moullec et al., 2016, 2019; Panzeri et al., 2024), with significant effects for fisheries-dependent economies and coastal societies (Hilmi et al., 2021; Hidalgo et al., 2022; Farahmand et al., 2023).

The GoL is at the center of future maritime spatial planning challenges, including offshore wind farm development, the expansion of marine protected areas, and potential reductions in bottom trawl fishing opportunities under the ongoing WestMed Plan. The WestMed Plan for instance, aimed at ensuring the conservation and sustainable exploitation of demersal stocks in the Western Mediterranean, with the objective of reaching maximum sustainable yield (MSY) by 2025 through progressive effort reductions and spatial-temporal closures (European Parliament, 2019).

These overlapping uses intensify conflicts, particularly around the removal of trawling gear. In parallel, the energy transition poses both challenges and opportunities for fisheries, with efforts focusing on decarbonization through fleet modernization and new technologies such as onboard AI systems and energy-efficient engines (electric, hybrid, or hydrogen) (France Filière Pêche, 2025).

2.2 Ecological-Discrete Event Network modelling framework

We applied the Ecological Discrete-Event Network (EDEN) modelling framework (Gaucherel and Pommereau, 2019) to build an exploratory model of the Gulf of Lion social-ecological system and to project its potential future pathways toward sustainability.

The EDEN framework is a qualitative modelling approach designed to explore the possible dynamics of SES. It is rooted in techniques from computer science, such as symbolic state spaces and model-checking from Petri nets (Cosme, 2022; Pommereau et al., 2022). The approach relies on a discrete-event formalism, where system evolution is described by events occurring at irregular intervals, i.e., system transitions take place discontinuously (Cassandras and Lafortune, 2009).
Unlike quantitative models, EDEN does not require quantitative parameters. Instead, SES entities are represented by Boolean variables, which take only two values: "+" (functionally present/active) or "−" (functionally absent/inactive). Each variable is associated with a threshold, above which it becomes active and able to influence other variables. For instance, for a variable *Biomass (B)*, if biomass exceeds its reference threshold (e.g., *B* > *Bmsy*), the variable is considered active (*B+*); below this threshold, it is inactive (*B-*). Threshold definitions are context-specific, ensuring that variables realistically capture system functioning and align the research objectives. The complete set of variable values at a given time defines a system state (Cosme et al., 2024). System dynamics emerge from a set of "i*f–then"* rules, which formalize ecological processes, human decisions and socio-economic interactions. The reaction rules modelling language (rr) lies at the core of EDEN (Pommereau et al., 2022). Rules specify both the condition under which an event can occur (e.g., "if biomass level is sufficient") and the realization of its consequences (e.g., "then catch becomes possible"). In other words, rules provide the semantics that make variables shift from "+" to "−" or vice versa. For instance, the rule *Biomass+ (B+) ⇒ Catch+ (Y+)* states that if biomass is above its functional threshold, high fishing yields (i.e., above its corresponding threshold) can occur (illustrated in the toy model in Figure 2). When a system state satisfies the condition of a rule, the rule is executed, generating a new state (i.e., a new configuration of variables values). This switch from one state to another is called a transition. Rules are executed asynchronously, one at a time. If multiple rules are applicable in a given state, each is executed independently, leading to alternative pathways that explore every possible sequence of events. This makes the model non-deterministic and possibilistic, as it exhaustively explores all potential sequences of events without assigning probabilities or timing (Gaucherel et al., 2020). Although state transitions occur chronologically, the model is untimed: events are not associated with specific durations or temporal horizons, but are only assumed to occur at some point in the future. Thus, an EDEN model is both exact and analytical: for a given set of variables and rules, it consistently produces an identical and exhaustive outcome.
The main output if the model is a State-Transition Graph (STG), in which nodes represent system states and edges represent transitions between them (Figure 2c). The STG provides a comprehensive representation of the system dynamics, including all possible trajectories. By mapping all these possible states and transitions, EDEN allows for the systematic investigation of long-term system behaviors and potential pathways toward target states.

As an illustration, Figure 2 presents a simplified example of a marine resource exploitation system, highlighting how EDEN formalizes system components and dynamics.

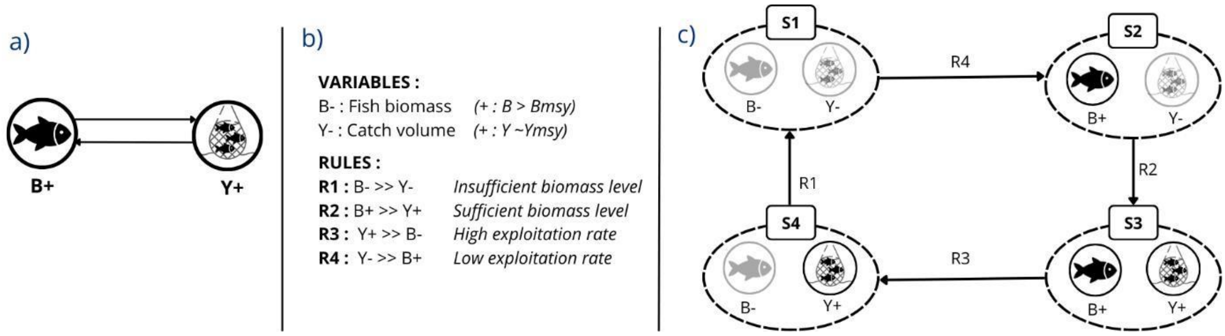

Figure 2: Illustration of a simplified marine resource exploitation system with its (a) interaction graph, representing variables interconnexion (b) its associated rule-based model made of two variables (B,Y) and four rules, and (c) its resulting state space (equivalent of the STG) with nodes representing states (S1 to S4) and edges representing transitions through actions firing. Note that starting from the initial state (S1) it is possible to compute all system state and rule executions.

Starting from state S1 (*B-*, *Y-*), the set of rules is evaluated sequentially. Rule R1 is applicable because its condition *B-* is satisfied; however, as variable *Y* is already inactive (*Y-*), applying this rule does not generate a new state, and the system remains in S1. Rules R2 and R3 cannot be applied because their conditions are not met. Rule R4 is then considered: here, the condition *Y-* is satisfied, and its application allows biomass to be restored under low exploitation pressure, leading to a new state S2 (*B+*, *Y-*).

2.3 Model description: the GoL-EDEN model

The GoL-EDEN model is defined as a network of 22 states variables representing its key social-ecological components and 76 rules representing the main interactions among them (Tables S3.1 and S4). This configuration was chosen to balance computational feasibility with ecological and social realism. The spatial and temporal scales of the model were determined by the research questions. The model's temporal resolution is approximately a decade, corresponding to the minimum duration of the most rapid transitions required for variables to stabilise around equilibrium values (i.e., consistent with the equilibrium-based concepts of MSY and MEY). The temporal horizon of the analysis extend to 2050-2060, a consistent upper bound that aligns with most international and national sustainability targets set for 2050. Consequently, social-ecological processes occurring at intra-annual or annual time scales were not considered. Regarding the spatial scale, we considered a single spatial unit, the Gulf of Lion. The study area extends from Cap Creus to the tip of Marseille. All ecological and socio-economic processes operate at this spatial scale. The model is therefore spatially implicit.

2.3.1 State variables

The selection of variables followed a multi-step process combining a literature review with sustainability frameworks. An extensive bibliographic survey was first conducted to gather knowledge on GoL fisheries and their social-ecological dynamics, including current and future challenges. In parallel, the first outcomes of the ADAPT[1] participatory workshops, which brought together fishery stakeholders (e.g., fishers, scientists, decision-makers, managers and environmental NGOs) to co-construct representations of the GoL social-ecological system, provided additional contextual insights. These two sources of information enabled the identification of an initial set of relevant social-ecological components (i.e., state variables) and their interactions. A participatory workshop with a group of fisheries scientists and ecosystem modelers (MARBEC, May 2025) subsequently refined and prioritized the components considered most relevant for the GoL context.

The variables were then organized into the five “GESTE” dimensions (Governance, Economic, Social, Technology, and Environmental), enabling a holistic assessment of sustainability in social-ecological systems and inspired by Aguilar’s (1967) PESTEL[2] approach. Except for the climate change variable (Cc) wich represent an external driver, each variable was then associated with sustainability criteria (Table S3.1), either identified in the scientific literature (Stephenson et al., 2018; Gascuel and Dewals, 2020; Quemper et al., 2025) or derived from European policy frameworks, notably the Marine Strategy Framework Directive (MSFD, 2008/56/EC), which aims to achieve “Good Environmental Status” (GES) in all EU marine waters by defining 11 descriptors, each composed of several indicators, for an integrated assessment of ecosystem status. Overall, the sustainability criteria considered in the model are consistent with the objectives of the French National Strategy for the Marine Environment (Ministère de la Transition écologique, 2024), aligned with the UN Sustainable Development Goals (United Nations, 2015) and the GFCM 2030 Strategy (FAO, 2021).

The 22 resulting variables were associated with an acronym, a definition, a quantitative threshold, and an initial state representing the current situation of the GoL SES (see Table S3.2 for details and justifications). The environmental dimension is represented by six state variables, including the physical environment (coastal (*Hco*) and offshore benthic habitats (*Hof*)), bentho-demersal exploited resources (spawning stock biomass (*Ssb*), recruitment (*Rec*)) and sensitive species (*Yss*), and the ecosystem impacts of fishing (mean maximum length in community *Lmx* (Shin et al., 2005)). The GoL-EDEN model focuses on bentho-demersal resources, which are the main target of both small-scale and bottom-trawlers fisheries (Ifremer, 2024b, 2024a), Appendix S1). Due to data limitations for the entire GoL, *Lmx* was also restricted to the bentho-demersal community (Bitetto et al., 2019).

The economic dimension included nine state variables to capture fishing activities and their viability, adopting a fleet-based approach centered on bottom trawlers (*bt*) and small-scale fisheries (*sf*), the two dominant fleets in the GoL. This approach reflects their distinct dynamics and spatial use of marine areas. Spatialization was introduced implicitly by dividing the habitat variable into coastal and offshore zones, assuming that small-scale fisheries operate within 3 nautical miles and bottom trawlers beyond this limit. Considering sustainability transitions, our framework allows exploration of scenarios where

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[1] ADAPT is a France Filière Pêche project aiming to develop scenarios and adaptation strategies for sustainable fisheries in the face of global change in the Mediterranean Sea and the Eastern English Channel/North Sea.

[2] PESTEL is a strategic analysis framework that provides a mnemonic guideline to describe an organization’s external environment through six dimensions: Political, Economic, Socio-cultural, Technological, Environmental, and Legal

trawling effort decreases in favour of small-scale fisheries. Fishing effort (*Ebt*, *Esf*) and catch (*Ybt*, *Ysf*) state variables describe fishing fleet activities, while their economic viability is reflected by profit (*Pbt*, *Psf*), profitability (*BtP*, *SfP*), and subsidies (*Sub*), which capture fleets' dependency on financial support. Effort variables approximate fishing mortality by nominal fishing effort, expressed as vessel-fishing days. While this is a strong assumption given the variability of the fishing mortality-fishing effort relationship across gears, species and stocks (Certain et al., 2022), it simplifies the model and reflects the effort-based management approach prevailing in the Mediterranean Sea.

The social dimension included three state variables at the fisher's scale: working conditions (*Wor*) representing worker well-being, sector attractiveness (*Ima*) captured through young fishers' perception of the profession and employment (*Emp*), representing engaged crews.

Technological and regulatory aspects were integrated via three state variables: selectivity (*Sel*) representing technical measures such as trawl mesh size, a major weakness in GoL bottom trawl fisheries (Lucchetti et al., 2020, 2021; Quemper et al., 2025); technological innovations on vessels are represented by the smart devices variable (*Dev*), which includes both advanced technologies (e.g., artificial intelligence, hybrid engines) and devices that can reduce sensitive species incidental catch; and Common Fisheries Policy (*CFP*), the governance variable that captures potential effects of effectives CFP implementation, including MSY-based stock management, ecosystem-based approaches and stakeholder engagement.

Each variable is defined by a threshold reflecting the study objectives of assessing the reachability of an "ideal" sustainable state for the GoL SES. Although some thresholds may appear ambitious, they are grounded in scientific literature, participatory workshop outcomes or existing fisheries management reference points (Appendix S3, Table S3.2). Both MSY and MEY were included as thresholds in the model. Including both reference points allows combining a management approach already implemented in the Mediterranean Sea (MSY, aimed at maximizing yields at stock level) with a more integrative economic approach (MEY), which maximizes expected economic profits while requiring lower yields and effort than MSY (MEY ≈ 80–90% of MSY; Munro and Scott, 1985). In adapting these reference points to the EDEN formalism, which only distinguishes two states relative to a threshold, state variables linked to MSY and MEY (i.e., *Ybt*, *Ysf*, *Pbt*, *Psf*) were defined with thresholds corresponding to ±5% of the reference point, with "−" states otherwise (Figure 3).

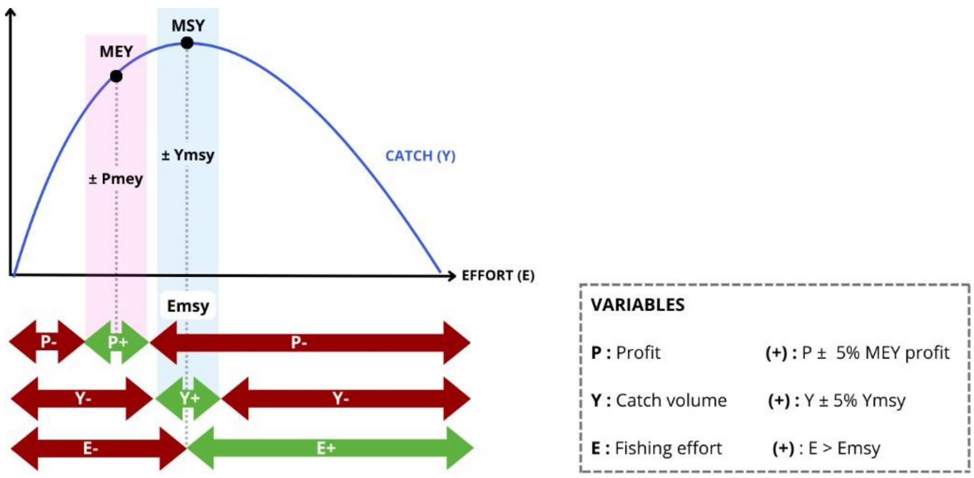


Figure 3: Schematic representation of the thresholds for the variables fishing effort (E), catch volume (Y) and profit (P)

Finally, the initial state represents the system in the early 2020s, characterized by a marine ecosystem already degraded (*Hco*-, *Hof*-, *Ssb*, *Lmx*-, *Rec+*, *Yss+*) by intense fishing activities (*Ebt+*, *Esf+*) and other anthropogenic pressures, marked by low selectivity (*Sel*-) and limited technological innovation (*Dev*-). This configuration translates into poor economic performance of the fleets, with low productivity and profits despite the persistence of capacity-enhancing subsidies (*Ybt*-, *Ysf*-, *Pbt*-, *Psf*-, *BtP*-, *SfP+*, *Sub*-). At the social level, the sector appears unattractive (*Emp*-, *Ima*-), with difficult working conditions (*Wor*-), while EU fisheries management objectives remain largely unmet (*CFP*-).

2.3.2 Rules

The GoL-EDEN model represents the social-ecological interactions of the fisheries system through 76 rules, encompassing ecological, economic, social, and governance processes (Appendix S4). Ecological rules represent habitat functionality, marine population dynamics, climate change impacts, and fishing effects on habitats, target and non-target species (e.g., incidental catch), and ecosystem structure. Bioeconomic rules capture the economics of fishing activity, including production states (under-, full-, or overexploitation) and fleet profitability. Social rules describe employment dynamics and the attractiveness of the profession, while governance and policy rules incorporate the fisheries management context, including technological innovations and their consequences for both economic performance and environmental impacts.

To represent SES processes, only direct relationships between components are translated into rules, while indirect links emerge through their sequential execution. For example, the process *"effective CFP implementation reduces fishing effort, thereby reducing pressures on habitats and resources"* can be translated into three rules: *CFP+ >> effort-; effort- >> habitats+; effort- >> resources+.* In cases where processes are multifactorial (e.g., affecting *Ssb* or *Rec*), several variables can appear jointly in the condition and are treated as acting simultaneously. Not all influential variables are included in rule conditions, particularly when their functionality (+/−) does not alter the outcome. This may occur when the defined threshold does not allow the variable to switch from one functionality to another. For instance, in rule R9 (*Ssb-, Ebt+, Esf+ >> Rec-*), recruitment collapses under overexploitation regardless of habitat quality. Athough degraded habitat could exacerbate the collapse, good habitat alone cannot reverse it. Thus, habitat is omitted from the condition despite its acknowledged ecological importance (Beck et al., 2001).

The rules were formulated through logical reasoning, grounded either in the scientific literature or in fisheries population dynamics theory. In the latter case, thresholds of the relevant state variables (i.e., spawning stock biomass, recruitment, catch, effort, profit) were defined with reference to the Gordon–Schaefer surplus production model, and rules were expressed to represent the different possible scenarios (Appendix S5).

2.4 Target states, alternative scenarios, and State-Transition Graph analyses

The EDEN model produces a State-Transition Graph (STG), which provides a complete representation of all possible system dynamics given the defined state variables and rules. Analyses of the STG were conducted at three complementary levels: states, transitions and trajectories for exploration of sustainability pathways. States were analyzed in terms of their existence (i.e., whether they can be reached from the initial state through valid transitions) and their persistency (i.e., whether they can be maintained over the long term). Persistent states represent potential long-term equilibria of the GoL SES, while non-persistent states correspond to transient configurations. Trajectories or pathways, i.e., sequences of successive transitions, were analyzed to characterize the diversity of possible system evolutions. This includes identifying alternative pathways (branching points where multiple rules may apply), feedback loops, and irreversible transitions (processes leading to states from which some desirable configurations can no longer be reached). By mapping all reachable trajectories, the STG allows the investigation of the conditions under which sustainable states emerge, as well as the constraints that may prevent their attainment. This possibilistic exploration highlights not only desirable equilibria but also critical thresholds, tipping points, or “traps” that can lock the system into unsustainable states.

