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The minimum complexity necessary: The value of a simple Social-Ecological systems analysis in holistic marine environmental management

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ABSTRACT

The marine environment is a complex adaptive system, in which natural components interact with pressures from human activities and climate change. Effective marine management must navigate this complexity to protect biodiversity and ensure societal benefits. Increasingly, it is recognised that a functional, integrated approach is essential for sustainable management. This paper presents a comprehensive interrogation of nine existing Social-Ecological System (SES) frameworks, aiming to learn from these and identify the most suitable approach for managing the complex and adaptive nature of marine systems. Through a rigorous SWOT analysis and the application of appropriate characteristics criteria derived from the Ecosystem Approach principles, we evaluate various frameworks potential for operationalising ecosystem-based marine management. Key attributes such as holism, resilience, cross-scale interactions, stakeholder involvement, and adaptive learning emerge as critical to effective marine management. Our analysis reveals that while no single framework is perfect, the Integrated Systems Analysis (ISA) demonstrates the potential due to its holistic approach, explicit learning design, stakeholder inclusion, and proven application in marine and coastal contexts. Nonetheless, recognising ISA's limitations, we propose integrating elements from other frameworks and Systems Thinking tools to create a refined, practical approach termed 'Simple SES.' The resulting 'Simple SES' aims to provide a tailored, yet manageable approach for practitioners, deciphering the complexity of marine systems and supporting well-informed decision-making. This work advances SES theory and practice, developing an operationalised framework that aligns with the goals of sustainable and successful marine management thereby making ecosystem-based management more achievable and integrative by applying a systems approach.

1. Introduction

A healthy ocean is essential for human well-being, yet marine systems are under increasing pressure from human activities, climate change, and other environmental stressors, making effective management crucial [1]. Marine ecosystems are intricately linked to ecosystem services, which provide societal goods and benefits that depend on the health and resilience of these systems [2]. However, managing marine environments is particularly complex due to the high level of interconnectedness between species, habitats, ecosystems and human activities, defining marine systems as Complex Adaptive Systems (CAS) [3]. This complexity is further compounded by spatial, temporal, and jurisdictional dimensions that influence the behaviour of Social-Ecological Systems (SES) [4,5].

Given these challenges, traditional management approaches often are limited because they tend to focus on isolated aspects of the system, neglecting the broader, integrated nature of marine ecosystems. In contrast, SES frameworks provide a more holistic and adaptive approach, capable of addressing the dynamic interactions between ecological, economic and social dimensions of marine environments. By incorporating economic and ecological valuation, governance structures, and societal involvement [6], SES frameworks allow for a more comprehensive understanding of how human activities and natural systems are interlinked. This is particularly important when addressing

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global challenges such as climate change, which affects marine systems at multiple levels simultaneously. Thus, managing marine systems sustainably requires an SES Approach that can navigate the complexity, scale, and adaptive behaviour of these systems [7–9]. This paper addresses these many aspects inherent in the management of marine systems, with varying definitions; for clarity, Table 1 defines those aspects.

Despite the complexities of marine systems, management programmes are often led by resource-limited policymakers and administrators [16]. This creates a demand for a simple approach to understanding SESs that enables practitioners to conserve biodiversity and integrate ecosystem health with a resilient blue economy. Although a 'Simple SES' might seem contradictory given the inherent complexity of these systems, such a framework should balance key stakeholder involvement, governance, and future scenarios [16]. Several ecosystem-based management (EBM) tools, such as Natural Capital [18], Maritime Spatial Planning [19,20], and Ecosystem Modelling [21], support decision-making in marine management. However, Nygård et al. [15] argue that these Decision Support Tools (DSTs) are under-utilised. They propose integrating the outputs of DSTs to better fulfil the goals and principles of the Ecosystem Approach. Hence, a knowledge management tool would help to combine these EBM tools to achieve a more holistic marine management.

The Systems Discipline provides various fundamental approaches and tools to approach complex and 'wicked' situations [22]. The term *wicked* refers to issues that are exceedingly difficult or seemingly impossible to resolve due to incomplete, contradictory, and constantly evolving requirements that are challenging to identify [22]. These characteristics align with the dynamic marine environment and the governance challenges it faces [23]. Systems Thinking, rooted in social sciences, allows for a wide view of a system or focal issue, which can inform decisions. Thus, Systems tools, which are widely accepted within the discipline, provide a complementary perspective to achieving EBM goals and EA principles, i.e. they hold values of complexity, holism and interconnectedness at their core [11]. Some of these complementary elements include unpacking complexity, promoting cross-sectoral communication and ensuring the viability of a system [24,25]. Krause and Welp [26] further suggest that whilst several stakeholder-specific tools exist for Systems Thinking, a Systems Approach to modelling can deal with dynamic complexity to benefit sustainability research. It is emphasised that while EBM integrates human activities, their impact on ecosystems, and the management of the consequences, the Systems discipline approach extends this by increasing the focus on the broader socio-economic, technological, and political systems that are interacting in the sphere of marine governance and which influence human behaviour, i.e. the interconnection of the human systems that EBM considers in isolation. These influences add to the complexity of marine management and emphasise the value of a Simple approach. Rooted in cybernetic principles (the theory of communication [27]), an apposite definition of '*simple*' can be the '*minimum amount of complexity necessary'* [24] which is therefore used here to interrogate and illustrate methods of creating and achieving a Simple SES; in particular, this paper aims to fulfil a need to create an easily conducted and understood approach by analysing recent approaches.