To address the issue of the existence and persistence of a targeted sustainable state, as well as the possible trajectories leading to it, it is first necessary to define the characteristics of such a state, together with other states of interest through which the system may transition.

We define the target state to be reached as a *“sustainability ideal”*, encompassing all sustainable and desirable states of the SES. This ideal corresponds to overall sustainability across environmental, economic, and social dimensions, ensuring a sustainable exploitation of marine resources (*Ssb+*, *Rec+*, *Yss-*), minimized environmental impacts (*Hco+, Hof+, Lmx+*), and maximized human well-being (*Emp+*, *Wor+*, *Ima+*). Both fleets remain active under this ideal (*BtP+*, *Sfp+*, *Pbt+*, *Psf+*), ensuring viable fisheries.

In addition to this target, additional states inspired by prospective visions for the Mediterranean fisheries by 2050 (Doray et al., 2023; Davies et al., 2024; Chevallier et al., 2025; Theys et al., 2025) were defined in order to test whether trajectories passing through them may exist (Table 1). These additional states are just two scenarios among many; we selected them for a first preliminary exploration, but others could also be investigated.

- “De-trawling”: Effective implementation of the Common Fisheries Policy (CFP) and adaptive management progressively restore marine ecosystems, by reducing bottom trawling in favor of small-scale fisheries. This transition reduces fishing pressure on marine habitats and resources, improves working conditions, enhances the sector’s image, making it more attractive and creating new employment opportunities.

- Widespread crisis*:* Following the collapse of fish stocks, ecosystems degrade and scarce marine resources lead to low productivity and unprofitable fishing. Public subsidies rise to offset losses, while technological innovations attempt to reduce fishing costs. Low incomes and deteriorating working conditions reduce sector attractiveness, causing workforce losses as fishers leave or retain.

Table 1: Variables status in the state properties defining the states of interest in the model dynamics. In grey, variables not included in the property definition which can take either the + or – value.

Scenario	Cc	Hco	Hof	Rec	Lmx	Yss	Ssb	Ebt	Esf	Ybt	Ysf	Pbt	Psf	Sub	BtP	SfP	Emp	Wor	Ima	Sel	Dev	CFP
Sustainability target		+	+	+	+	-	+					+	+		+	+	+	+	+			
Detrawling		+	+	+	+	-	+	-		-		-	+		-	+	+	+	+			+
Widespread crisis		-	-	-	-		-			-	-	-	-	+	-	-	-	-	-		+	

Model computation was performed in Python 3.7.5 the module *ecco* on a Jupyter platform. The output of any EDEN model is a state space generated by all possible rule executions starting from a given initial state (Thomas, 1991). Because a complete representation of this state space is generally too large to interpreted, it can be represented as a STG, a labeled directed graph. Within an STG, several key topological structures can be identified: cyclic behaviors, transient states (or basins) and stable states. Cyclic behaviors are referred to as "structural stability" or "strongly connected components (SCCs)". They correspond to subsets of mutually reachable states where every change is reversible. A state, or set of states, that cannot be left (i.e., has no successor) is called a "stable state". When such stability takes the form of a structural stability, it is called a "terminal stability", and if it consists of a single state, it is referred to as a "deadlock". Transient states are called "basins"; they are composed of pathways that share common predecessor and common successor states.

For clarity, STGs can be merged by aggregating states according to their belonging to a common topological structure (e.g., SCCs, basins or deadlocks) or according to specific state properties (e.g., sustainability target, de-trawling, widespread crisis). This results in a more compact and interpretable merged STG (Figure 4).

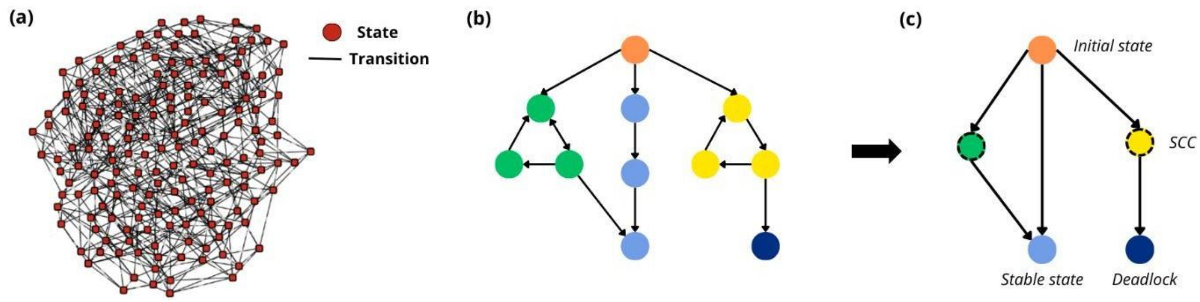


Figure 4: Illustration of a state space and its corresponding state-transition graph (STG) compacted with topological structures (adapted from Cosme et al., 2023) (a) A state space (b) STG, node colors indicates wich topological structure a state belongs to. The yellow states belong to the same SCC, the green ones belong to another SCC. Note that the light blue states represent transient states that necessarily ending in a stable state.
(c) Hierarchical transition graph corresponding to (a)

The resulting state space of the GoL-EDEN model was partitioned according to the state properties defined in Table 1, using *ecco*-specific functions such as `split`, `merge` and `explicit`. This portioning allow us to: verify or refute the existence of states satisfying these properties, test their reachability and persistence, and explore the trajectories leading to them. Dynamic properties were expressed as Computation Tree Logic (CTL) formulas (Table 2) (Monteiro et al., 2008). CTL is a temporal logic used to determine whether a property holds for some or all possible futures of a given system state. Partitioning the STG according to these properties separates states that satisfy them from those that do not, enabling a formal exploration of sustainability pathways. For more details on model-checking, see Thomas et al. (2022) and the *ecco* documentation on CTL (https://ecco.ibisc.univ-evry.fr/help/ctl-computation-tree-logic.html).

Table 2: Dynamical properties verified in this study. Each property is translated as a CTL formula where E is an existential operator ("it exist") and F, G are temporal operators for "finally" and "globally", respectively.

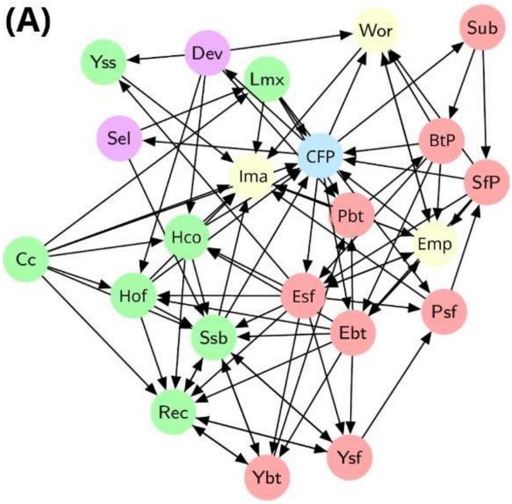
CTL formula	**Interpretation**
EF (*target*)	Target reachability : target could be reached
EF(EG (*target*))	Target persistence : target could persist
EF(*detrawling* & EF (*target*))	The target could be reached after a detrawling scenario
EF(*widespread crisis* & EF (*target*))	The target could be reached after facing a widespread crisis

3. RESULTS

3.1 The modelled social-ecological system

The interaction network represents interactions between the system components and forms a kind of skeleton of the social-ecological system (Figure 5A) (Gaucherel et al., 2024). The model variables are strongly interconnected, with some playing a more central role, such as fishing effort and spawning stock biomass. These appear most often in the rules, both as conditions and outcomes, while others (e.g., subsidies, incidental catches or smart devices) are more peripheral. This suggests that the system's functioning relies heavily on them, which is consistent with a marine SES centered on fishing activity and its dependence on natural resources.

(A)



(B)

Non applied rules	
Biomass	**R6** : *Esf+, Ebt+ >> Ssb-*
Offshore habitats	**R12** : *Ebt+ >> Hof-* **R13** : *Dev-, Ebt- >> Hof-*
Mean Lmax	**R14** : *Sel- >> Lmx-*
Sensitive species catch	**R25** : *Dev- >> Yss+* **R26** : *Dev+, Esf+ >> Yss+*
Bottom-trawler profit	**R45** : *Ebt+, Ybt+, Dev- >> Pbt-*
Working conditions	**R58** : *BtP-, SfP-, Emp-, Dev-, CFP- >> Wor-*

Figure 5: (A) The interaction network. An arrow between two variables indicates that at least one rule exists connecting these two variables (oriented from conditions to realizations). The display has been chosen to minimize edge crossing so that variables at the center are more connected than peripheral variables. Colors are attributed as following: Green for environement, pink for economic, yellow for social, purple for tehnological and blue for governance dimension (B) Table of rules which are never applied in the dynamic modelled

Over the 76 rules defined, 8 rules do not apply within the dynamics, while all the others are activated at least once (Figure 5B). Most of these rules relate to environmental variables (R6, R12, R13, R24, R25, R26), one concerns profit (R45), and another addresses working conditions (R58). Among the rules that occur, some of them occur frequently in the studied dynamics such as those influencing the state of coastal habitats and those related to the effects of climate change. This was determined visually thanks to the set of rules displayed in the State-Transition Graph (STG) presented in Appendix S6.

3.2 Description of the computed dynamics

The state space modelled is composed of 158 688 states and contains several structural stabilities but no deadlocks. Figure 6 presents a schematic of the GoL-SES state-space: among the pathways that reach the sustainability target, only the 'detrawling' and 'widespread crisis' trajectories are shown, together with one of the trajectories that fails to reach the target. Numerous other pathways exist but are not depicted. Numerous alternative pathways exist but are not depicted here in this report, only those discussed in the results are shown. In this representation, nodes correspond to sets of states and edges to the transitions between them, with states aggregated according to their properties (Tables 1, 2). For the following results, the sustainability ideal property may be referred to as the *sustainability target* (or simply *target*).

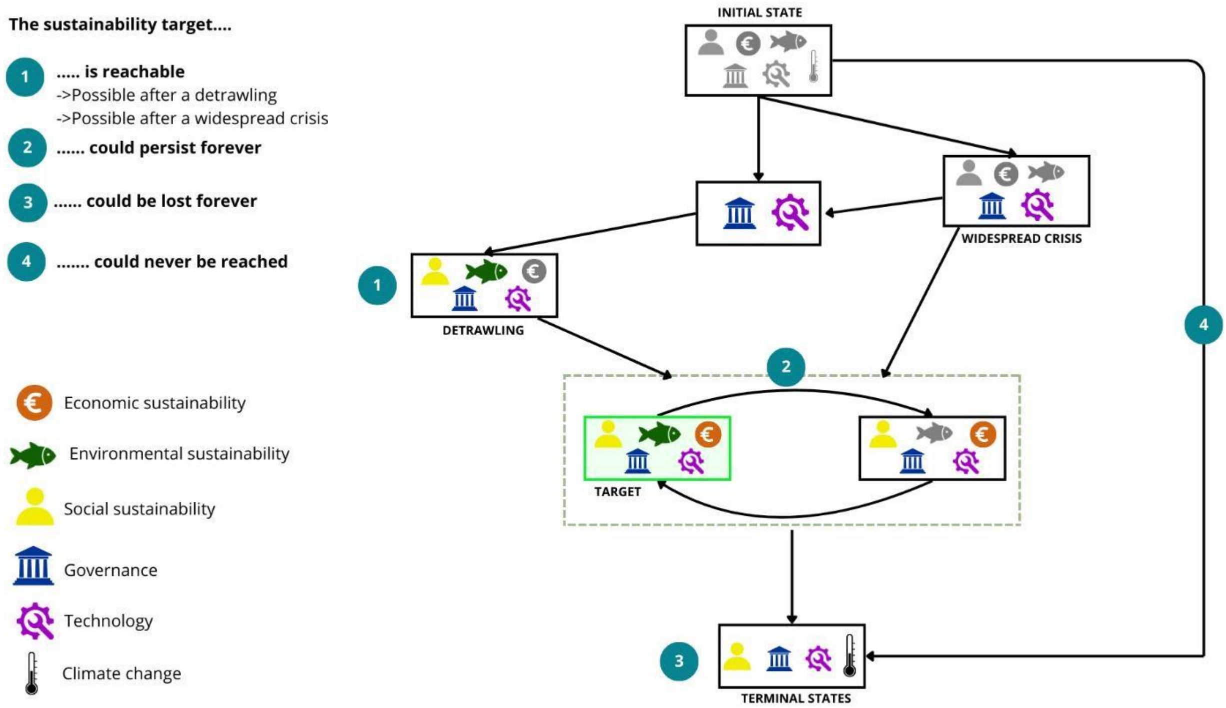


Figure 6: Simplified representation of the computed State-Transition Graph (STG) based on the complete STG in Appendix S6. Target states are shown in the green square. Pictograms indicate variables or groups of variables systematically "on" (colored) or "off" (grey) in each node. When coloured environmental sustainability correspond to the set (*Hof+, Hco+, Ssb+, Rec+, Lmx+, Yss-*), social to (*Emp+, Ima+, Wor+),* economic to (*Pbt+, Psf+, BtP+, SfP+)* and technology refers to *Dev+, Sel+.*

3.2.1. Target reachability

States verifying the *sustainability target*, *detrawling*, and *widespread crisis* properties exist and are reachable. Moreover, the target remains reachable after both detrawling and/or widespread crisis. This is confirmed by the validation of the CTL properties (Table 2) and their presence in the STG. The 16 states satisfying the target property are all characterized by low fishing effort (*Ebt-, Esf-*), effective CFP implementation (*CFP+*), and technological advances (*Sel+, Dev+).*

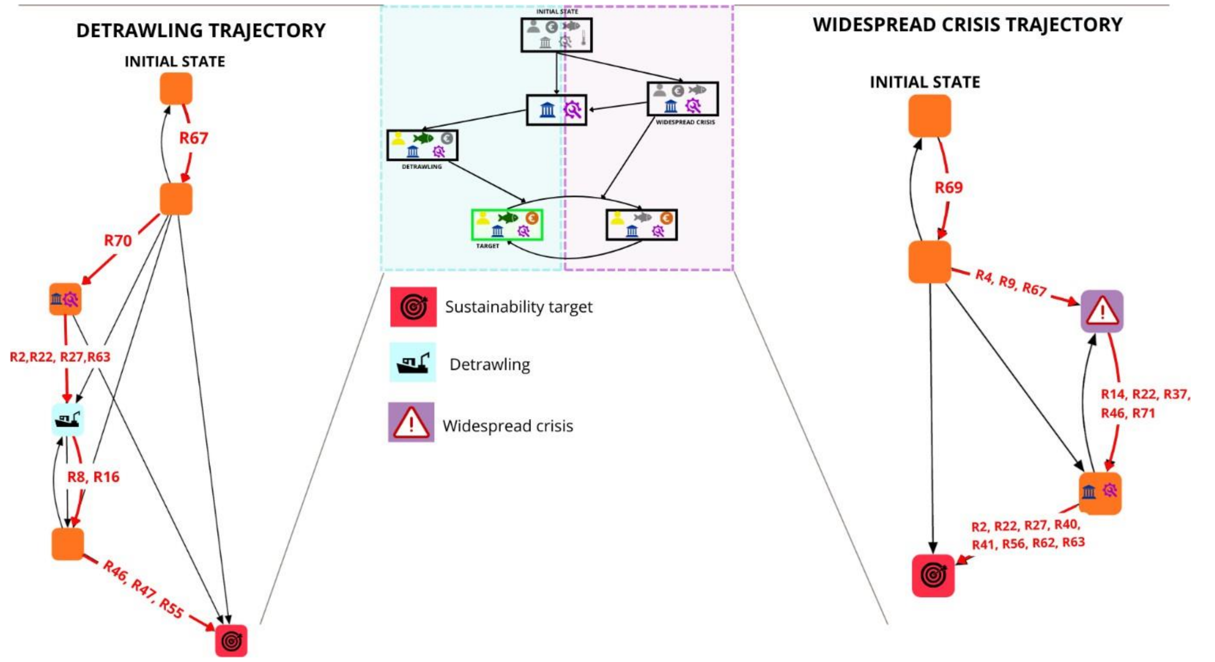


Figure 7: Detailed trajectories leading to the target after detrawling (left) and following a widespread crisis (right). Only the rules discussed in the analysis are shown here, refer to the complete STG for the full set of rules

From the initial state, it is possible to reach the states satisfying *target* by passing through those satisfying *detrawling*. These eight states, among the 158 688 possible configurations, not only meet their defining characteristics but are also all characterized by a reduction in small-scale coastal fisheries (SSF) effort (*Esf*-) (Figure 7, on the left). Among the many possible trajectories, one can be described as follows:

From the initial state, the system first can shift toward a set of states where the CFP is effectively implemented and technological advances emerge (*CFP+, Sel+, Dev+*), while the other system variables fluctuate. This transition may result from a CFP reform (R67) combined with reinforced measures to support the transition of fishing practices (R70).

The states satisfying *detrawling* then may become accessible through social dynamics, such as an increase in employment driven by better working conditions and greater attractiveness of the profession (R63), or through ecological dynamics, such as reduced incidental catches thanks to technological innovations improving selectivity (R27), or an increase in the mean Lmax of the bentho-demersal community due to larger trawl mesh sizes (R22).

From *detrawling*, the system can move toward a state of social sustainability, while environmental and economic sustainability remain partial, environmentally due to fluctuating biomass levels and coastal habitat quality (*Ssb*, Hco*,* where "*" means that variable can take + or –), and economically because it is achieved only for the SSF and not for the bottom trawl fleet (*Ybt*, Pbt*, BtP**). This configuration may result either from a decline in spawning stock biomass due to environmental pressures (R8), or from the degradation of coastal habitats caused by other activities (R16).