Table 1
Definitions of key terms within this paper.

Term	Acronym	Definition
Systems Discipline		Practitioner and academic spheres that address and use Systems Thinking.
Systems Thinking	ST	Given that ST respects and values diversity, it is perhaps not surprising that there is not a single definition of it. Well-used definitions that can provide understanding in the context of this paper include that of Senge [10] "System Thinking is used to analyse patterns… by looking at it from a holistic viewpoint rather than small unrelated manageable parts". Also, Jackson [11] adds further understanding to this definition by suggesting that ST "eschews simple solutions to complex problems. It embraces holism and creativity to handle complexity, change and diversity. "
Complex Adaptive System	CAS	A complex adaptive system is one where patterns at higher levels emerge from localised interactions and selection processes acting at lower levels, with nonlinearity and multiple possible outcomes [12].
Social-Ecological System	SES	An SES is "a complex adaptive system consisting of a bio-geophysical unit and its associated social actors and institutions, where the spatial or functional boundaries of the system delimit a particular ecosystem and its problem context" [13]. In the current paper, the term is also used as the method for management.
Ecosystem Based Management	EBM	Marine Ecosystem-Based Management (EBM) involves recognising and addressing interactions among different spatial and temporal scales, ecological and social systems, and stakeholder groups in coastal and marine areas [14].
Decision Support Tools	DST	Decision-support tools (DSTs) synthesise complex information to assist environmental managers in decision-making [15].
Governance		Governance of the marine environment refers to the sum of policies, politics, administration, and legislation of that system [16].
Ecosystem Approach	EA	The ecosystem approach is addressing both natural and societal features and applied through a series of 12 principles relating to planning and management, thus guiding biodiversity management in any situation [17].

1.1. Social-Ecological Systems

The term Social-Ecological System was first used by Ratzlaff in the 1970s [28] and first defined by Cherkasskii [29] as a system "consisting of two interacting subsystems: the biological (natural ecosystem) and the societal (human structures) subsystems where the biological subsystem is [the] governed object and the societal system acts as the internal regulator of these interactions". The concept later began to be developed as a framework for studying intertwined human and natural systems [30] which then led to various SES frameworks being developed. Notably, these have built upon the fundamental SES framework of Ostrom [31] in identifying the key variables influencing interactions and outcomes within human-environment systems. The SES framework has been instrumental in strengthening EBM, particularly by promoting adaptive approaches in marine management [32,33]. Acknowledging and accounting for the interdependent relationships between social and ecological systems can enhance resilience in these coupled systems. For example, improving social structures to build trust and resolve conflicts among marine users will lead to better ecological conditions, thereby sustaining ecosystem services through system changes [32].

SESs are defined depending on the purpose of application; the present analysis for marine management follows the encompassing definition that an SES is "a complex adaptive system consisting of a bio-geophysical unit and its associated social actors and institutions, where the spatial or functional boundaries of the system delimit a particular ecosystem and its problem context" [13]. This adequately addresses the interaction between ecological and societal elements, and recognises both the complexity of the system, and the way in which spatial and functional boundaries may need to be incorporated into applying an SES approach. Furthermore, Colding and Barthel [28] highlight the increasing complexity of Social-Ecological Systems (SES) research, where the scope is increasingly adaptive and non-linear. This shift reflects a growing recognition of the need for flexible, context-specific frameworks.

In line with this, Norberg and Cumming [34] suggest that SES theory can "…offer some simple guidelines and rules of thumb that could…

provide the basis for a quiet revolution in the theory and practice of the management of natural resources". This 'quiet revolution' has fostered a more nuanced focus in SES literature, encompassing themes such as adaptive co-management [35], the acknowledgment of complexity [5], institutional frameworks [36] and cross-scale dynamics (Reyers & Selig) [37]. Furthermore, recent approaches emphasise inclusivity, with a growing emphasis on equity, diversity and justice [38]. Consequently, this underscores that the definition of SES relies on its specific application, reflecting the diverse and context-dependent nature of the system under study.

In previous reviews of SES concepts and frameworks while Binder et al. [39] and Colding and Barthel [28] provided valuable insights, they did not specifically address the marine environment. Refulio-Coronado et al. [40] identified emerging concepts unique to coastal and marine SESs; however, their study primarily focused on the Ostrom [41] Social-Ecological Systems Framework and they gave a general overview without recommending specific frameworks for operationalisation in a marine context.

Hence, this present study differs by identifying appropriate frameworks for implementing an SES approach specifically within the marine environment. In contrast to Refulio-Coronado et al. [40], who highlighted areas for future research within the Ostrom [41] framework, this research evaluates multiple SES frameworks for practical use in marine settings. Recent developments in SES literature since Binder et al. [39] and Colding and Barthel [28] necessitate a re-evaluation of existing frameworks, especially regarding spatial considerations and SES data; for example, the significant innovation in SES research methods, particularly through developing transdisciplinary approaches and decision support tools [42]. Refulio-Coronado et al. [40] noted a lack of alignment and consistency in SES models, particularly in spatial dimensions, but this was only regarding the Ostrom SES framework. In response, our study broadens the analysis to assess multiple SES frameworks and their applicability in marine management. Given the unique complexity of marine ecosystems, the need for SES frameworks that can accommodate multi-scale dynamics, stakeholder involvement and adaptive management is critical. Moreover, this present study aligns with the call by Ostrom [41] to move beyond simplistic, one-size-fits-all solutions and instead develop adaptable frameworks for managing complex environments.

This paper presents a comprehensive analysis and summary of the available SES frameworks, to draw valuable lessons from previous SES proposals. The goal is to develop an approach that builds on the best practices of those previous SESs, as well as advancing our understanding of SES concepts. Hence, we address the following research questions:

- What marine SES frameworks exist within the literature?
- What are the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of various existing SES frameworks when applied to marine management?
- Can a Simple SES be recommended to satisfy the demands of different types of users, some of whom may not be experts in the many aspects of marine environmental management?

2. Methodology

This study uses a dual approach to analysing those SES frameworks which emerged from a comprehensive literature search; the appropriate characteristics criteria developed from the Ecosystem Approach Principles [43] were applied and analysed together with a SWOT analysis. This requires the literature search methodology, the creation of criteria and the SWOT analysis basis to be described.

2.1. Literature search

This literature search used a systematic style methodology (see also [28]) searching: Scopus (Elsevier), Web of Science (BIOSIS) and Academic Search Premier (EBSCO). As the SES concept is multidisciplinary by nature, these search engines were chosen given their scope in both life sciences and multidisciplinary databases. The identification of 3127 duplicate papers indicated saturation in the literature search, suggesting that these three databases provided adequate coverage to represent the broad state of SES literature. This search was undertaken in December 2022 and included papers to that date. The following keywords were used to identify potential papers regarding SES approaches, models, frameworks or methods:

"("social-ecological" OR "socio-ecological*" OR socioecological* OR "human-environment*") AND (marine OR ocean* OR coast* OR estuar* OR environment*) AND (model* OR framework* OR approach* OR method*) AND (manag* OR "Decision-Making" OR "Decision Making")"*

The three searches returned 4697 papers; once duplicates were removed, 1570 papers remained for a title and abstract screening.

During the screening process, we excluded papers that:

- incorporated Decision Support Tools (DSTs) and modelling since these topics fall outside the scope of our study, which primarily aims to develop a Simple SES framework;
- solely detailed the outcomes from using a pre-existing framework;
- cover existing procedural frameworks, such as for Integrated Coastal Zone Management (ICZM), Integrated Water Resources Management (IWRM), and Strategic Environmental Impact Assessment (SEIA), as indicated by Binder et al. [39].

Papers were included that:

- primarily incorporated both social and ecological components and how they interact;
- provided critical concepts for the operationalisation of the SES;
- gave frameworks which were general in nature because they were explicitly designed for use in a variety of contexts [39];
- primarily were conceptual frameworks, i.e. how a system is examined and understood, which have or can be used for the pragmatic operationalisation of EBM.

Fifty-six papers remained after the above screening, and eight prominent frameworks were identified from the papers, although the Ecocycle framework was identified through citation in Berkes [44], resulting in nine overall SES frameworks for review (Table 2).

2.2. The appropriate characteristics criteria

The 'appropriate characteristics criteria' (Table 3) is a set of standards derived from the globally agreed-upon 12 principles of the Ecosystem Approach (EA) [43]. This emphasises sustainable development with the aspiration of three goals: the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of benefits arising from genetic resources [43]. The EA principles are central to this evaluation of SES Approaches due to the shared goal of what both an SES and the EA principles aim to achieve, i.e. the fair and sustainable use of natural resources. Hence, this study aims to assess the fitness of SES frameworks in achieving broad and far-reaching goals of good management outlined in the EA principles (Supplementary Material B).

2.3. SWOT analysis

The underlying questions used to interrogate the nine SES frameworks (Table 4) relate to the EA principles and the appropriate characteristics, hence applying a rigorous qualitative analysis of the frameworks.

Table 2
The 9 SES frameworks which emerged from the literature search.