Finally, the *target* states can be reached from this configuration through improved profitability of the trawler fleet (R55) or maximization of their profits (R46, R47).

Another trajectory leading from the initial state to the target can pass through a widespread crisis of the fishing sector. In addition to meeting their defining characteristics, the two states associated with widespread crisis are characterized by *Cc-, CFP+, Sel+, Esf+,* and *Yss+* (Figure 7 , on the right).
From the initial state, capacity-enhancing subsidies can increase when the CFP is poorly implemented, in a political context that favors support for fishing activity during tense periods (R69). This situation can push the system into a widespread crisis, triggered by stock collapse due to recruitment overexploitation and high fishing activity (R4, R9). It is important to note that this crisis can occur even when the CFP is properly implemented and certain technical measures, such as selectivity, have been improved (*CFP+, Sel+*), it will be later discuss.
Recovery from the crisis may lead the system to states characterized by effective CFP implementation and technological advances (*CFP+, Sel+, Dev+*). This transition is made possible by management measures such as the transfer of catch to the SSF (R37), the reduction of trawler effort and the use of gear minimizing seabed impact (R14), as well as the effects of measures already in place: improved selectivity can increase the mean Lmax in the bentho-demersal community, while the reduction of *capacity-enhancing* subsidies supports the implementation of less impactful practices (R71).
From this set of states, reaching the sustainability target can result from different processes. On the social level, it is possible if working conditions improve through vessel modernization, adequate remuneration, and greater attractiveness of the profession for young fishers, promoting effective generational renewal (R63). On the ecological level, the target can be reached through the rebuilding of SSB (R2), increasing mean Lmax via better selectivity (R22), or reducing incidental catch thanks to more selective onboard technologies (R27). Finally, on the economic level, the target can be attainable if the SSF remains profitable and optimized (R40, R41, R56). Note that in the rest of the dynamics, crises of this type occur only before reaching the sustainability target, not after.

3.2.2. Target persistency

States satisfying the target property belong to a structural stability, a cyclic dynamic in which the system can remain indefinitely (Gaucherel and Pommereau, 2019). This stability is subdivided into two sub-stabilities, or loops: one with, and one without, the effects of climate change (Figure 8).

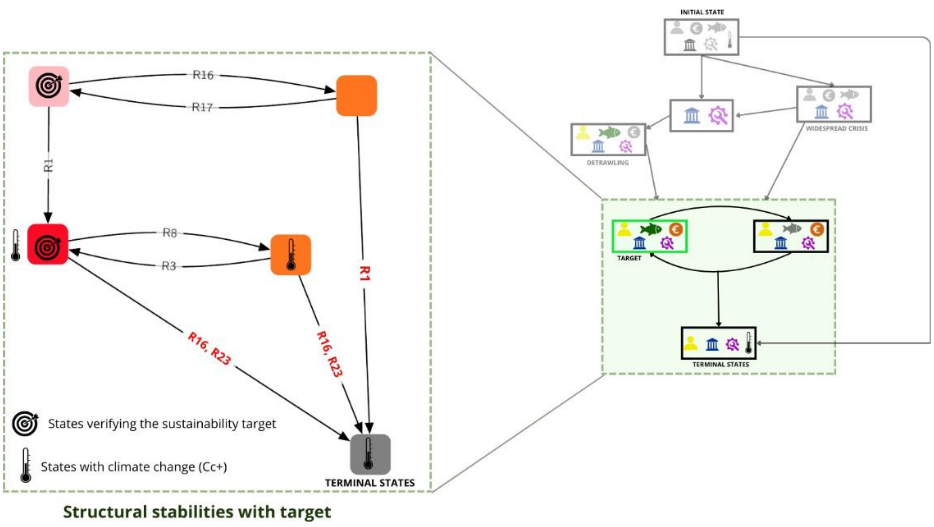


Figure 8: Structural stabilities in which the target can persist. Nodes: pink for states verifying target without climate change effects (Cc-), red for those with effects (Cc+), orange the intermediate sustainability states, and grey the terminal stability. Red transitions correspond to rules leading to a definitive loss of the target

First, the sustainability target can persist indefinitely without climate change effects, cycling with a set of intermediate sustainability states in which all variables match the target except for degraded coastal habitats (*Hco*-). Transitions between these states occur through rules acting on coastal habitats: their degradation due to other anthropogenic activities (R16), which shifts the target state toward the intermediate one, or their restoration (R17), resulting from reduced fishing and other human activities added to moderate climate change effects, which allows the system to reach the target. This stability can irreversibly shift to another structural stability containing the target when moving to a regime with marked climate change effects (R1). Under such conditions, the target can still persist, cycling with a set of intermediate sustainability states that share the same characteristics as the target but with biomass levels below Bmsy (*Ssb*-). Transitions between these states depend on biomass dynamics: degradation driven by climate change effects (R8) pushes the target into the intermediate state, while restoration through reduced fishing activity, functional essential habitats allows the system to return to the target (R16).

3.2.3. Loss of target

Although the target can be reached through different trajectories and may persist, it can also be lost irreversibly. Processes linked to climate change effects (R1, R23) or to other anthropogenic activities (R16), which influence the state of marine ecosystems, can drive the system into a set of intermediate sustainability states that are terminal. In other words, once the system enters this set of states, it cannot leave them anymore (Figure 8: rules in red). These terminal states are characterized by pronounced climate change effects (*Cc*+), stricter fisheries policy (*CFP*+) with reduced overall fishing effort for both fleets (*Ebt-, Esf-),* and technological improvements (*Sel+, Dev+)* that lower pressure on habitats (Hof+) and living resources (*Yss-).* States in which onboard working and living conditions (*Wor*+) are improved, thereby enhancing the profession's attractiveness (*Ima+, Emp*+). In this set of states, social sustainability is ensured, environmental sustainability is only partially achieved since all stocks have not achieved MSY (*Ssb**), and economic sustainability fluctuates for both fleets: apart from fishing effort, all economic variables change sign at least once in these states.

3.2.4. *Failure to meet target*

Among all possible system trajectories, some never reach the target and instead drive the system into states from which the target can no longer be reachable (grey states in Figure 9). From the initial state, the system can directly shift into these states through several processes: the impacts of climate change (R1); the degradation of coastal habitats (R15, R16, R21), caused by increased fishing pressure in nearshore areas or by other anthropogenic stressors, sometimes coupled with offshore habitat degradation (R23). The system may also follow these trajectories due to regulatory reductions in fishing capacity (R73), a decline in sectoral attractiveness leading to job losses (R64), or a sectoral crisis characterized by the absence of profitability, employment (R66) and low fleets activity (R74). Once in these sets of states, the target becomes irreversibly unreachable. The system may then undergo periods of crisis, particularly economic, which can escalate into generalized crises (via the application of rule R36 within this trajectory). Along such trajectories, the system could ultimately converges toward terminal states without ever reaching the sustainability target.

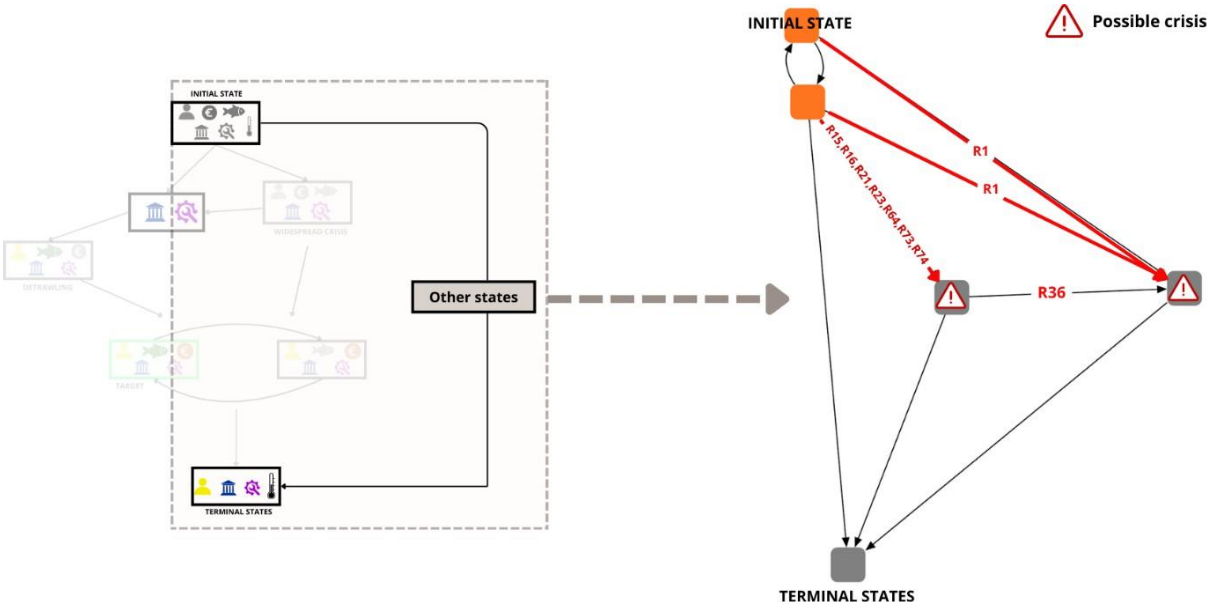


Figure 9: Schematic representation of the trajectory along which the target can never be reached. Grey: set of states from which the target can no longer be attained; orange: states from which reaching the target is still possible

4. DISCUSSION

This study aimed to explore sustainable pathways for the Gulf of Lion marine social-ecological system using a holistic sustainability framework. We modelled the SES through a multidimensional approach, employing possibilistic, event-based qualitative modelling. The constructed model describes which sustainable states the current SES could potentially reach and identifies the different pathways leading to these states.

There is a growing recognition of the need for holistic approaches that consider sustainability within social-ecological systems (Liu et al., 2015; Roberts et al., 2024). In this context, we applied the EDEN framework to model the social-ecological dynamics of the GoL, representing the first application of EDEN in a marine SES. Its qualitative approach is particularly well suited for studying SES at an integrated scale, as it captures system complexity by incorporating a wide range of variables that represent both ecosystem dynamics and the human interactions that depend on them. Unlike models that focus primarily on stability through feedback loops (e.g., loop analysis; (Gourguet et al., 2021; Thermes et al., 2024)) or on illustrating the relative influence of pressures on SES components (e.g., fuzzy cognitive maps; (van Vliet et al., 2010)), EDEN provides a comprehensive exploration of all possible system states and their transitions, without assigning probabilities as probabilistic models do, and without predicting a single deterministic trajectory. This allows the identification of key processes or leverage points that may enable, or conversely prevent, the achievement of desirable sustainability states through a sequence. Modelling a marine SES and addressing sustainability in its full multidimensionality remains a challenge, and while this study represents a significant advance, limitations persist**.**

4.1 Model limits and perspectives

First, while the current model captures part of the complexity of the GoL-SES, particularly through well-developed economic and environmental dimensions related to fishing activities, other aspects such as social and governance components remain underrepresented, highlighting points for further model refinement. Our model is a preliminary step for understanding and representing dynamics of a marine social-ecological system: focusing initially on the core of system dynamics by representing fishing activities through a fleet-based approach, in order to establish a reliable baseline model to which additional modules can later be added to make it more integrative. EDEN does not impose strict limits on the number of variables that can be included in the model, although parsimony is required because each additional variable exponentially increases the number of possible states. We plan to extend this model to a more integrative scale by including variables that better capture the social and governance dynamics of the Gulf of Lion. This could include spatial planning issues currently relevant in the Mediterranean Sea, such as the continuation of the WestMed plan with new spatio-temporal closures (Journal officiel, 2025), the strengthening of the marine protected areas network (Vilas et al., 2021) and the development of offshore wind farms (DIRM, 2022a). It would also be relevant to extend the dynamics to the downstream part of the fisheries sector, encompassing both cultural and heritage aspects (e.g., cultural identity, tourism) and economic aspects (e.g., onshore employment, market supply and distribution channels, seafood consumption).

Approximations were necessary for reasons of parsimony and due to data limitations. It was not always possible to find data specific to the Gulf of Lion, as most information is generally available at the scale of the entire Mediterranean or Geographical Sub-Area 7 (i.e., operative areas for which boundaries were established by the General Fisheries Commission for the Mediterranean Sea). The model was constructed to best reflect the context of the Gulf of Lion, but it could be made even more representative by integrating the perspectives of stakeholders from the sector. This type of model is particularly well suited for co-construction with stakeholders, as it lends itself to workshops focused on identifying the essential components and processes to include in the model (De Lapparent et al., 2025). One such workshop was conducted during the study with a scientific group specialized in fisheries and sustainability issues, and another workshop will be held at the end of the internship to discuss the model, its construction and results with fisheries professionals.

Although the qualitative nature of the model offers many advantages such as parsimony or its ability to implement it with sparse data, the binary representation of variables can reduce precision. The current model is largely based on the theory of fisheries models, such as the Gordon-Schaefer model. In these models, MSY is not the only relevant reference point: Elim, the limit effort above which stock recruitment may be affected, is particularly useful to account for potential overexploitation of recruitment. Additionally, Emey could be included to represent the effort corresponding to the Maximum Economic Yield. The current model represents these cases through rules, which are not always fully representative and remain largely narrative. Interpretation can be challenging, as different cases are difficult to distinguish. For example, for fishing effort, E+ can indicate values above MSY, but it is unclear whether this means slightly above MSY or well above Elim, which could have very different effects on population dynamics such as recruitment. Similarly, E- only indicates effort below MSY, without specifying whether it is near zero or close to Emey, while the narrative in the rules may provide this information, it complicates interpretation. Extending the current rule-based language of the model to a multivalued rules-reaction (MRR) framework could address this limitation. In MRR, variables remain qualitative, but multiple thresholds can be defined, allowing finer distinctions (Pommereau and Gaucherel, 2024). This model extension is still under development, but it could be highly relevant for capturing such nuanced relationships.

Decision-making in most management contexts primarily relies on quantified outcomes linked to probabilities, uncertainty, or risk assessments, which facilitate option comparison and the justification of choices (McKane et al., 2020; Barzehkar et al., 2021). In this regard, EDEN models may appear less directly suited to highlight decision-making. Indeed, the core principle of this model lies in its exhaustive and possibilistic approach, which makes it difficult to assign probabilities or estimate the risk of missing a target. Moreover, even though this approach produces a dynamical representation of the system, time is not explicitly represented. Consequently, the model created does not hint at temporal aspects: as rules are optional, and no assumption is made about the length of time between two rules, several of them can be applied during the defined period (mid to long term scale in our case), as well as none. As a result, the absence of a direct link between the number of rules composing a transition and the actual time it would take for this transition to occur complicates the re-contextualization of model trajectories within real-world management frameworks.

Nevertheless, the robustness of the modeled trajectories and states can be assessed by confronting them with past SES dynamics (Cosme et al., 2024; Gaucherel et al., 2024), which places the model outputs in relation to observed patterns. In addition, a broad sensitivity analysis could further strengthen the assessment of result reliability. The model exhaustively provides all possible states, and as long as the model definition is validated (i.e., its variables and rules), the results are considered exact within the defined possibilities. A sensitivity analysis would involve testing the dependence of the system dynamics on specific rules, for example, by removing a rule and observing whether the resulting trajectories remain similar or become radically different. In the latter case, this would indicate that the system dynamics are strongly driven by that process. Such an analysis would provide a valuable complement to the current model results and contribute to their validation. Finally, EDEN remains highly valuable for discussion and understanding of system dynamics. It can highlight the importance of specific components or processes in the overall system dynamics and is particularly well suited for participatory approaches, which are increasingly favoured in decision-making processes (Gourguet et al., 2021; Chevallier et al., 2025).

The model contains a wealth of information, but not all of it is necessarily reflected in the results. As mentioned earlier, some rules never apply in the modeled dynamics. This can be related to the chosen initial state: in EDEN models, it is sometimes observed that with a single initial state, some rules are never activated. It may also come from the definition of other rules, which prevent certain variable combinations from occurring. For example, rule R6 never applies because no state simultaneously presents *Esf+, Ebt+,* and *Ssb*+, which is consistent with our assumptions: if E > Emsy, then B will necessarily be lower than Bmsy in the long term. To broaden the exploration of the modelled dynamics, it would be valuable to consider multiple initial states (made possible by the use of non-conditioned variables) in order to assess the influence of the initial state on system dynamics. One could also identify the initial states that may lead to sustainability targets, as has already been explored in previous studies (Thomas et al., 2022; Cosme et al., 2024).

Despite its limitations, the modelled dynamics of the Gulf of Lion provide valuable insights into the characteristics of this social-ecological system and the trajectories that could lead to its sustainability.

4.2 Pathways toward sustainability: opportunities and risks

4.2.1 Gradual sustainability pathway via trawling reduction

The *detrawling* trajectory illustrates a gradual transition from low sustainability to improved social-ecological outcomes, driven by stronger regulations and technical measures. This pathway appears plausible: past CFP reforms (e.g., 2002, 2013) were often triggered in contexts of crisis and overexploitation (European Parliament, 2025), and significant improvements in selectivity remain achievable, especially in the Mediterranean Sea where current technical requirements are still limited (Colloca et al., 2013; Bahamon et al., 2024). The new spatio-temporal closures envisaged in the GoL as part of the continuation of the WestMed plan support this scenario involving reduced trawling effort (European Parliament, 2019; Journal officiel, 2025).

Yet, some mechanisms in the model results are less intuitive. The trajectory partly relies on increasing employment and sectoral attractiveness, while current trends point in the opposite direction: generational renewal is low, and new entrants are scarce, particularly in the Mediterranean where small-scale fisheries dominate. Although these fisheries create more jobs, they struggle to attract successors, as younger fishers are more likely to work on larger vessels such as trawlers (Carif-Oref Occitanie, 2023). Reversing this trend would require substantial improvements in working conditions and in the social recognition of the profession. If resources recover and fishing practices become more sustainable, the perception of the profession could gradually shift toward a more valued and environmentally responsible activity, making it more attractive (Power et al., 2014; Gascuel and

Dewals, 2020; Szymkowiak and Rhodes-Reese, 2022), a possible but ambitious outcome.

The trajectory also presents a counterintuitive sequence: social sustainability is reached before ecological and economic sustainability. In practice, it is more common to observe the opposite, with economic viability maintained while social or ecological dimensions are undermined (Barclay, 2012). This can be explained by the vulnerability of resources to climatic and anthropogenic pressures, which create uncertainty around stock recovery and fleet profitability. The small pelagic crisis in the Mediterranean illustrates this dynamic, where the collapse of catches gradually led to the disappearance of pelagic trawlers in the Gulf of Lion due to their low economic profitability (Huret et al., 2024).

Ultimately, reaching the sustainability target would rely on maintaining employment in small-scale fisheries (Quemper et al., 2025), ensuring ecological stability despite external pressures, and improving the profitability of a reduced trawler fleet through efficiency gains or better product valorization. While this pathway aligns with the current regulatory context and the gradual shift toward less impactful fishing practices, its feasibility remains uncertain. It depends on demanding conditions: significant advances in technical measures, effective CFP implementation with all stocks at MSY, and effective ecosystem-based management. Given the current context of the GoL-SES and the additional uncertainty of climate change, such a sequence would require profound regulatory and social transformations. Thus, although optimistic, this trajectory remains possible, while highlighting the major challenges of its practical implementation.

4.2.2 Pathway through crisis and risk of missing the target sustainability

Before reaching the sustainability target, the system may experience a widespread crisis which could be triggered by an environmental one. Increased subsidies, by artificially sustaining high levels of fishing effort, can drive overexploitation (Sumaila et al., 2019) and ultimately lead to stock collapse. Since natural resources form the basis of the production system, their degradation often generate economic and social repercussions. This was notably illustrated by the anchovy collapse in the Bay of Biscay, which had significant consequences for fisheries, employment, and downstream industries (Beckensteiner et al., 2024; Huret et al., 2024). Such dynamics show how an environmental crisis can cascade through the entire sector and evolve into a widespread systemic crisis.

Such a scenario may occur despite the implementation of the CFP and technical measures, showing that the regulatory framework alone is not always sufficient to prevent crises. External factors, such as climate change, habitat loss, or shifts in international policy, can destabilize the system and exacerbate its vulnerabilities (Pita Vaca, 2024). These findings are consistent with the multifactorial nature of crisis drivers.

The existence of a trajectory involving a crisis on the path to the sustainability target highlights the role of such a crisis as a driver of change. It can expose social, ecological, and economic vulnerabilities and act as a catalyst, triggering reforms or structural adjustments that would be difficult to implement otherwise. However, its occurrence remains undesirable, and recovery is uncertain: simultaneously restoring social, ecological, and economic dimensions is complex, and historical evidence shows that the rebuilding of collapsed stocks and fisheries is often unpredictable, particularly under strong climatic pressures (Murawski, 2010).

Finally, a crisis does not necessarily ensure a transition toward sustainability: it can also push the system beyond points of no return, where the target becomes irreversibly unattainable. The system's dynamics indeed include other critical thresholds: beyond certain levels of ecological degradation (loss of coastal or offshore habitats, climate change impacts) or socio-economic decline (loss of attractiveness of the profession, disappearance of fishing units), no trajectory allows a return to sustainability (see 3.2.4). This trajectory thus highlights the ambivalent role of crises, acting both as a catalyst for change and as a risk of tipping into undesirable terminal states. While passing through a crisis before reaching the target appears plausible, the subsequent rebuilding of fisheries after such a severe crisis is far less certain. It remains difficult to achieve and would, as in the *detrawling* trajectory, rely on profound regulatory transformations.

4.3 Fragile persistence of the sustainability target

The sustainability target can only be persistently maintained through cycles involving intermediate sustainability states. These loops, oscillating between the target and intermediate states, may be interpreted as a form of flickering, where the system shifts back and forth between regimes in response to external pressures such as climate change and other anthropogenic activities (Tilman et al., 2024). Maintaining the target without pronounced effects of climate change (*Cc*- loop) highlights the need for an integrated land-sea management approach: the restoration of coastal habitats, essential for reaching the target, cannot rely solely on reducing fishing activity but also requires mitigating other coastal anthropogenic pressures. The management of these essential habitats is crucial to maintain ecological functioning of the system, support resource life cycles, and sustain coastal human communities (Barbier et al., 2011; Lau et al., 2019). This underscores the importance of rethinking current governance towards a more holistic management of the land-sea continuum. However, the feasibility of such stability is limited. The ongoing progression of climate warming (Forster et al., 2024) and persistent challenges in reducing coastal pressures suggest that the *Cc*- loop may eventually shift towards an alternative stability where the impacts of climate change can no longer be neglected.
In this second stability, where the effects of climate change are pronounced (*Cc*+), the persistence of the target depends on particularly demanding conditions: rebuilding of bentho-demersal biomass despite climate pressures, supported by healthy habitats, reduced fishing effort, and improved selectivity limiting environmental impacts. The simultaneous fulfilment of these conditions makes the persistence of the target fragile: although fishing pressure is reduced and selectivity enhanced, fish populations remain highly vulnerable to climate change (e.g., bottom-up mechanisms, physiological impacts), making their renewal only moderately plausible (Sguotti et al., 2019). Given these constraints and the fragility of target persistence, it appears more realistic that the system will ultimately evolve towards a set of intermediate states representing a "compromise" form of sustainability. The transition to this state is irreversible: once the system shifts, it remains locked within it. Such a transition, driven by the induced effects of climate change, highlights the major role of climate change in triggering regime shifts in socio-ecological systems, as observed in other contexts (Scheffer et al., 2001; Möllmann et al., 2015; Hagstrom and Levin, 2017).
This set of states represents the final attractor of the system's dynamics. It corresponds to a form of partial sustainability, maintained through stricter management measures requiring both a global reduction in fishing effort and technical improvements. In this configuration, social sustainability is largely preserved: despite fluctuating profitability, the profession remains locally attractive and

working conditions relatively stable. However, economic instability results from the variability of resource status. From an environmental perspective, sustainability remains incomplete: while technological innovations and reduced fishing effort help to limit bycatch, and the relaxation of trawling pressure supports the partial restoration of offshore habitats, the overall situation remains fragile. Biomass remains sensitive to environmental fluctuations, while the quality of coastal habitats is difficult to stabilize, as it also depends on non-fisheries pressures such as land-based activities.

Thus, although the target may be reached and persist under certain conditions, it appears more plausible that, in the long term, the system will shift toward a compromised state of sustainability. This state is supported by reduced fishing pressure made possible through technological advances and regulatory measures, which allow the system to avoid collapse but remain insufficient to achieve the full sustainability target due to exogenous factors such as climate change.

From a management perspective, these results highlight the importance of a precautionary approach to avoid undesirable trajectories, such as passing through a widespread crisis or failing to reach the sustainability target, often linked to overexploitation or stock collapse. They also emphasize the central role of climate change: pronounced effects can push the system toward states where maximum sustainability becomes irreversibly unattainable, underlining the need for adaptation and mitigation measures.

Finally, fisheries management alone is not sufficient; achieving an optimal state of sustainability requires an integrated land-sea approach, including coastal habitat restoration and coordinated spatial planning of maritime and coastal activities, to reduce cumulative impacts and maintain the social and economic viability of the sector. In the Mediterranean, while efforts have been made to integrate land-sea approaches (European Comission et al., 2021), their application remains uneven and often limited to specific areas or sectors. Coordination among various stakeholders and the effective implementation of these approaches continue to pose significant challenges (Rodriguez-Perez et al., 2023).

5. CONCLUSION

This study developed a qualitative, discrete-event, possibilistic model to investigate the sustainability pathways of the Gulf of Lion social-ecological system, adopting a holistic and multidimensional approach. Our results demonstrates that the sustainability of the GoL social-ecological system depends on a combination of ecological, economic, and social processes, whose interactions determine whether sustainability targets can be reached and maintained. However, achieving an integral form of sustainability appears difficult to maintain in the long term, as climate pressures and social constraints make the emergence of partial and compromised sustainability states more likely. Our initial research question—whether the three pillars of sustainability can be simultaneously achieved and maintained—thus finds a nuanced answer: yes, the system can reach such a state, but it remains fragile and contingent upon profound transformations in practices, governance, and social conditions in fisheries. Among the multiple pathways, some highlight the role of structural crises, which can act as triggers of change leading toward desirable states but also destabilize the system and jeopardize its recovery. Irreversible regime shifts further underline the systemic vulnerability of fisheries SES and the central role of climate change and anthropogenic pressures in shaping their futures.

These dynamics also illustrate the importance of anticipating such tipping points through a precautionary approach, particularly with regard to anthropogenic pressures exerted on marine resources. As the foundation of the production system, the integrity of these living resources strongly conditions the subsequent dynamics of the social-ecological system. Building on this, our findings ultimately emphasize the need for integrated land–sea governance and participatory approaches with stakeholders, in order to co-construct collective pathways toward more resilient and sustainable Mediterranean social-ecological systems.

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7. APPENDICES

Appendix S1: Data on the characteristics of French fisheries in the Gulf of Lion

The data presented below originate from publicly available datasets provided by the Scientific, Technical and Economic Committee for Fisheries (STECF):

- Fisheries Dependent Information (FDI), available at: https://stecf.ec.europa.eu/data-dissemination/fdi_en
- Annual Economic Report (AER) on the EU fishing fleets, available at : https://stecf.ec.europa.eu/reports/economic-and-social-analyses_en

Hereafter, these sources will be referred to as STECF-FDI and STECF-AER, respectively. Fleet-level aggregation was made following the methodology developed by Quemper et al., 2025.

<u>Methodological choices</u>:

-Year: Average over 2019–2023 (or 2018–2022 when 2023 data were not available)

-Country: France

-Principal subregion: GSA7

-Fishing technique aggregation per fleet and vessel length classes:

- Bottom-trawlers: `fishing_technique = DTS` and all vessel length classes (`VL0612`, `VL1824`, `VL2440`)
- Small-scale fisheries: `fishing_technique = DFN, FPO, HOK, PGO, PGP, PMP` and vessel lengths < 12 m (`VL0006`, `VL0612`)
- Others: all remaining fishing techniques

Table S1: Aggregated characteristics of Gulf of Lion fleets averaged over 2019–2023 (capacity, effort, landings)

	Bottom trawlers	**Small scale fisheries**	**Others**
Annual number of vessels (number)	53	897	193
Annual total fishing days	482 618	83 018 247	560 858
Landings volume (tons)	34 900	32 960	4526
Landing value (euros)	150 419 725	238 666 664	11 879 517
Mean unit price (euros/kg)	4.31	7.24	2.63

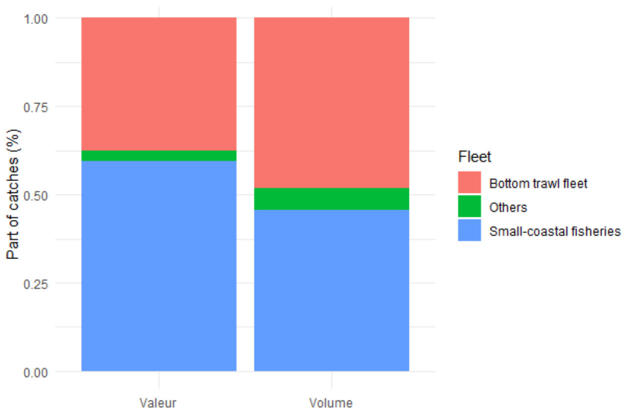


Figure S1.1 : Part of GoL fleets in landings value and volume

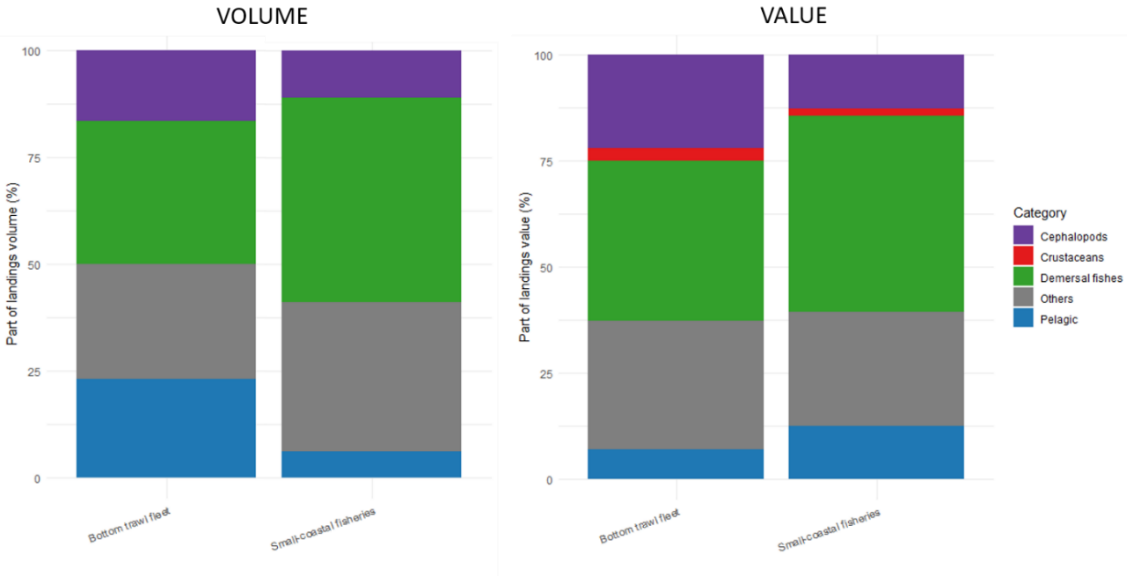


Figure S1.2: Part of resource type for BT and SSF fleet in landings value and volume

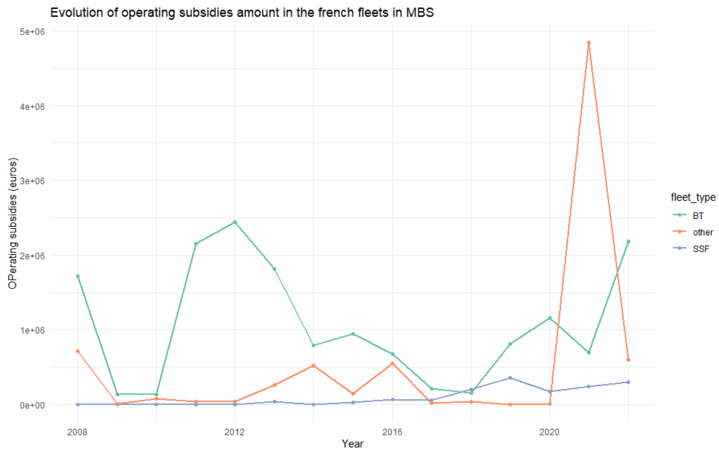


Figure S1.3: Evolution of operating subsidies amount for French fleets

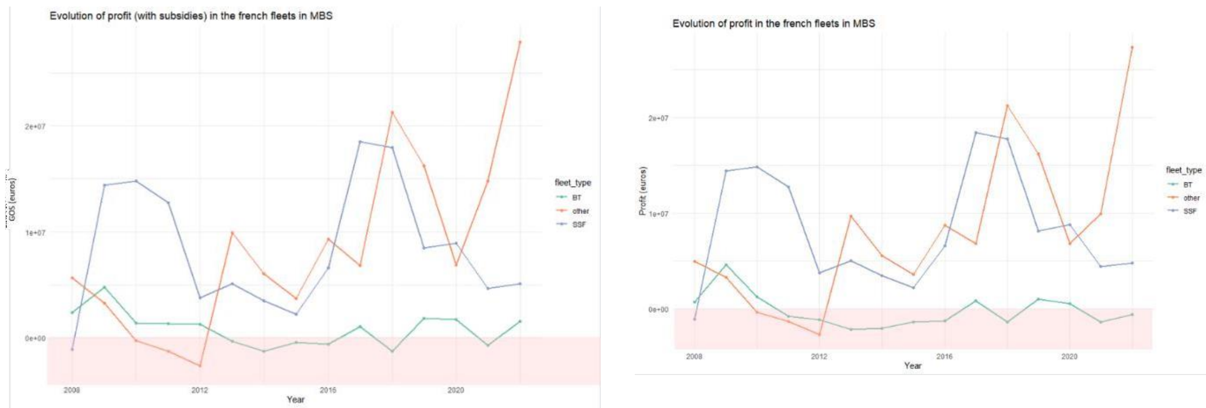


Figure S1.4: Evolution of the gross operating surplus for French fleets (left) and of the profit (right)

Appendix S2: Stock assessment data for bentho-demersal species targeted by bottom-trawler fleets and small-scale coastal fisheries

The following data originate from stock assessments reports (FAO, 2024; Mannini et al., 2025; Vermard and Ulrich, 2025) and publicly available datasets provided by the General Fisheries Commission for the Mediterranean (GFCM) :

- Stock Assessment results (STAR) : https://www.fao.org/gfcm/data/star/en/
- Stock Assessment forms (SAFs) : https://www.fao.org/gfcm/data/safs

Species	**Stock**	**F2023/(Fmsy or F0.1)**	**Biomass**	**Scientific advice (STECF)**	**Stock status**	**Catch trend**
European hake (*Merluccius merluccius)*	GSA 1,5,6,7	3.27	B2023 < Blim	No sign of biomass recovery (stable), catches must be reduced	Depleted and in overexploitation	Increasing
Red mullet (*Mullus barbatus)*	GSA 7	0,71	B2023 > Bilm,Bpa,Bmsy	Biomass increase, do not increase fishing mortality	Rebuildable, sustainably exploited	Increasing
Deep-water rose shrimp (*Panapenaus longirostris)*	GSA 5,6,7	0,59	Non estimated	Biomass increase	Rebuildable	Increasing
Blue and red shrimp (*Aristeus antennatus)*	GSA 6,7	4,32	Bmsy > B2023 > Blim	Catches must be reduced	Overexploited	
Blackbellied angler (*Lophius budegassa)*	GSA7	2,1	B2023 < Blim	Reduce fishing mortality must be reduced	Possibly overexploited, degradaded	Stable, slightly declining
Horned octopus (*Eledone cirrhosa*	GSA 7	0,49	B2023 > Btarget > Blim	Do not increase fishing mortality	Possibly sustainably exploited	Stable, fluctuating

Appendix S3: Variables of the GoL-SES model, their detailed description and justifications

Table S3.1: Variables of the GoL socio-ecological system, their initial state, thresholds, dimensions, and associated sustainability criteria. BT : Bottom-trawlers ; SSF : Small scale coastal fisheries. Colors: green : environment, orange : economy, yellow : social, purple : technology and blue : governance. Variables choice is based on the specific characteristics of the GoL's SES and sustainability criteria defined by (1) the ADAPT participatory workshops, the work of (2) Quemper et al., 2025, (3) the objectives of the MSFD, the work of (4) Gascuel and Dewals 2020 and (5) Stephenson et al., 2018.