SES Framework	Main features	Indicative References
Ecocycle Framework (EF)	The Ecocycle framework aims to analyse different activities and relationships within a system to identify obstacles and opportunities for progress, accounting for the natural fluxes in system components. The four phases include exploitation, conservation, creative destruction, and renewal [45,46]. This also provides a framework for integrating a nested level of social and ecological systems in the analysis [47].	Hurst and Zimmerman [48]
Ecosystem Services Framework (ESF)	The ESF analyses and integrates information on the benefits of ecosystem services. Encompassing a process that initially identifies issues of ecosystem service provisions and the social, economic and political-cultural contexts in relation are defined.	Turner and Daily [49]
Integrated Ecosystem Assessment (IEA)	Based upon principles of ecosystem-based management, the IEA is an approach that engages scientists, stakeholders, and managers to integrate all components of an ecosystem, including human needs and activities, into the decision-making process so that managers can balance trade-offs and determine what is more likely to achieve their desired goals.	Harvey et al. [50]
Integrated Systems Analysis (ISA)	This framework links 14 sub-systems of social and ecological nature relating to existing environmental management approaches. These subsystems account for elements such as governance, stakeholders, problem identification data provenance, and feedback of learning. It possesses an underpinning problem structuring method (DAPSI(W)R(M) (pronounced *dap-see-worm*, [51], see text) to structure the analysis. This framework suggests a three-step process of defining the problem, obtaining sufficient information/data and using the information to problem-solve with stakeholders.	Elliott, et al. [7]
Social-Ecological System Framework (SESF)	The framework provides a basis for analysing the interactions between ecosystems and society, and how these interactions influence sustainable resource use and management. The framework is nested with 4 overarching systems: (i) resource systems, (ii) resource units, (iii) governance systems, and (iv) users. Each system has subsystems of second-tier variables to consider.	Ostrom [41]
Social-Ecological Action-Situations framework (SE-AS)	The Social-Ecological Action Situations (SE-AS) framework focuses on the Action Situation (AS) as a unit of analysis, like its predecessors, the Institutional Analysis and Development (IAD) framework and the SES framework. This framework puts human-to-non-human interaction at the centre of focus.	Schlüter et al. [52]
Sustainable Livelihood Approach (SLA)	Identifies and analyses the combination of livelihood assets. This approach is based on the recognition that all people have abilities and assets that can be developed to help them improve their lives. Analyses the assets within the context of vulnerability and governing structure and processes.	Serrat [53]
The Systems Analysis Framework (SAF)	Including six key steps, the SAF modified the existing framework presented by Hopkins [54], these steps include: issue Identification, system design, system formulation, system assessment, implementation, and monitoring and evaluation.	Støttrup et al. [55]
Vulnerability Framework (VF)	This framework was designed to analyse a location facing multiple changes and hazards. It considers human conditions and environmental conditions together with risk/hazards and pressure and release models to identify and map the sensitivity and resilience of the system within local, regional and global contexts.	Turner et al. [56]

3. Results

The qualitative SWOT analysis gave relevant evidence for awarding each criterion (Table 5). The eight characteristics outlined in Table 3 served as indicators to assess whether or not the approaches failed to meet the predefined criteria. This binary assessment is supplemented by qualitative justification of the inclusion or exclusion of a given criterion, as explained below. The analysis was reviewed and validated by all authors, as well as by the Marine SABRES project (see Acknowledgements) leaders and external reviewers. The complete SWOT analysis is given in Appendix A.

3.1. *Simple in application*

Simplicity here refers to how easily an approach can be conducted and understood by users (practitioners, academics, and managers). The SWOT analysis indicated that none of the existing frameworks were classified as simple, as they are inherently academic and often require specialised training or expertise to be applied effectively [57]. This presents a challenge for practitioners to implement these approaches. One SES, the SAF framework [58], came the closest to achieving this criterion as it offers relatively clear, prescribed steps. However, despite the SAF step-by-step approach, its application is not simple, as it necessitates an experienced team, including systems dynamics specialists, and may take 12–18 months to complete. As a result, none of the frameworks were deemed simple, reinforcing the need for a more 'simple' approach for practitioners across various settings.

3.2. *Resilience and adaptive features*

All assessed frameworks demonstrated resilience (i.e. the ability to respond positively to changes) and adaptability. The circular and reflective nature of several approaches, such as the IEA framework, incorporated feedback loops, highlighting an adaptive quality desirable for a Simple SES [59]. Additionally, frameworks such as the EF enable management actors to enhance the system capacity for variability and to

Table 3
The appropriate characteristics criteria, their description and a link to the corresponding EA principle from UN [43].