Sustainability criterion	Symbol	Variable	Description	Threshold ('+' significance)	Initial state
	Cc	Climate change	Mean annual SST in the GoL by 2040 under the SSP2–RCP4.5 scenario	> 18,6 °C	-
Minimize habitat fishing footprint (1) (2) (3)	**Hco**	Coastal habitats	Area of benthic habitats within the 3 nautical miles in good ecological condition	> 75%	-
	Hof	Offshore habitats	Area of benthic habitats out the 3 nautical miles in good ecological condition	> 90%	-
Minimize ecological fishing footprint (1) (4)	**Rec**	Recruitment	Number of recruits of exploited bentho-demersal stocks	> recruits number at Blim	+
	Lmx	Mean maximum length in community	Mean maximum length in bentho-demersal community	> 65,2 cm	-
	Yss	Sensitive species incidental catch	Number of annual sensitive species incidental catch landed by both fleets (i.e. elasmobranchs, turtles, birds, mammals)	> 25 ind./kT landed	+
Good resources management (1) (3) (4)	**Ssb**	Spawning stock biomass	SSB of exploited bentho-demersal stocks	> Bmsy	-
	Ebt	BT fleet fishing effort	BT fleet annual fishing effort (in vessel*days)	> Emsy	+
	Esf	SSF fishing effort	SSF annual fishing effort (in vessel*days)	> Emsy	+
	Ybt	BT fleet yield	BT fleet annual catch volume	± 5% of Ymsy	-
	Ysf	SSF yield	SSF annual catch volume	± 5% of Ymsy	-
Economic profitability (1) (4)	**Pbt**	BT fleet profit	BT fleet annual profit : Income – Costs	± 5% of MEY profit	-
	Psf	SSF profit	SSF annual profit : Income – Costs	± 5% of MEY profit	-
	Sub	Subsidies	Annual amount of fishery subsidies : capacity enhancing and beneficial subsidies (Sumaila et al. 2019)	> 1,38 M€	-
	BtP	BT fleet profitability	BT fleet annual gross operating surplus : GOS = Profit + subsidies	> 0	-
	SfP	SSF profitability	SSF annual gross operating surplus : GOS = Profit + subsidies	> 0	+
Sector attractiveness (1) (4)	**Emp**	Employment	Number of crew members in both fleets	> 2 339 engaged crew	-
	Wor	Working conditions	Working conditions for fishers including onboard conditions (safety, comfort), work quality of life (remuneration, work-life balance), recognition of work, gender equity	Improving	-
	Ima	Fishing image	Perception of fishing profession by new entrants	Positive	-
Minimise habitat and ecological fishing footprint (1) (2) (3) (4)	**Sel**	Size selectivity	Proportion of bottom trawlers equipped with a 50 mm square mesh cod-end	100%	-
	Dev	Smart devices	Proportion of modernised vessels with bycatch- or impact-reducing technology (BT: smart & energy-efficient gear; SSF: equipment to reduce sensitive species bycatch)	100%	-

Good governance structure (1) (4) (5)	**CFP**	Common Fisheries Policy	Effective CFP implementation at Mediterranean level	Achieved objectives	-

Some precisions about the thresholds: Yss threshold corresponds to a 90% reduction in the current number of sensitive species catch. Sub threshold corresponds to a level 10% higher than the current amount of subsidies. Emp threshold corresponds to an employment level 30% higher than the current one. For qualitative threshold (Wor, Ima, CFP) : Wor+ indicates an improvement in working conditions, with notable advances in safety at sea, promotion of decent work, better remuneration, greater gender inclusivity, and enhanced onboard comfort and safety. Ima+ means that the younger generation of fishers has a positive perception of the profession, increasing the sector's attractiveness. CFP+ means that the objectives set by the 2013 reform, along with other goals (e.g., sustainable stock exploitation, EBFM, stakeholder involvement), are achieved, resulting in effective policy implementation.

Table S3.2 : Detailed information on variables : justification of their definition, threshold and initial state

Acronym	Variable	Definition details	Threshold justification	Initial state justification
Cc	Climate change	The SSP2 RCP4,5 scenario corresponds to the continuation of current socioeconomic and technological trajectories (SSP2), the SST is a good proxy of environmental and physico-biogeochemical change induced by climate change. Climate change could drive physical and biogeochemical shifts, altering marine ecosystems through acidification, deoxygenation, extreme events, changes in productivity, and cascading impacts on community structure, trophic networks, and species distributions. We consider that by 2040, the effects of global warming in the SSP2 RCP4.5 scenario will be visible as suggested by certain models (Moullec et al., 2019, 2023)	Value of mean annual SST projected in 2040 in the SSP2 RCP 4.5 scenario for the GoL (estimated at 18,6°C by IPCC, 2023; Copernicus Interactive Climate Atlas). We have chosen to set the SST threshold in relation to 2040 and not beyond, so that it is consistent with the model's time horizon (2050-2060) and the duration of the process (medium-long term: effects of the process by 10-20 years).	**(-)** because the SST in the GoL is currently estimated at 18°C on average (for the period 2021-2040, by IPCC, 2023; Copernicus Interactive Climate Atlas)
Hco	Coastal habitats	Good ecological condition for benthic habitats corresponds to a condition that preserves seafloor integrity, ensuring that the structure and functions of ecosystems are safeguarded and that benthic ecosystems are not adversely affected. (Directive 2008/56/EC D1 : descriptors D1 and D6 , European Parliament ; Council of the European Union, 2008; Boyé et al., 2023)	Values based on the results of a participatory science workshop conducted as part of the ADAPT project, bringing together fisheries and conservation stakeholders of the GoL They define a target state by 2050 of 75% of the continental shelf in good ecological condition (coastal habitats) and 100% of the canyon and abysses (offshore habitats) in good ecological condition (revised to 90% in the model to be more representative)	**(-)** because according to the environmental report of the (DIRM, 2022b) in 2018 none of the benthic habitats achieving good ecological status in Mediterranean (all have an intermediate or high gap to it) and the study of Jac et al., 2020 shows that the majority of coastal habitat are concerned by a loss of habitat and the majority of offshore habitats by adverse effects and none of both habitat types achieve good ecological status in the GoL
Hof	Offshore habitats			
Rec	Recruitment	The recruitment corresponds to the number of juvenile incorporated into adult populations after their survival in nurseries and migration towards adult habitats (Cheminée et al., 2016), species considered are the 15 principal species fished by SSF and BT	Number of recruit at Blim: we chose to use Blim as the threshold value for recruitment in order to illustrate the processes linking biomass to recruitment. Recruitment is independent of spawning stock biomass as long as it is greater than Blim (Hockey-Stick stock-recruitment relationships). Below this level, low biomass can affect recruitment and affect stock renewal, hence the choice of the number of recruits at Blim.	**(+)** because on the 5 bentho-demersal stocks assessed for which a Blim estimate exists in the GoL, 3/5 have SSB > Blim (red mullet, horned octopus, blue-red shrimp) and the 2 others have SSB < Blim (European hake, blackbellied angler). So we consider that the current state of bentho-demersal stock is B > Blim in average so number of recruits > recruits at Blim so Rec+ for the initial state, it's a strong assumption
Lmx	Mean maximum length in community	The mean Lmax in community is a size based indicator wich quantifies relative abundances of large and small individuals in a community and is defined in Bitetto et al., 2019	Value of Lmax in the bentho-demersal community is higher than 65,2 cm : according to the Bitteto et al., 2019 study (Fig.S3) for the GSA7 for 1995-2015, the estimated value of Lmax for bentho-demersal community was the highest in 1995 at 65,2cm, it's 3cm more than the latest estimation of mean Lmax in 2015 (62,2 cm)	**(-)** because the current mean Lmax in bentho-demersal community if estimated at 62.2 cm. The most recent information available for estimating Lmax dates from 2015. Given the trend illustrated in the study by Bitetto et al., 2019, it is assumed that the current value is less than or equal to that of 2015.
Yss	Sensitive species incidental catch		We choose a decrease of 90% of bycatch according to the current value (i.e. 25 individuals/kT) to have a threshold that is consistent with the objectives set by stakeholders during the ADAPT project's participatory workshop.	**(+)** because the number of bycatch by both fleets in Mediterranean Sea is equal to 245 individuals/kT We used the method of Quemper et al., 2025 to calculate this value by multiplying average bycatch rates/days at sea per fishing gear in the Western-Mediterranea Sea (ICES, 2022) with days at sea for french BT fleet and SSF (STECF FDI)
Ssb	Spawning stock biomass	species considered are the 15 principal species fished by SSF and BT	Bmsy is a reference point used in stock assessments reflecting the state of a stock's biomass and is also one of the descriptor of the MSFD (D3C2) reflecting the good ecological status of commercial	**(-)** because on the 5 bentho-demersal stocks assessed for which a Bmsy estimate exists in the GoL : 2/5 stocks have B > Bmsy (horned ocotpus, red mullet), and 3/5 have B<Bmsy (european hake,

			species	blackbellied angler, blue and red shrimp), so we consider that the current state of bentho-demersal stock is B<Bmsy in average so Ssb-
Ebt	BT fleet fishing effort		Fmsy (~Emsy in our study) is a reference point used in stock assessments to reflect the fishing pressure exerts on stock and is also one of the descriptor of the MSFD (D3C1) reflecting the good ecological status of commercial species	**(+)** because on the 6 bentho-demersal stocks assessed for which a Fmsy estimate exists in the GoL : 3/6 stocks have F > Fmsy (european hake, blue and red shrimp, balck bellied angler), so by measure of precaution we consider that the current state of the fishing effort is E > Emsy
Esf	SSF fishing effort			
Ybt	BT fleet yield		Ymsy corresponds to the theorical maximum catch volume associated to the Emsy in the Gordon-Schaefer model (Gordon, 1954)	**(-)** because given the current situation of fishing effort for assessed stocks (3/6 with F > Fmsy), we can consider that stocks are overexploited, which translates into lower catch levels than the Ymsy
Ysf	SSF yield			
Pbt	BT fleet profit	**Profit = Income – Costs** (STECF 2024, STECF AER, Quemper et al., 2025). **- Income**: mean annual fleet income = value of landings + other income (from alternative activities or leasing out quotas; subsidies are excluded) **Costs**: mean annual fleet costs = labour + energy + repair & maintenance + other operating costs *Labour costs*: personnel remuneration, taxes, social contributions + unpaid labour ; *Energy costs*: fuel purchase (taw-free diesel exemption counted as "Subsidies") ; *Repair & maintenance*: regular upkeep of vessels and equipment ; *Other operating costs*: Lease/rental payments for quota (not relevant in French Mediterranean fisheries, set to 0 in STECF AER data); *Other operating costs* : other that are not belonging to the previous categories	The profit at MEY corresponds at the equilibrium to the maximum profit of a fishery (according to a given effort level lower than the Emsy) in the Gordon-Schaefer model (incomes are proportional to catch and costs proportional to fishing effort)	**(-)** because the profit is negative for bottom trawler fleet (without the subsidies) Pbt = - 375 755.3€ , and is positive for SSF with Psf = 8 774 496.4 € (STECF AER, mean 2018-2023) but probably lower than the profit at MEY according to the corresponding effort level which is higher than MSY (STECF AER, mean 2018-2023)
Psf	SSF profit			
Sub	Subsidies	Subsidy is define by WTO as a "financial contribution" by a government or any public body which confers "benefit" to the private sector via transfers of funds. We can subdivide it in two main categories regarded their impact on fish stocks over time (Sumaila et al., 2019) -**Capacity-enhancing subsidies** (could indirectly lead to overexploitation of the fishery resource) : publical subsidies (i.e. operating subsidies, short terms financial supports), tax-free diesel, fisheries access subsidies, investments for vessels construction, renewal and modernization -**Beneficial subsidies** (could indirectly lead to sustainable management): investments in the promotion of fishery resource conservation and management (fishery management programs : stocks assessments, monitoring control and surveillance), fisheries research and development (increase scientific and technological knowledge)	The value of % is arbitrary for now, higher subsidies could be interpreted as higher investment in beneficial subsidies or in capacity-enhancing, so that we could illustrate both in the model	**(-)** because the current amount of subsidies according to French fishing fleets is 1 254 310€ (mean annual amount over 2018-2023, STECF AER) with 252 847€ for SSF and 1 001 463€ for BT fleet In the EU fishing fleet (considering all countries), 53% of subsidies were for capacity enhancement, 40% for beneficial and 7% for ambiguous ones (Sumaila et al, 2019)

BtP	BT fleet profitability	This variable is added to make it easier to integrate subsidies into the model by using profit and subsidies to give profitability (~GOS) : illustrate cases when fisheries are highly dependent on subsidies or not -The GOS represents the financial resources available by a fishing fleet, its an accounting aggregate which corresponds to the income from which costs have been deducted and public subsidies added (Quemper et al, 2025), as we have an aggregate subsidy variable, we consider all subsidy in the GOS GOS = Profit + subsidies = Income - costs + subsidies	A positive GOS (i.e. a profitable fishing activity) was one of the sustainability targets set by stakeholders during the ADAPT project's participatory workshop	**(-)** because the current GOS is negative for BT fleet (-6257€ , mean over 2018-2023, STECF AER)
SfP	SSF profitability			**(+)** because the current GOS is positive for SSF (9027343.4€ mean over 2018-2023, STECF AER)
Emp	Employment		Value is based on the results of a participatory science workshop conducted as part of the ADAPT project, who have proposed "an increase in the number of jobs in the fisheries sector". Given the 31.5% decline in the number of active fishers since 2010 (2,626 fishers; Daures et al., 2013)) and the stakeholders' expressed desire to increase employment in the sector, we set a threshold 30% higher than the current crew level.	**(-)** because the current number of active crew in the GoL is 1799 for the Mediterranean facade (mean over 2019-2023, Ifremer 2024)
Wor	Working conditions	Definition adapted from ADAPT (working rythm balanced, well-being at work) and Gascuel & Dewals 2020 sustainability criteria n°7 (Criteria 7,2: remuneration; Criteria 7,3 : social justice in employment -> remuneration, intergenerational equity, gender, Criteria 7,4 : labour law and social rights, Criteria 7,5 : safety on board. (number of accident/number of fishing days) and n°9,1 (working conditions)	This variable has a qualitative threshold. We chose a fairly distinct threshold to reflect unfavorable working conditions and idealized working conditions as suggested during ADAPT workshops	**(-)** because professional fishing in France is characterized by an intense work rhythm , with atypical hours, long absences at sea, and cumulative fatigue, combined with highly variable incomes dependent on catch results, and financially precarious (Charvet et al., 2016). Vessels are generally old and often poorly equipped to improve comfort or safety on board (average age in the Mediterranean: 32.5 years; Ifremer 2024). It is also one of the most accident-prone professions, with fishing remaining the most dangerous sector in France in terms of fatal occupational accidents, at 5.3 deaths per 10 000 FTE compared with 0.28 in other sectors (Ministère de la transition ecologique, 2017). Women represent only 4% of fishers across all French fisheries, and young people just 10% of the workforce (Carif-Oref Occitanie, 2023a).
Ima	**Fishing image**	Definition adapted from Gascuel and Dewals (2020) sustainability criterion no. 9.2, this indicator reflects the influence of the fleet's image and the fishing profession's perception on its attractiveness. Note that this refers specifically to the perception held by potential new entrants such as students in maritime training programs rather than the public's opinion. It concerns how young people envision a career in fishing, a perception that may be shaped by public discourse (e.g., NGOs), the state of fishery resources, or working conditions	This variable has a qualitative threshold. We chose a fairly distinct threshold to reflect the current situation of low attractiveness of the profession, as well as the idealized case of the profession being attractive to young people, with high intergenerational turnover as suggested during ADAPT workshops	**(-) b**ecause the Mediterranean fisheries face weak generational renewal: young fishers represent only 10% of the workforce, while 47% are over 45. Few graduates from maritime training enter the profession, often diverted by default choices or geographic constraints. Despite declining workforce numbers, recruitment remains strained as retirements are hard to replace due to the sector's low attractiveness (Carif-Oref Occitanie, 2023a). The aging of the profession is more pronounced in the Mediterranean than in other regions.
Sel	**Size selectivity**		We choose a 50 mm square mesh size for the BT codend because it is a recommendation of the European Council (with incentive measures: Council Regulation (EU) 2025/219 of 30 January 2025). According to the results of Luchetti et al. (2021), the L50 for certain species (e.g. *Merluccius merluccius* and cephalopods)	**(-)** because the current mesh size for bottom trawlers in Mediterranean sea is at 40mm (Council Regulation (EC) No 1967/2006 of 21 December 2006), even with a such mesh size the catch of immature fishes are still high (Luchetti et al, 2021), only few bottom trawlers have higher mesh size

			would not prevent immature fish from being caught, even with a 50 mm square mesh size. A square mesh size of 45–50 mm was also chosen in the study by Bahamon et al, (2024) to assess the selectivity of BT in GSA6. The choice of 100% of the vessels are equipped with this mesh size is more arbitrary.	
Dev	Smart devices	Proportion of vessels equipped with modified gear or smart devices: *Bottom trawlers*: share of “smart” vessels using technologies to reduce seabed impact (e.g. beam, AI-based selectivity : Connect and Reverse projects), bycatch of non-target species (Game of Trawl), or improve energy efficiency (biofuels, hybrid/electric engines : Oléan 100 Sète, Hyba project). *Small-scale fisheries*: share of vessels using devices to limit sensitive species bycatch (pingers, hook modifications, bird-scaring lines). Both fleets are considered due to their respective bycatch issues (SSF: birds, mammals; BT: elasmobranchs)	The choice of 100% of the vessels are equipped with this mesh size is more arbitrary.	**(-)** because the majority of fishing vessels are not equipped with devices that reduce the bycatch of sensitive species, and "smart" vessels, such as smart bottom trawlers, are still in the testing phase (there are no operational vessels yet).
CFP	Common Fisheries Policy	**Objectives to achieve :** Based on the 2013 reform of the Common Fisheries Policy (Regulation (EU) No 1380/2013), scientific recommendations (Drouineau et al., 2023) and the European Parliament resolution (European Parliament, 2024), the overarching goal is to ensure the environmental, social, and economic sustainability of fisheries. This includes sustainable exploitation of stocks (MSY), ecosystem-based management, landing obligation, multi-annual management plans, and stronger stakeholder participation. More ambitious objectives include reforming subsidies (e.g., phasing out tax exemptions for marine diesel), supporting decarbonization, and improving technical measures to better align fishing practices with stock conservation	A qualitative threshold, defined as an aggregated variable encompassing multiple sustainability objectives (e.g., ecosystem-based fisheries management, stakeholder involvement). It will be essential for identifying a target state under a governance framework that ensures long-term sustainability	**(-)** because The CFP is weakly implemented, with objectives only partly achieved: **Unsustainable exploitation:** Of 264 Mediterranean species, only 12 Gulf of Lion stocks are assessed, and just two (red mullet, horned octopus) are sustainably exploited. **Insufficient ecosystem-based management:** Tools exist to assess impacts on food webs and socio-ecosystems, but integration into fisheries management and EU environmental policies is limited. **Need for better technical measures:** Improved knowledge of species biology and fishing patterns is required to assess stocks and design effective regulations. **Limited stakeholder involvement:** Participation is mainly via subsidies or bans; Article 17 CFP allows broader inclusion, but in practice it remains poorly effective.

Some precisions about initial state: to define the initial values of Rec, SSB, Ebt, and Esf, we relied on available stock assessments for species targeted by SSF and BT fleets (see Appendix X). Due to the limited number of current assessments in the Mediterranean, we assumed that the current stock status (biomass, recruitment, fishing effort) can be approximated by the average status of all assessed bentho-demersal stocks in the Gulf of Lion (GSA7)

Appendix S4: Rules of the GoL-SES model and their detailed description

Table S4: Rules of the socio-ecosystem modelled and their description

Category	Name	Rule	Explanation	Precision	Source
Climate change	**R1**	Cc- >> Cc+	By 2040, the SST could rise and resulting climate-induced changes on marine ecosystems and living resources could increase		IPCC 2023, Copernicus
Ssb recovery	**R2**	Cc-, Rec+, Ebt-, Esf- >> Ssb+	The SSB could exceed Bmsy with moderate climate impacts, good recruitment, and a drastic reduced fishing pressure	No Hco, Hof, Sel in the rule because whatever their condition (+ or -) the realization is similar	(Fiorentino et al., 2008; Maynou et al., 2014; Martín et al., 2019; Moullec et al., 2023)
Ssb recovery	**R3**	Cc+, Rec+, Ebt-, Esf-, Sel+, Hco+, Hof+ >> Ssb+	The SSB could exceed Bmsy with significant climate-induced changes if those effects are offset by good recruitment, reduced fishing pressure, more selective fishing, and good ecological state of habitats		Assumption Climate induced changes : (Occhipinti-Ambrogi, 2007; Cheung et al., 2011; Blanchard et al., 2012; Seitz et al., 2014; Moullec et al., 2016, 2019b; González-Andrés et al., 2024)
Stock collapse	**R4**	Esf+, Ebt+, Ysf-, Ybt- >> Ssb-, Rec-	A stock collapse could occur if stocks are affected by recruitment overfishing	Stock collapse corresponds to B < Blim and an affected recruitment due to a high fishing pressure E > Elim and the corresponding low catch (Y-)	Population dynamics theory
Ssb decline	**R5**	Rec- >> Ssb-	The SSB could fall below Bmsy if stock renewal is affected		Cheminée et al., 2016
Ssb decline	**R6**	Esf+, Ebt+ >> Ssb-	The SSB could fall below Bmsy if stocks are subject to high fishing pressure	No Rec, Ssi, Hco, Hof, Cc in the rule because whatever their condition (+ or -) the realization is similar	Population dynamics theory (Gordon Schaefer model see appendix S5)
Ssb decline	**R7**	Cc-, Rec+, Ebt-, Esf-, Sel- >> Ssb-	The SSB could fall below Bmsy, despite moderate climate impacts and good recruitment, if the stock is already too depleted and fishing pressure isn't enough reduced	No Hco, Hof in the rule because whatever their condition (+ or -) the realization is similar	Assumption
Ssb decline	**R8**	Cc+, Rec+, Ebt-, Esf- >> Ssb-	The SSB could fall below Bmsy, despite good recruitment and a reduced fishing pressure if the climate-induced changes impact negatively the biomass	No Hco, Hof, Sel in the rule because whatever their condition (+ or -) the realization is similar	Assumption : The cumulative negative effects on SSB are not well known, as a precaution, we consider that the accumulation of pressures (low selectivity, negative effects of CC) may prevent the biomass from reaching Bmsy despite lower effort (even a drastic reduction) Climate induced changes : (Occhipinti-Ambrogi, 2007; Cheung et al., 2011; Blanchard et al., 2012; Seitz et al., 2014; Moullec et al., 2016, 2019b; González-Andrés et al., 2024)
Recruitment overfishing	**R9**	Ssb-, Ebt+, Esf+ >> Rec-	The stock renewal could be affected because of recruitment overfishing	No Hco, Hof in the rule because whatever their condition (+ or -) the realization is similar	Population dynamic theory (stock-recruitment relationship with the Hockey-Stick model : see appendix S5

Affected recruitment	**R10**	Cc+, Hof-, Hco- >> Rec-	Stock renewal could be affected by a combination of negative pressures, including increased environmental variability and mismatch phenomena due to climate change, as well as poor habitat quality		(Cushing, 1990; Lejeusne et al., 2010; Cheminée et al., 2016; Stergiou et al., 2016)
Recruitment recovery	**R11**	Hof+, Hco+ >> Rec+	The recruitment of bentho-demersal stocks can be maintained thanks to the functionality of essential fish habitats	(No Ebt, Esf — as long as Elim is not reached, recruitment is not affected by fishing effort, meaning it can occur in both E+ and E- situations)	Beck et al., 2001; Gianoulaki et al, 2013 ; Colloca et al, 2015 ; Seitz et al., 2015
Degradated offshore habitat quality	**R12**	Ebt+ >> Hof-	The proportion of offshore habitats in good ecological condition could decline if fishing pressure from physically disruptive active gears, like bottom trawlers, remains high.	No Dev in the rule because whatever their condition (+ or -) the realization is similar	(Hinz et al., 2009; Collie et al., 2017; Durán et al., 2023)
Degradated offshore habitat quality	**R13**	Dev-, Ebt- >> Hof-	The proportion of offshore habitats in good ecological condition could decline despite a reduced fishing pressure of bottom trawlers if any technical devices reduced their impact on benthic habitats		Assumption
Improved offshore habitat quality	**R14**	Dev+, Ebt- >> Hof+	The proportion of offshore habitats in good ecological condition could increase if bottom trawlers fishing pressure is significantly reduced and all are equipped with technical devices reducing their impact on benthic habitats		Assumption
Degradated coastal habitat quality	**R15**	Esf+ >> Hco-	The proportion of coastal habitats in good ecological condition could decline due to high fishing pressure of SSF combined with other pressure sources (e.g. climate change and other coastal human activities)	No Cc in the rule because whatever its condition (+ or -) the realization is similar	Current situation
Degradated coastal habitat quality	**R16**	Esf- >> Hco-	The proportion of coastal habitats in good ecological condition could decline despite reduced SSF fishing pressure if pressures from other coastal human activities or climate change remain high.	No Cc in the rule because whatever its condition (+ or -) the realization is similar The CC variable doesn't stand here because we lack the variable "other uses" : Cc-, Esf- >> Hco- (other human coastal activities) and Cc+, Esf- >> Hco- (Cc pressure)	(Danovaro et al., 2018; Verges et al., 2014; Pairaud et al., 2013).
Improved coastal habitat quality	**R17**	Cc-, Esf- >> Hco+	The proportion of coastal habitats in good ecological condition could increase with moderate climate change effects and if SSF fishing pressure and other coastal human activities are reduced		Assumption
Effort transfert BT -> SSF, improved offshore habitat quality	**R18**	Dev+, Ebt-, Esf+ >> Hof+, Hco-	In the context of effort transfer from BT to SSF (detrawling), the proportion of offshore habitats in good ecological condition could increase due to a significant reduced fishing pressure of BT pressure while that of coastal habitats could decline due to coastal strip saturation		Combination of rules R15 and R16
Effort transfert BT -> SSF, degradated offshore habitat quality	**R19**	Dev-, Ebt-, Esf+ >> Hof-, Hco-	In the context of effort transfer from BT to SSF (detrawling), the proportion of offshore habitats in good ecological condition could decline despite reduced fishing effort if less-impacting technical devices are not used, while that of coastal habitats could also decline due to coastal strip saturation		Combination of rules R14 and R16
Effort transfert SSF	**R20**	Cc-, Ebt+, Esf- >> Hof-, Hco+	In the context of effort transfer from bottom trawlers to small-scale		Combination of rules R13 and R18

-> BT, improved coastal habitat quality			fisheries (national withdrawal), the proportion of coastal habitats in good ecological condition could increase under moderate climate change effects if SSF and other coastal human activities are reduced, while that of offshore habitats could decline due to significant fishing pressure exerted by BT		
Effort transfert SSF -> BT, degardated coastal habitat quality	**R21**	Ebt+, Esf- >> Hof-, Hco-	In the context of effort transfer from bottom trawlers to small-scale fisheries (national withdrawal), the proportion of coastal habitats in good ecological condition could decline despite reduced fishing effort if pressures from other coastal human activities remain high, while that of offshore habitats could also decline due to significant fishing pressure exerted by bottom trawlers		Combination of rules R13 and R17
Greater Lmax	**R22**	Cc-, Sel+ >> Lmx+	The mean Lmax in community could increase if BT size-selectivity improves		(Nguyen and Larsen, 2013; Lucchetti et al., 2021b; Moullec et al., 2023)
Lower Lmax	**R23**	Cc+, Sel+ >> Lmx-	The mean Lmax in the community could decline despite improved BT size-selectivity if climate change induces a shrinking body size phenomenon		(Sumaila et al., 2011; Cheung et al., 2013; Moullec et al., 2019)
Lower Lmax	**R24**	Sel- >> Lmx-	The mean Lmax in community could decline if BT size-selectivity is weak		Current situation
Increased sensitive species catch	**R25**	Dev- >> Yss+	The number of sensitive species incidental catch could increase if vessels species-selectivity is weak		Current situation
Increased sensitive species catch	**R26**	Dev+, Esf+ >> Yss+	The number of sensitive species incidental catch could increase despite improved vessel selectivity if the SSF fishing pressure remains high		Assumption
Decreased sensitive species catch	**R27**	Dev+, Esf- >> Yss-	The number of sensitive species incidental catch could decrease if vessel selectivity improves and SSF fishing pressure decreases		(Beddington et al., 2005; Grafton et al., 2010; Northridge et al., 2017)
Underexploitation BT	**R28**	Ssb+, Ebt- >> Ybt-	The catch volume of BT could decrease in a situation of stock under exploitation		Gordon-Schaefer production surplus model
Underexploitation SSF	**R29**	Ssb+, Esf- >> Ysf-	The catch volume of SSF could decrease in a situation of stock under exploitation		Gordon-Schaefer production surplus model
Full-exploitation BT	**R30**	Ssb+, Ebt- >> Ybt+	The catch volume of BT could increase in a situation of stock full exploitation, with fishing effort slightly below Emsy		Gordon-Schaefer production surplus model
Full-exploitation SSF	**R31**	Ssb+, Esf- >> Ysf+	The catch volume of SSF could increase in a situation of stock full exploitation, with fishing effort slightly below Emsy		Gordon-Schaefer production surplus model
Full-exploitation BT	**R32**	Ssb-, Ebt+ >> Ybt+	The catch volume of BT could increase in a situation of stock full exploitation, with fishing effort slightly above Emsy		Gordon-Schaefer production surplus model
Full-exploitation SSF	**R33**	Ssb-, Esf+ >> Ysf+	The catch volume of SSF could increase in a situation of stock full exploitation, with fishing effort slightly above Emsy		Gordon-Schaefer production surplus model
Overexploitation BT	**R34**	Ssb-, Ebt+ >> Ybt-	The catch volume of BT could decrease in a situation of stock overexploitation		Gordon-Schaefer production surplus model
Overexploitation	**R35**	Ssb-, Esf+ >> Ysf-	The catch volume of SSF could decrease in a situation of stock		Gordon-Schaefer production surplus model

SSF			overexploitation		
Fall in catch with stock collapse	**R36**	Ssb-, Rec- >> Ybt-, Ysf-	The catch volume of both fleets could fall if the stock collapses	Both fisheries depend on the same resource, so a simultaneous reduction in catches can be envisaged; implementing Ybt and Ysf jointly in the rule means this occurs synchronously.	Common sense : not enough resource -> low long term yield
Catch transferability	**R37**	Ebt-, Esf+ >> Ybt-, Ysf+	The catch volume of SSF could increase, while that of BT could decrease, if a catch transfer from BT to SSF occurs	SSF fishing effort would not necessarily exceed MSY if such a transfer occurred, but it is used here to illustrate the transfer between fleets in the model	Martin et al., 2019 ; Mouillard and Gascuel 2025
Profit decrease SSF (underexploitation, insufficient income)	**R38**	Esf-, Ysf-, Lmx- >> Psf-	The profit of SSF could decrease despite low costs if income is insufficient in a situation of stock under exploitation		Common sense : income not sufficient to maximize profit
Profit decrease SSF (overexploitation, economic over investment)	**R39**	Esf+, Ysf- >> Psf-	The profit of SSF could decrease, potentially becoming very low or negative, if costs are too high and income insufficient in a situation of economic over-investment (overexploitation).		Common sense : costs > income
Profit increase SSF (MEY)	**R40**	Esf-, Ysf- >> Psf+	The profit of SSF could be maximized if fishing effort is at MEY	No Lmx in the rule because whether Lmax increases (in under exploitation with profitable prices despite low volumes) or decreases (at MEY, where current Lmax can still yield maximum profit), profit maximization can be assumed	Gordon-Schaefer bioeconomic model
Profit increase SSF (high economic value inherent to SSF)	**R41**	Esf-, Ysf+ >> Psf+	The profit of SSF could be maximized with low costs and high income, thanks to the higher economic value of SSF products in a situation of full exploitation	No Lmx is included in the rule because the high added value of SSF products is sufficient to ensure adequate income despite low costs	Quemper et al., 2025
Profit increase SSF (high economic value of larger individuals)	**R42**	Esf+, Ysf+, Lmx+ >> Psf+	The profit of SSF could be maximized despite high costs if income is high enough thanks to a higher economic value of larger SSF products in a situation of full exploitation	An increase in Lmax (Lmax+) enhances the commercial value of products and helps offset high costs	Common sense : sufficient income to offste high costs Influence of Lmax on price : (Gates, 1974; Tsikliras and Polymeros, 2014; Sjöberg, 2015; Yildiz et al., 2023)
Profit decrease BT (low economic value)	**R43**	Ebt-, Lmx- >> Pbt-	The profit of BT could decrease despite low costs if income is insufficient, due to the lower economic value of trawl fishery products and the absence of price increases in both full and under exploitation situations	No Ybt in the rule because, whether in full exploitation with high catch volume (Ybt+) and low costs (Ebt-), profit is limited by the lower economic value of trawl products and their lack of increase with fish size (Lmx-), or in under-exploitation (Ybt-, Ebt-) combined with low commercial value (Lmx-), catch volume is insufficient to maximize profit	Common sense : income not sufficient to maximize profit BT trawlers products have low added value : Quemper et al., 2025
Profit decrease BT	**R44**	Ebt+, Ybt- >> Pbt-	The profit of BT could decrease, potentially becoming very low or		Common sense : costs > income