Characteristic	Description	Relation to EA principle
Simple in application	Is the framework and approach clear and concise, and does it include a prescribed set of application steps?	This relates to Principle 2, which promotes decentralised management to the lowest appropriate level, involving local stakeholders and knowledge.
Resilience and adaptive features	Is the framework capable of adapting and evolving according to changing circumstances?	It aligns with Principle 9, which recognises that change is inevitable and advocates for adaptive management to respond to changes and surprises.
Unbiased	Can the framework balance the consideration and inclusion of natural and various societal factors and groups?	This connects to Principle 1, which states that management should consider the economic, cultural, and societal needs of different stakeholders, including indigenous peoples as rights holders, and balance both biological and cultural diversity.
Cross-scale	Is the framework able to capture evolving cross-scale dynamics?	This relates to Principle 7, which highlights the importance of undertaking the ecosystem approach at appropriate spatial and temporal scales, considering the interaction and integration of genes, species, and ecosystems.
Holistic	Does the framework consider various relevant system dynamics within its stated boundaries as well as potential interactions beyond system boundaries?	This aligns with Principle 3, which emphasises the need for managers to consider the effects of their activities on adjacent and other ecosystems, not just the target ecosystem.
Learning from implementation in practice	Is the framework responsive to local conditions and sufficiently rigorous to enable cross-application comparison and learning, together with promoting reflection of the process undertaken?	This connects to Principle 11, which emphasises the importance of considering all relevant information, including scientific, indigenous, and local knowledge, to inform effective management strategies.
Stakeholder inclusive	Is the framework based on an inclusive approach to the engagement of stakeholders?	This relates to Principles 2 and 12, which advocates for involving all relevant sectors of society and scientific disciplines at appropriate levels from local to international.
Applied in the marine environment	Has the framework been applied to marine circumstances previously?	While not directly related to a specific principle, this characteristic ensures that the framework applies to marine ecosystems, which is central to this study.

strategically adapt to transformation [60,61]. The ISA framework feedback loop allows for adaptation between applications by assessing the process itself [7]. Similarly, the VF framework incorporates adaptive and resilient features related to system vulnerability [56]. The presence of adaptability in all approaches underscores its importance as a key feature of marine SESs, which must be considered in their operationalisation to address the complexity of the marine environment.

Table 4
SWOT Analysis template which was applied to the frameworks.

Strengths	Weakness
· What are the merits of the SES? - Do these merits best apply to the goals of sustainable and successful marine management? · Does the framework have a holistic and integrated approach? · What are the Strengths of the SES framework to achieve: - well-informed decision-making; -consideration of both conservation and protection of biodiversity and the delivery of societal goods. · Are stakeholders directed to be engaged appropriately in the approach?	· What areas of the framework need improvement? · Is the framework lacking sufficient information? · Is this approach too complex to be applied to a defined marine area? · Are there barriers present within the framework to achieve a holistic and integrated approach? · Are there aspects of the goal this framework does not achieve? -Do other frameworks do these things better? · Is there any bias to the social or ecological expected outcomes that negatively impact the application to balance the two competing interests?
Opportunities	**Threats**
· What Opportunities exist within the larger world that might support the application of the framework to help achieve these goals?	· What threats exist that might undermine the application of the framework to help achieve these goals? · Are there other factors for the SES to consider?

3.3. Unbiased

The analysis evaluated the balance between natural and social factors in the frameworks, ensuring that no approach favoured one over the other. Frameworks such as SESF, SEAS, SAF and ISA demonstrated an unbiased perspective, recognising the interconnectedness of human and natural systems, considering multiple scales, and giving equal weight to social and ecological factors ([62]; Støttrup et al., 2018; [7,57]). In contrast, the VF and SLA frameworks exhibited biases and were not awarded this criterion. The VF lacks prescriptive methods, leading to inconsistent application and reflecting an anthropocentric bias [56]. Similarly, the SLA is driven by social systems, prioritising anthropocentric outcomes. While it acknowledges Final Ecosystem Goods and Services (FEGS), it overlooks marine processes and ecosystem services essential for societal benefits [2]. An unbiased approach is crucial not only for understanding marine systems but also for ensuring fair, just and equitable outcomes. This balance must extend beyond ecological and social elements to include equity and fairness, which are essential for the success of any framework. Although the SWOT analysis focused on social-ecological balance, it is emphasised that the development of the Simple SES must embed these broader considerations to ensure inclusive and adaptable outputs across diverse settings.

3.4. Cross-scale

The cross-scale characteristic was present in several frameworks, and the criterion was awarded where frameworks explicitly addressed the application across different spatial or temporal scales. The EF framework stood out for its ability to incorporate cross-scale dynamics, together with its resilience and adaptive features. Its use of the Panarchy concept addresses the intersection of different scales and disciplines, demonstrating how change can be orchestrated across temporal and spatial dimensions [63]. Similarly, frameworks such as the SESF recognise the importance of considering multiple spatial scales and levels of organisation [36]. The ISA framework incorporates both endogenic and exogenic pressures, enabling informed decision-making for preventative and mitigative measures within and outside the system [7]. In contrast, the SAF framework does not explicitly mention cross-scale capabilities, and thus was not awarded this criterion. The SWOT analysis supported that 5 out of the 9 frameworks accounted for cross-scale attributes in SES.

Table 5
Appropriate Characteristics Criteria Results. A ✓ indicates the award of a characteristic to a framework and a × indicates that this characteristic was lacking.