(overexploitation, economic over-investment)			negative, if costs are too high and income insufficient in a situation of economic over-investment (overexploitation).		
Profit decrease BT (costs too high without tech)	**R45**	Ebt+, Ybt+, Dev- >> Pbt-	The profit of BT could decrease if income is insufficient to cover high costs without improvements in energy efficiency		STECF AER (high part of fuel costs in total costs)
Profit increase BT (MEY)	**R46**	Ebt-, Ybt- >> Pbt+	The profit of BT could be maximized if fishing effort is at MEY		Gordon-Schaefer bioeconomic model
Profit increase BT (high economic value)	**R47**	Ebt-, Ybt+, Lmx+ >> Pbt+	The profit of BT could be maximized with low costs and high income, thanks to the higher economic value of BT products due to higher prices in a situation of full exploitation		Common sense : sufficient income to maximize profit
Profit increase BT (technology reduces costs)	**R48**	Ebt+, Ybt+, Dev+ >> Pbt+	The profit of BT could be maximized if high costs are reduced through improved energy efficiency and income remains sufficient		Assumption : Improved engines are significantly more energy-efficient and can greatly reduce the part of fuel costs in fleet total costs
Unprofitable activity BT	**R49**	Pbt-, Sub- >> BtP-	BT fishing activity could be unprofitable if subsidies are insufficient to offset negative profit		Common sense
Unprofitable activity SSF	**R50**	Psf-, Sub- >> SfP-	SSF fishing activity could be unprofitable if subsidies are insufficient to offset negative profit		Common sense
Artificial profitability BT	**R51**	Pbt-, Sub+ >> BtP+	BT fishing activity could be profitable if subsidies are sufficient to offset negative profit, creating a situation of artificial profitability		Quemper et al., 2025
Artificial profitability SSF	**R52**	Psf-, Sub+ >> SfP+	SSF fishing activity could be profitable if subsidies are sufficient to offset negative profit, creating a situation of artificial profitability		Quemper et al., 2025
Profitable activity BT (positive profit)	**R53**	Pbt- >> BtP+	BT fishing activity could be profitable if profit remains positive, even if not maximized		Common sense
Profitable activity SSF (positive profit)	**R54**	Psf- >> SfP+	SSF fishing activity could be profitable if profit remains positive, even if not maximized		Common sense
Profitable activity BT (maximum profit)	**R55**	Pbt+ >> BtP+	BT fishing activity could be profitable if profit is maximized		Common sense
Profitable activity SSF (maximum profit)	**R56**	Psf+ >> SfP+	SSF fishing activity could be profitable if profit is maximized		Common sense
Better well being of fishers	**R57**	BtP+, SfP+, Emp+, Dev+, CFP+ >> Wor+	Fishers' well-being could improve with good quality of work life (fair remuneration, balanced work–life rhythm), comfortable and safe onboard conditions from vessel modernization, and a feeling of recognition through their inclusion in decision-making processes		Assumption
Poor working conditions for	**R58**	BtP-, SfP-, Emp-, Dev-, CFP- >> Wor-	Working conditions could deteriorate with poor quality of work life (unstable remuneration, intense work rhythm), rudimentary and unsafe		Assumption

fishers			onboard conditions without vessel modernization, and a sense of malaise or misunderstanding due to the lack of fisher inclusion in decision-making processes		
Youth disinterest in fishing	**R59**	Yss+, Ssb-, Hco-, Hof-, Lmx-, Cc+ >> Ima-	New entrants could develop a negative view of fishing if the activity is perceived as harmful to ecosystems, especially when these ecosystems are perceived as degraded and uncertain in their ability to sustain the natural resources essential for the profession, with climate change further exacerbating these uncertainties.		Power et al., 2014 ; Seara et al., 2020 ; Harper et al., 2023
Youth attractiveness to fishing	**R60**	Yss-, Ssb+, Hco+, Hof+, Lmx+, Cc- >> Ima+	New entrants could develop a positive view of fishing if the activity is perceived as sustainable and ecosystems are seen as healthy, with a reliable capacity to provide the natural resources essential for the profession ("nourishing sea" perception), and if concerns about climate change effects remain moderate		R59 contrary
Youth disinterest in fishing	**R61**	Emp-, Pbt-, Psf-, Wor- >> Ima-	New entrants could develop a negative view of fishing if the activity is perceived as economically unviable, with limited job opportunities, low profits, and a poor quality of life.		Power et al., 2014 ; Tam et al., 2018 ; Spyros 2023 ; Theodorou and Spyrou 2023
Youth attractiveness to fishing	**R62**	Emp+, Wor+ Psf+, Pbt+ >> Ima+	New entrants could develop a positive view of fishing if the activity is perceived as economically sustainable and dynamic, offering job opportunities, good profits, and an improved quality of life		R61 contrary
Good generationnal turnover	**R63**	Ima+, Wor+ >> Emp+	Number of crew members could increase if the profession attracts younger generations and promotes well-being at work, facilitating generational turnover		Common sense
Ageing profession	**R64**	Ima-, Wor- >> Emp-	Number of crew members could decrease if the profession is unattractive to younger generations and if working conditions deteriorate, leading to an ageing profession		Current situation
SSF generating jobs	**R65**	Esf+, SfP+ >> Emp+	Number of crew members could increase if SSF fishing activity is sustained, regardless of bottom-trawler activity	No Ebt, BtP in the rule because whether bottom trawler activity is sustained (Ebt+, BtP+) or not (Ebt-, BtP-), it is mainly small-scale fisheries activity that drives employment generation	Quemper et al., 2025
Fall in employment	**R66**	Esf-, SfP-, Ebt-, BtP- >> Emp-	Number of crew members could fall if a crisis affects the fishing activity of both fleets		Common sense
CFP reform	**R67**	CFP- >> CFP+	The CFP implementation could be effective if reformed into a policy emphasizing a stronger ecosystem-based approach, enhanced protection and conservation measures, and greater stakeholder involvement in management and decision-making, thereby enabling the achievement of its objectives		Not reformed since 2013
CFP reform triggered by a crisis	**R68**	Cc+, Ssb-, Hco-, Hof-, Lmx-, BtP-, SfP-, Emp- >> CFP+	The CFP could be reformed and effectively implemented in response to a widespread crisis affecting both the environment and fishing sector		Historic observations : PCP successive reforms, bluefin tuna Mediterranean crisis 2000's
Increase in capacity-	**R69**	CFP- >> Sub+	Capacity-enhancing subsidies could increase in a context of socio-economic crisis or under a productivist policy orientation to support		Historical observations: The COVID-19 pandemic and the fuel price surge linked to the war in

enhancing subsidies			fishing activity		Ukraine
Transition to low-impact fishing practices	**R70**	CFP+ >> Sub+, Dev+, Sel+	Effective CFP implementation towards conservation goals could drive a transition to low-impact fishing, supported by transition subsidies, selective gear adoption, and vessel upgrades to reduce impacts on sensitive species and habitats		Previous CFP reforms
Decrease in capacity-enhancing subsidies	**R71**	CFP+ >> Sub-, Dev+	Effective CFP implementation towards conservation goals could drive a transition to low-impact fishing by reducing capacity-enhancing subsidies (e.g., removal of tax exemptions for marine diesel) and encouraging the adoption of more energy-efficient technologies		Current context : Energy Taxation Directive under negotiation
Decrease in BT fishing capacities	**R72**	CFP+ >> Ebt-	Bottom-trawler fishing capacity could decrease with the reinforcement of existing multiannual management plans, such as through the continuation of the West Med Plan		Arrêté du 25 avril 2025 portant nouvelles zones de fermetures spatio-temporelles en mer Méditerranée pour certains navires battant pavillon français pour l'année 2025
Overall decrease in fishing capacities	**R73**	CFP+ >> Ebt-, Esf-	Overall fishing capacity of Gulf of Lion fleets could decrease under effective CFP implementation to achieve conservation objectives, such as reaching MSY for all exploited stocks		Assumption
Fall in fishing activities with crisis	**R74**	Emp-, BtP-, SfP- >> Ebt-, Esf-	Effort in both fleets could decline if the sector faces a socio-economic crisis, with insufficient workforce and unprofitable activities		Historical obsevrations : Covid-19 pandemic
Overall increase in fishing activites	**R75**	CFP-, Emp+, BtP+, SfP+ >> Ebt+, Esf+	Effort in both fleets could increase under a policy context favoring productivity, with weak CFP implementation and socio-economically supported fisheries		Doray et al., 2025
Increase in BT activity	**R76**	CFP-, Emp+, BtP+ >> Ebt+, Esf-	Effort of BT could increase while that of SSF could decrease under a national withdrawal scenario, with a neglected CFP in favor of individualistic policies aimed at sustaining economic growth, thereby favoring fleets ensuring continuous and abundant landings		Doray et al., 2025 ; Chevallier et al., 2025

Some explanations on the variables considered as influencing the following ones :

Ssb: The level of SSB results from the combination of multiple factors: recruitment, which can determine the subsequent adult cohort; fishing pressure and harvest (effort, selectivity, catches); environmental conditions, particularly the functionality of essential habitats (Seitz et al., 2014) and the effects induced by climate change, such as bottom-up effects or shifts in community structure (Cheung et al., 2011; Blanchard et al., 2012; Moullec et al., 2016; González-Andrés et al., 2024). SSB may increase if fishing effort is drastically reduced under moderate climate change (R2), or if strong climate impacts are offset by good habitat condition combined with reduced and more selective fishing pressure (R3). Conversely, SSB may fall below Bmsy in cases of stock collapse (R4), affected recruitment (R5), excessive fishing pressure (R6), depleted stocks unable to recover despite reduced fishing (R7), or negative impacts of climate change (R8).

Rec: Recruitment results from the interplay of multiple factors and can decline when SSB falls below the critical threshold Blim, when fishing pressure exceeds

Elim leading to recruitment overexploitation (R9), or simultaneously with SSB collapse (R4). It is also shaped by environmental parameters such as habitat quality, which is essential for early life stages (Beck et al., 2001), as well as climate change, which may strongly influence match–mismatch dynamics (R10, R11 : Lejeusne et al., 2010; Stergiou et al., 2016). For both SSB and recruitment, coastal and offshore habitats are considered, as essential habitats of bentho-demersal resources occur in both areas (Giannoulaki et al., 2013; Colloca et al., 2015).

Hof: Offshore benthic habitats, located beyond the 3-nautical-mile zone, are mainly affected by trawling activity, which causes significant disturbances (Hinz et al., 2009; Collie et al., 2017; Durán et al., 2023). Offshore habitats are assumed to be less sensitive to climate change than coastal ones, which is why variable *Cc* is not included in the rules. The proportion of offshore habitats in good ecological condition may increase if fishing pressure is strongly reduced and trawls are fully equipped with low-impact gear mitigating seafloor disturbance (R13), provided these innovations prove effective. Conversely, excessive fishing pressure (R12) or insufficient reduction without technological improvement (R12) may lead to further degradation.

Hco: Coastal habitats within the 3-nautical-mile zone are influenced not only by fishing but also by land-based and coastal activities (e.g., urbanization, pollution, tourism, boating) and by climate change effects, including physico-chemical, invasive species, and extreme events such as marine heatwaves, all of which accelerate benthic habitat degradation (Danovaro et al., 2018; Verges et al., 2014; Pairaud et al., 2013). This combination of pressures may prevent the achievement of good ecological status despite reduced fishing (R15, R16), although recovery is possible if both fishing and other anthropogenic pressures are limited and climate impacts remain moderate (R17). The rules representing effort transfer scenarios result from the combination of previously established rules affecting both coastal and offshore habitats.

Lmx: Mean Lmax in bentho-demersal communities is influenced by gear selectivity, with low bottom-trawl selectivity potentially disrupting demographic structure (R24). Increasing size selectivity in bottom trawls protects juveniles, enhancing recruitment, biomass, and demographic balance, and leads to more large individuals in the population (Moullec et al., 2023) (R22). Climate could induce a shrinking-body size effect on individuals, leading to a reduced mean Lmax (R23) (Sumaila et al., 2011; Cheung et al., 2013).

Yss: Incidental catches of sensitive species mainly result from fishing activities, with SSF accounting for 45% of such bycatch in the Western Mediterranean, compared to only 11% for trawlers (ICES, 2022; Quemper et al., 2025). The model therefore assumes bycatch is primarily driven by SSF effort.
Reducing fishing mortality and improving gear selectivity (e.g., AI-equipped trawls, Turtle Excluder Devices (TEDs) for trawlers, and modified hooks, lines for SSF) can reduce sensitive species catch (R27) otherwise they remain high (R25,26).

Ybt, Ysf: According to the Gordon-Schaefer surplus production model, equilibrium catch depends on biomass and fishing effort. Fleet-specific rules were defined based on the several possible exploitation scenarios (Appendix S5). Catch may increase under full exploitation (R30-33) or decrease with under-exploitation (R28, 29), over-exploitation (R34, 35), or stock collapse (R36). SSF catches can rise while trawler catches fall if effort shifts from trawlers to SSF (R37), as illustrated by Mouillard and Gascuel, (2025) and supported by Martín et al., 2019.

Pbt, Psf: Profit depends on both costs and revenues, which are implicit in the model. Costs are linked to fishing effort and may be reduced by technological innovations, such as more energy-efficient engines. Revenues depend on landings and market price, partly influenced by fish size since larger individuals are more valuable (Gates, 1974; Tsikliras and Polymeros, 2014; Sjöberg, 2015; Yildiz et al., 2023). Accordingly, variables such as *Ebt, Esf, Ybt, Ysf, Lmx,* and *Dev* can affect fleet profitability (see Fig. X). Profit may decline sharply or even become negative in case of overinvestment (R39, R44) and remain low due to high costs (R45) or insufficient revenues (R38, R43). It is maximized when fishing effort approaches MEY (R40, R46) and revenues increase through the sale of larger individuals (R42, R47). Specifically, SSF profit increases thanks to the high market value of its products (R41), while BT profit improves mainly through reduced fuel costs made possible by energy-efficient engines (R48).

BtP, SfP: Fleet profitability corresponds to the gross operating surplus (GOS) and depends on both profit and subsidies. Fishing activity may be unprofitable (GOS < 0) when profit is negative and subsidies are insufficient (R49, R50). Profitability can also be artificial (Quemper et al., 2025), meaning that profit is negative but the activity remains profitable (GOS > 0) due to subsidies (R51, R52). Finally, activity is profitable as long as profit is positive, whether below MEY (R53, R54) or close to MEY (R59, R60).

Wor: This variable is aggregated and includes criteria such as onboard safety and comfort, remuneration, work-life balance, and recognition of work. Fishers' well-being improves when profitability ensures fair remuneration, sufficient labor allows a balanced workload, vessel modernization enhances safety and comfort, and greater involvement in decision-making fosters recognition (R57). Conversely, working conditions deteriorate when low profitability reduces income, labor shortages increase workload, onboard safety and comfort remain poor, and limited participation in decision-making generates feelings of misunderstanding and discontent (R58).

Ima: Young people's perception of the fishing profession depends on the ecological state of marine resources and ecosystems (Ssb, Hco, Hof, Lmx, Yss), the economic viability of the activity (Pbt, Psf), and the quality of life it provides (Wor). A positive perception emerges when is seen as sustainable, supported by healthy ecosystems and stable resources (Seara et al., 2020; Harper et al., 2023), or when the activity is viewed as a viable and dynamic (Spyros et al., 2023; Theodorou & Spyrou, 2023) that offers an improved quality of life (Power et al., 2014; Tam et al., 2018), making the profession attractive to young people

(R60, R62). Conversely, degraded ecosystems, economic unviability, and difficult working conditions foster a negative perception, discouraging new entrants (R59, R61).

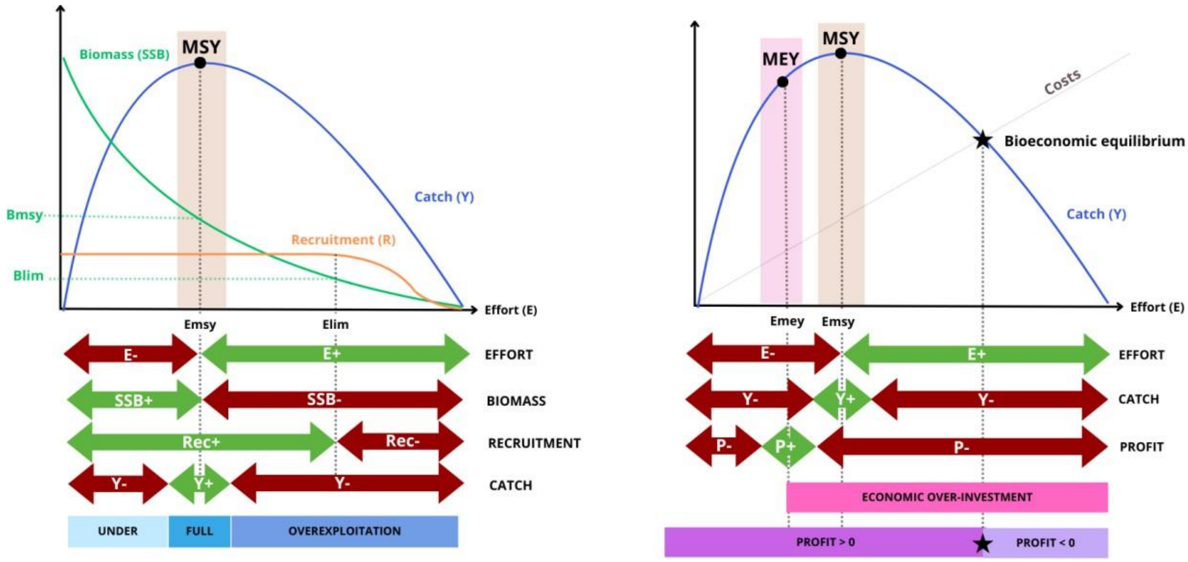
Emp: The number of engaged crew depend on fishing effort, fleet type, economic profitability, and job attractiveness. Jobs can increase with sustained SSF activity, which generates more employment per unit of catch than BT (R65, Quemper et al., 2025) or if generational turnover is supported by the profession's attractiveness (R63). Conversely, employment may decline if fishing effort collapses, the activity becomes unprofitable for both fleets (R66), or an ageing workforce is not replaced due to low job appeal (R64). Note that there is no equivalent rule for BT (*Esf+, Prosf+ >> Emp+*), as Emp is aggregated across fleets and current thresholds do not capture employment gains from BT alone, given that SSF is structurally more employment-intensive.

CFP: The effective implementation of the CFP—that is, achieving its objectives to ensure the environmental, social, and economic sustainability of the fisheries sector—remains essential. Transitioning from the current CFP to a better-implemented policy that guarantees long-term sustainable resource management, marine ecosystem protection, food security, and the livelihoods of fishing communities could occur through a CFP reform (RXX). As the policy is revised every 10 years, the last revision has not taken place since 2013. Widespread crises can act as catalysts for change, driving improved implementation, as has been observed in previous CFP reforms (1992, 2002, 2013) or in specific fisheries, such as the bluefin tuna crisis in the 2000s leading to new management policies.