Criteria	EF	ESF	IEA	ISA	SESF	SEAS	SLA	SAF	VF
Simple in application	×	×	×	×	×	×	×	×	×
Resilience and adaptive features	✓	✓	✓	✓	✓	✓	✓	✓	✓
Unbiased	✓	✓	✓	✓	✓	✓	×	✓	×
Cross-scale	✓	×	×	✓	✓	✓	×	×	✓
Holistic	✓	✓	✓	✓	✓	✓	×	✓	×
Learning from implementation in practice	✓	✓	✓	✓	×	×	✓	✓	✓
Stakeholder inclusive	×	✓	✓	✓	✓	×	✓	✓	×
Applied in the marine environment	✓	✓	✓	✓	✓	✓	✓	✓	✓

3.5. Holistic

By definition, an SES should be holistic, encompassing both natural and social science aspects. The analysis reaffirmed the selection criterion that most SES frameworks demonstrated this holism, as expected, given that SESs are inherently coupled human-nature systems [13]. For instance, the EF framework accounts for multiple scales and disciplines through Panarchy, illustrating this trait [63]. Similarly, the ESF framework recognises the complexity and interconnectedness of ecosystems and their multiple functions and values [18]. The IEA includes a wide range of actors [59,64], while the ISA integrates diverse factors and interactions, providing a holistic view of the marine environment through the DAPSI(W)R(M) problem-structuring method [7]. Additionally, the SESF highlights the interdependence of human and natural systems, recognising the need to consider multiple scales and levels of organisation [62]. The SEAS framework emphasises human-environment interactions and emergent phenomena, such as how whale-watching ecotourism reflects the cultural benefits of whales, reinforcing the holistic principle that "the whole is greater than the sum of its parts" [65]. Similarly, the SAF framework focuses on the interconnectedness of marine ecosystem factors, offering a comprehensive view of these systems (Støttrup et al., 2017). In contrast, the SLA and VF frameworks were not awarded the criterion of holism, aligning with the rationale for the unbiased criterion: if an approach is biased, it cannot be truly all-encompassing. The SLA framework does not fully account for marine processes and functions essential to ecosystem service production, showing a bias towards anthropocentric outcomes. Similarly, the VF framework lacks clear guidance on stakeholder inclusion and fails to address its integration with social systems such as governance or politics. These shortcomings limit both frameworks in capturing the full complexity of SESs, hence, they were not awarded the criterion of holism as they do not consider all social aspects alongside natural elements.

3.6. Learning from implementation in practice

Frameworks such as the EF, IEA, ISA, and SAF explicitly promote learning through their cyclic, reflective design, incorporating feedback loops and iterative processes to support continuous improvement and adaptability to local conditions. This responsiveness enables these frameworks to remain flexible across diverse settings while maintaining sufficient rigour for cross-application comparison and learning. In contrast, while the SESF and SEAS frameworks offer strong theoretical foundations, their lack of clear prescriptive implementation may limit their ability to facilitate learning in real-world applications [57,66,65]. This disparity illustrates the trade-off between theoretical sophistication and practical applicability. While theoretical robustness offers valuable insights into the complexity of SESs, frameworks must also be sufficiently flexible and practical to adapt to specific local contexts and knowledge while allowing for meaningful cross-case learning.

3.7. Stakeholder inclusive

Stakeholder inclusivity is increasingly recognised as essential in marine EBM, aligning with Principles 2 and 12, which require involving all sectors of society and scientific disciplines at local to international levels [43]. Many frameworks emphasise stakeholder involvement in the SES approach. For instance, the SAF integrates inclusivity into its design, offering tools and transdisciplinary approaches to foster cooperation (Støttrup et al., 2018; [67]). The IEA actively engages stakeholders in decision-making to promote integrated management [50], while the ESF encourages stakeholder participation to support ecosystem service solutions by recognising diverse perspectives [64,18]. Similarly, the ISA promotes citizen engagement through horizontal management integration [7], and both SESF and SLA emphasise inclusive decision-making [62,68]. In contrast, the EF lacks guidance on stakeholder involvement [69], the VF does not prioritise it, and while the SEAS acknowledges societal values, it does not provide direction for stakeholder inclusion; hence these frameworks were not awarded this criterion.

3.8. Applied in the marine environment

The SWOT analysis indicated that all frameworks have been applied in the marine environment. This facet was part of the selection criteria, alongside a further analysis regarding the required characteristics; the experience in marine systems was relevant to the SWOT analysis as this impacted the relevance of the frameworks applicability. The IEA framework, for example, has been widely employed in marine and coastal research to support EBM [70,59]. The SAF, specifically designed for the Baltic Sea, was successfully implemented in the BONUS BaltCoast Project (Støttrup et al., 2018). Additionally, while the SESF has primarily been applied to sector-specific issues such as forest management, it has also been adapted to other sectors, including fisheries [66]. The development of the SEAS framework, following the SESF model, further demonstrates its application in lake ecosystems in Germany and Canada [57].

Similarly, the ISA framework evolved from the DPSIR model into the DAPSI(W)R(M) approach, explicitly integrating social and ecological elements within marine contexts [71,72]. This method highlights human **D**rivers and **A**ctivities that generate **P**ressures, leading to **S**tate Changes on natural systems and **I**mpacts on human **W**elfare, necessitating **R**esponses through management **M**easures (Fig. 1) [51]. A key strength of the ISA framework is its design specifically for the marine environment. Overall, all frameworks demonstrated their applicability to marine systems either through their design or via case studies, highlighting their ability to address the specific marine challenges.

The above analysis therefore indicated that all frameworks align to some extent with the core EBM principles and the blueprints of appropriate marine EBM. However, several approaches demonstrated the highest applicability: the EF, the EIA the ISA, the SAF and the SESF. The applications of these SES approaches over time illustrate the evolution of SES methodologies to include a more holistic understanding of the interconnectedness between ecological and social components. The importance of resilience and adaptability in managing complex adaptive systems, the integration of multi-scale dynamics, and the inclusion of diverse stakeholder perspectives will all enhance decision-making and policy implementation in marine management. Consequently, the

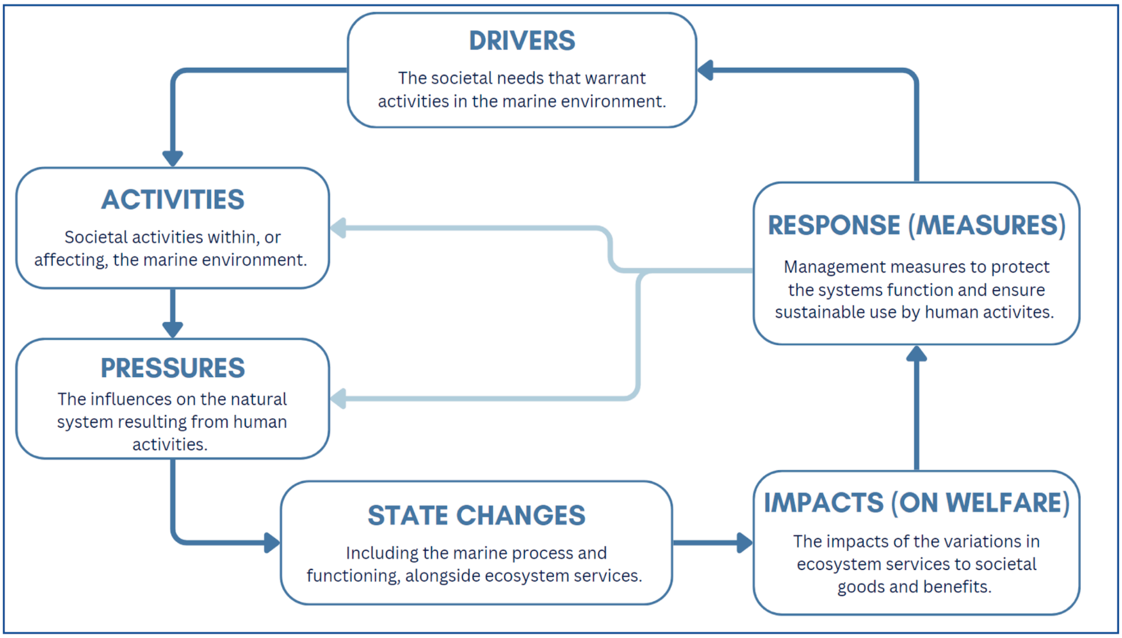

Fig. 1. A Schematic of the DAPSI(W)R(M) framework illustrating the various elements of the problem structuring framework. Redrawn with descriptions of elements from Elliott, et al. [51].

Simple SES proposed from this review will incorporate the strengths of these frameworks, aiming to address the identified gap in simplicity and enhance practical application. The next section explicitly discusses the relevance of the characteristics of these frameworks for incorporation into the proposed Simple SES.

4. Lessons learned and a proposed simple SES

The above narrative indicates that there was no need to develop a novel framework, as several existing approaches offered a robust foundation for constructing a Simple SES model. Applying EA principles in evaluating these frameworks enabled clarification of the core objective of an SES: achieving a sustainable equilibrium between environmental protection and the delivery of societal goods and benefits. However, all assessed approaches exhibited shortcomings, particularly in their complexity of use.

The central value of a Simple SES approach for holistically managing the marine environment lies in its potential to facilitate uptake and application by practitioners. The presence of holism in multiple frameworks highlights its importance in the field of systems analysis, as it provides a valuable and meaningful way to take a wide view and considered approach to integrated management. By focusing on the interdependencies, interconnections and emergent outcomes within a system, a Simple SES approach offers a move from only ecocentric or anthropocentric focuses whilst still providing a guided and simple way to reduce the complexity to a manageable size in making informed management decisions. This move can provide valuable information that traditional approaches may have overlooked; for example, the SESF has traditionally focused on classic common-pool resource (CPR) systems such as fisheries, forestry, and irrigation, whereas more recent trends apply the SESF and have designed other SESs to larger-scale and hybrid commons, such as coastal systems and pond aquaculture [66]. However, this would only occur where an approach exists with only Strengths and Opportunities, which has been shown here not to be the case.