Sub, Dev, Sel: Some components of the system depend on the political and regulatory context. The amount and type of subsidies allocated to the fishing sector can shift according to political priorities. In times of socio-economic crisis (e.g., a sharp rise in fuel prices due to armed conflict, the Covid-19 pandemic), governments may increase *capacity-enhancing* subsidies to sustain fishing activity (e.g., fuel price support, temporary cessation compensation). A more broadly productivist policy orientation, aimed at maximizing fishing output, can also promote such measures to maintain or increase fleet capacity (R69). Conversely, when the Common Fisheries Policy (CFP) is effectively implemented to achieve its conservation and resource preservation goals, a transition in fishing practices can occur. This may involve increased transition subsidies for fleet decarbonization, the adoption of more selective and less seabed-damaging gear, and vessel upgrades to reduce bycatch of sensitive species (R70). In the same context, another trajectory could involve reducing *capacity-enhancing* subsidies (i.e. which could indirectly lead to overexploitation of the fishery resource (Sumaila et al., 2019)) such as phasing out the marine diesel tax exemption, on which the trawler fleet is highly dependent, thereby encouraging the adoption of more energy-efficient technologies (e.g., smart trawls combined with hybrid engines) (R71).

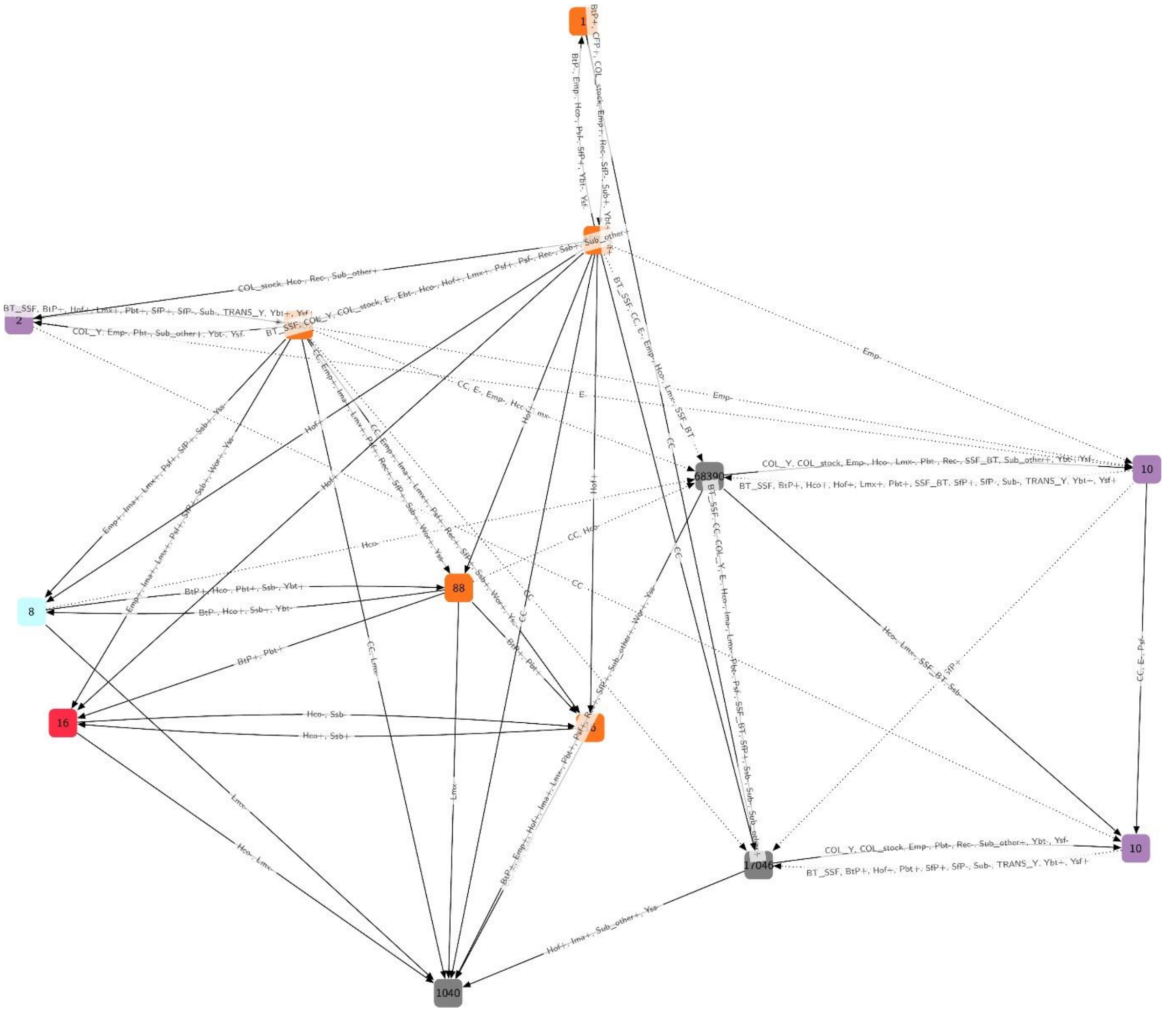
Ebt, Esf: Fishing effort is shaped by regulation, fleet conditions, and economic context. Effective implementation of the CFP can reduce fishing days to support conservation and resource preservation (R72), for example, bottom-trawler capacity could decrease through the reinforcement of the WestMed Plan with new spatio-temporal closures in the GoL (Journal officiel, 2025). Effort reductions in both fleets may be necessary to achieve CFP conservation objectives, such as reaching MSY across all commercial stocks (R73). Conversely, effort depends on available labor and profitability: fishing activity may decline during crises with workforce shortages and low returns, as seen during COVID-19 (R74,(OCAPIAT, 2022)). In contrast, weak CFP enforcement combined with socio-economic support and policy favoring productivity can increase fleet activity (R75), sometimes boosting trawler effort while SSF declines (R76), especially under national withdrawal strategies prioritizing fleets that ensure high landings and continuous supply (Doray et al., 2023; Chevallier et al., 2025).

Appendix S5 : Schematic representation of the thresholds for the variables based on the Gordon-Schafer model to determine the different scenarios for rule construction



Appendix S6: The complete compact merge state-transition graph

Number in nodes correspond to the number of states, nodes were color according to their belonging to a state or dynamical property : red : verifying “sustainability ideal”, blue : verifying “detrwaling”, purple : verifying “widespread crisis”, orange : states from which target is always reachable, grey : states from which target is never reachable (the purple states that are on the right belong to states form which target isn’t reachable)



Appendix S7 : Jupyter notebook with the model computation and analysis

```
%run -m ecco GoL_final.rr
model.rr

### ------------------------------------------ 1. Static analysis: model description ---------------------------------------------------

# Visualisation : colored variables according to the dimension they belong to
dim_color = ['#aaffaa','#aaffaa','#aaffaa','#aaffaa','#aaffaa','#aaffaa','#aaffaa',              # green : ENV
          '#ffaaaa', '#ffaaaa','#ffaaaa','#ffaaaa','#ffaaaa','#ffaaaa','#ffaaaa','#ffaaaa','#ffaaaa', # red : ECO
          '#fdffd5','#fdffd5','#fdffd5',                                                        # yellow : SOC
          '#f0b1ff','#f0b1ff',                                                                  # purple : TECH
          '#c1e9ff']                                                                            # blue : GOUV

# Interaction graph
model.ecograph(nodes_fill_color = dim_color, layout = 'gv-neato')

# Interaction table
model.charact()

# Run the model dynamic
STG = model()
STG.nodes

# size = 158 688 states contains SCC but no DEADLOCK

### -----------------2. Dynamic analysis: reachability, persistency of targeted states, trajectories---------------------

######-----------------2.1. Test properties --------

# State properties
target = "(Hco & Hof & Lmx & Ssb & Rec & ~Yss & Emp & Wor & Ima & BtP & SfP & Pbt & Psf)"
# Sustainbaility ideal
detrawl = "(CFP & Hco & Hof & Lmx & Ssb & Rec & ~Yss & Emp & Wor & Ima & ~BtP & ~Pbt & ~Ebt &
~Ybt & SfP & Psf)"             # Detrawling
wide_crisis = "(~Hco & ~Hof & ~Lmx & ~Ssb & ~Rec & ~Emp & ~Ima & ~Wor & ~Pbt & ~SfP & ~ BtP &
~SfP & ~Ybt & ~Ysf & Sub & Dev)"  # Widespread crisis

# Dynamical properties (state reachability, persistence)
# Target reachability : splitting the STG based on this property separates states from which the target is
reachable from those from which it is unreachable
reach_target = f"EF({target})"                    # There exist states satisfying the target, and they are
possibly reachable

# Target persistence : splitting the STG based on this property separates states from which the target can be
reached and maintained indefinitely, from states from which the target can be reached only temporarily or
unreached
can_reach_persistence = f" ~({target}) & EFEG({target})"          # There exist states from which the target
could remain indefinitely reachable

# Dynamical properties (trajectories)
T1 = f"(EF({detrawl} & EF{target}))"               # Initial state --> Detrawl --> target
T2 = f"(EF({wide_crisis} & EF{target}))"           # Initial state --> Wide_crisis --> target

# Test the state properties (are they existing in the state space ?)
STG.check(target = target,
        detrawl = detrawl,
        env_crisis = env_crisis,
        wide_crisis = wide_crisis)
# All the state properties are verified in the state space (STG.CONTAINS : properties)
```

```
# Test the dynamical properties (are they verified in the dynamic or not ?)
STG.check(reach_target = reach_target,
          can_reach_persistence = can_reach_persistence,
          T1 = T1,
          T2 = T2)

# All the dynamical properties are verified in the state space (STG.CONTAINS : properties)

##### ----------------Splitting the state space dynamic to obtain a synthetic and readable STG

# Palettes
# Visualisation graphique : Colorier les noeuds si ils vérifient une propriété (ex : EQUALS = target)
# Palette pour colorer target et reach_target
def col1(n, g):
    if n.name in g.equals("target"):            # red
        return '#ff2c48'
    elif n.name in g.isin("reach_target"):       # orange
        return '#ff751f'

    else:
        return 'grey'

# Palette quand ajout de detrawl
# Attention à l'ordre : mettre isin(reach_target à la fin car sinon les états qui vérifie cette prop et une autre
seront colorés selon reach_target seulement)
def col2(n, g):
    if n.name in g.equals("target"):            # red
        return '#ff2c48'
    elif n.name in g.equals("detrawl"):          # blue
       return '#c9fdff'
    elif n.name in g.isin("reach_target"):       # orange
        return '#ff751f'
    else:
        return 'grey'

# Palette quand ajout de wide_crisis
# Attention à l'ordre : mettre isin(reach_target à la fin car sinon les états qui vérifie cette prop et une autre
seront colorés selon reach_target seulement)
def col3(n, g):
#    if n.name in g.contains("INIT"):             # yellow
#        return '#fffc97'
    if n.name in g.equals("target"):            # red
        return '#ff2c48'
    elif n.name in g.equals("detrawl"):          # blue
        return '#c9fdff'
    elif n.name in g.equals("wide_crisis"):      # purple
        return '#ad81ba'
    elif n.name in g.isin("wide_crisis"):        # purple
        return '#ad81ba'
    elif n.name in g.isin("reach_target"):       # orange
        return '#ff751f'

    else:
        return 'grey'

#Palette pour le STG final simplifié
def col_final(n, g):
    if n.name in g.hasno("reach_target"):        # états qui ne permettent pas d'atteindre target
        return 'grey'
    elif n.name in g.contains("INIT"):           # yellow
```

```
        return '#fffc97'
    elif n.name in g.contains("target"):            # red
        return '#ff2c48'
    elif n.name in g.contains("detrawl"):           # blue
        return '#c9fdff'
    elif n.name in g.has("wide_crisis"):            # purple
         return '#ad81ba'
    else:
        return '#ff751f'

# Palette pour splitter la boucle sur la cible avec Cc
def col_cc(n, g):
    if n.name in g.isin("target") and n.name in g.isin("Cc"):            # red foncé
        return '#ff0a24'
    if n.name in g.isin("target") and n.name in g.hasno("Cc"):            # red clair
        return '#ffbac1'

    elif n.name in g.isin("reach_target"):         # orange
        return '#ff751f'

    else:
        return 'grey'

### 1. STG global : reachability, persistence and losing target
# Split according to target

g0 = STG.split(INIT, target = target).untrap(4)
g0.draw(edges_label = "")
# Split according to reach_target

g1 = g0.split(reach_target = reach_target, can_reach_persistence = can_reach_persistence).untrap(8) # si
toujours un trap faire untrap(10)
g1.n["col"] = lambda n : col1(n,g1)
g1.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")

### 2. STG complet et simplifié : trajectoires
# Splitter selon detrawl (uniquement le composant avant d'arriver dans target)
g2 = g1.split(7, detrawl = detrawl).untrap(14)
g2.n["col"] = lambda n : col2(n,g2)
g2.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")

# STG final : Splitter selon wide_crisis (tout le STG)
g3 = g2.split(wide_crisis = wide_crisis).untrap(18)
g3.n["col"] = lambda n : col3(n,g3)
g3.draw(layout = "gv-dot", nodes_fill_color = "col", edges_label = "")

# Obtenir un STG simplifié propre : regrouper les composants par stabilité
g4 = g3.merge(1,28).merge(13,15).merge(19,20).merge(21,22).merge(17,27).merge(11,12)
g4.n["col"] = lambda n : col_final(n,g4)
g4.draw(layout = "gv-dot", nodes_fill_color = "col", edges_label = "")

### 3. STG avec trajectoires propres seules
#### 1.Detrawl
# Avec toutes les stabilités : il faut reprendre la dynamique complète
g6 = g3.drop(9,10,20,21,22,17,19)
g6.n["col"] = lambda n : col2(n,g6)
g6.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")
#### 2. Widespread crisis
# Avec toutes les stabilités : il faut reprendre la dynamique complète
g7 = g3.drop(9,10,13,15,19,20,21,22)
```

```
g7.n["col"] = lambda n : col3(n,g7)
g7.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")
### STG focus sur la persistence de la target
##### Reprendre le graph g1
# Splitter les états qui bouclent avec le CC
g8 = g1.split("Cc", 3,7).untrap(9)
g8.n["col"] = lambda n : col_cc(n,g8)
g8.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")
#Supprimer les composantes qui ne sont pas reliées à la boucle
g9 = g8.drop(1,35,11,12,34)
g9.n["col"] = lambda n : col_cc(n,g9)
g9.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")
### Focus sur les états qui ratent la cible
# STG avec seulement les chemins sur lesquels la cible est manquée
g11 = g1.drop(3,9)
g11.n["col"] = lambda n : col1(n,g11)
g11.draw(edges_label = "", layout = "gv-dot", nodes_fill_color = "col")
```

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Auteur(s) : Miléna FERRET Date de naissance* : 03/04/2001	Organisme d'accueil : MARBEC Adresse : Université de Montpellier Place Eugène Bataillon - bât 24 - CC093 34 095 MONTPELLIER Maître de stage : Fabien MOULLEC
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Titre français : Les trajectoires de durabilité dans les socio-écosystèmes marins méditerranéens : le cas du golfe du Lion

Titre anglais : Pathways toward sustainability in Mediterranean marine social-ecological systems: the Gulf of Lion as a case study

Résumé : Dans un contexte de changement global, les socio-écosystèmes (SES) font face à des défis de durabilité dépassant le cadre purement écologique, nécessitant une approche holistique et multidimensionnelle de la durabilité. Cette étude vise à explorer la possibilité d'atteindre un état de durabilité intégrant simultanément les dimensions écologique, économique et sociale, garantissant l'exploitation durable des ressources marines tout en minimisant les impacts environnementaux et en maximisant le bien-être des communautés côtières. Nous avons appliqué le cadre qualitatif et possibiliste EDEN (Ecological Discrete-Event Network), pour la première fois à un SES marin. EDEN représente les dynamiques du SES à travers des variables qualitatives interagissant via des règles de type « si-alors », permettant d'identifier les états durables potentiels du SES et les trajectoires y conduisant. Les résultats révèlent l'existence d'un état de durabilité idéal, avec des trajectoires incluant des transitions graduelles, des crises systémiques et des trajectoires critiques pouvant empêcher son atteinte. Bien qu'atteignable théoriquement, sa persistance reste fragile face aux pressions climatiques et anthropiques et le système semble tendre vers des compromis de durabilité en raison de points de bascule. Ces conclusions mettent en évidence les points clés où la gouvernance et la gestion des pêches jouent un rôle essentiel, illustrant l'intérêt des modèles qualitatifs pour favoriser le dialogue avec les parties prenantes et les décideurs.

Abstract : In the context of global change, social-ecological systems (SES) face sustainability challenges that go far beyond purely ecological concerns, calling for a holistic approach to consider the multidimensional sustainability nature. The present study aimed to explore the possibility of achieving a sustainability state that simultaneously integrates ecological, economic, and social dimensions, ensuring responsible use of marine resources while minimizing environmental impacts and supporting the long-term well-being of coastal communities. We applied the qualitative and possibilistic Ecological Discrete-Event Network (EDEN) modelling framework, marking its first application to a marine SES. EDEN represents SES dynamics through qualitative variables interacting via if-then rules, identifying potential sustainable states and pathways leading to them. Results revealed the existence of an ideal sustainability state, with pathways leading to it including gradual transitions, systemic crises, and critical trajectories that may prevent achievement. While fully integral sustainability is theoretically attainable, persistence is fragile under climatic and anthropogenic pressures, and the system tends toward compromised sustainability due to tipping points. These findings highlight key points where governance and fisheries management play a critical role, showing how qualitative models can support dialogue with stakeholders and decision-makers.

Mots-clés : Trajectoires de durabilité – Socio-ecosystème marin – Qualitative modelling
Key Words: Sustainability pathways– Marine social-ecological system – Modélisation qualitative

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