The ISA approach is deemed an appropriate foundation for creation of the Simple SES as the SWOT analysis detailed a structured approach and the capacity to integrate environmental and societal considerations. Nevertheless, the analysis demonstrated areas where additional refinement is necessary for simplicity and operational practicality, comparable to challenges found in assessed frameworks. Therefore, elements from other evaluated approaches were incorporated, together with relevant concepts from the Systems Discipline. This will result in a Simple SES framework designed to be both operationally feasible for practitioners and contextually adaptable, while maintaining a balance between rigour and usability.

4.1. Development of the simple SES

The EF, ISA, IEA, SAF, and SESF frameworks embody key SES principles such as holism, adaptation, and interconnectedness, making them strong candidates for constructing a Simple SES. Among these, the ISA framework shows potential for marine applications due to its holistic approach, stakeholder inclusiveness, and established use in marine, estuarine, and coastal environments. However, no framework is without limitations, and the ISA requires refinement. While the Simple SES framework is required to achieve a 'win-win' balance between environmental protection and societal benefits, practical challenges such as power imbalances, complex governance and political dynamics often hinder this goal in real-world applications [73,74]. A key challenge highlighted in the SWOT analysis is the high data requirements across several frameworks, including the ISA, SAF, IEA, and SEAS. In data-poor regions, these demands may limit implementation [57,75]. These challenges must be acknowledged, and trade-offs are to be addressed in any practical application of the framework.

To overcome the limitations of existing SES frameworks and manage inherent trade-offs between complexity, data availability, and stakeholder inclusion, we propose supplementing the ISA base of the Simple SES framework with key characteristics from other approaches. For example, the SAF offers a prescriptive structure that can guide the Simple SESs implementation, addressing operational detail. However, the SAF was not used as the base framework due to its complex terminology and the reliance on expert implementation reduces its accessibility and suitability for creating a standalone system [67]. The SESF, rooted in common pool resource theory and institutional analysis [31], adds valuable insights into the rules and norms shaping actor behaviour [36]. Integrating the SESF principles of institutional analysis into the Simple SES framework will improve understanding of governance systems that influence marine resource management. Furthermore, the EF focus on cross-scale dynamics, particularly through the concept of Panarchy [63], will add to the Simple SES holistic perspective and the SAF structured approach, making the use of the Simple SES more robust in managing diverse marine contexts.

Simplicity is necessary in aligning with sustainable marine management goals. While no framework achieves the simple characteristic, the ISA consistent use of the DAPSI(W)R(M) cause-consequence_problem-structuring framework comes close. This problem-structuring feature simplifies stakeholder consultation and data comparison once operationalised. Moreover, prescribing key actions and tools from the SAF would further streamline the ISA implementation by clarifying the data and resources needed. Also, supplementing concepts from Systems Thinking provides adaptive tools for reducing the complexity of marine management [16]. Applying the principle of 'minimum complexity necessary' [76] ensures that only essential data are collected for the focal issue, preventing unnecessary burdens on the users. Although this may not create the perfect database for the future, this will provide a snapshot of the system from the iteration and serve as a foundation upon which to learn in future iterations or analysis of an area. Additionally, when upscaled, ISA can facilitate data-sharing to predict and mitigate cumulative effects through systematic mapping and organised data use [51].

4.2. The simple SES

The Simple SES is structured around three key phases—Setting Priorities, Gathering Information, and Using Information—derived from the original 14 subsystems used to address different components of an SES (see Fig. 2 in [7]). At its core, the framework uses the cause-consequence-response DAPSI(W)R(M) approach as a central organising structure, ensuring that the social-ecological elements are comprehensively addressed. These phases, together with the sub-systems, work within a nested operational system that adapts to the complexities of marine environments. The Simple SES differs from previous approaches discussed by integrating interlinked sub-systems such as data provenance, governance, resource delivery, process achievement and feedback mechanisms. This configuration is an evolution of the original model proposed by Elliott et al. [7], reflecting the lessons learned from other SES frameworks. Rather than functioning independently, these sub-systems operate synergistically within the overall management system, ensuring a holistic and adaptable approach (Fig. 2).

The emphasis on simplicity (*aka* the minimum complexity necessary) is crucial, not as a means of standardising outputs across different systems, but to ensure that the process itself is adaptive and can apply to various contexts. This is particularly important given the complex, adaptive nature of marine ecosystems. The Simple SES is designed to accommodate these complexities by ensuring that human activities and ecological factors are understood as intertwined components of the system. As highlighted by Hughes et al. [33], social-ecological outcomes cannot be disentangled from the ecological and human dimensions of marine systems. The ability to account for this interconnectedness, while remaining adaptive, is present through feedback loops throughout the Simple SES framework.

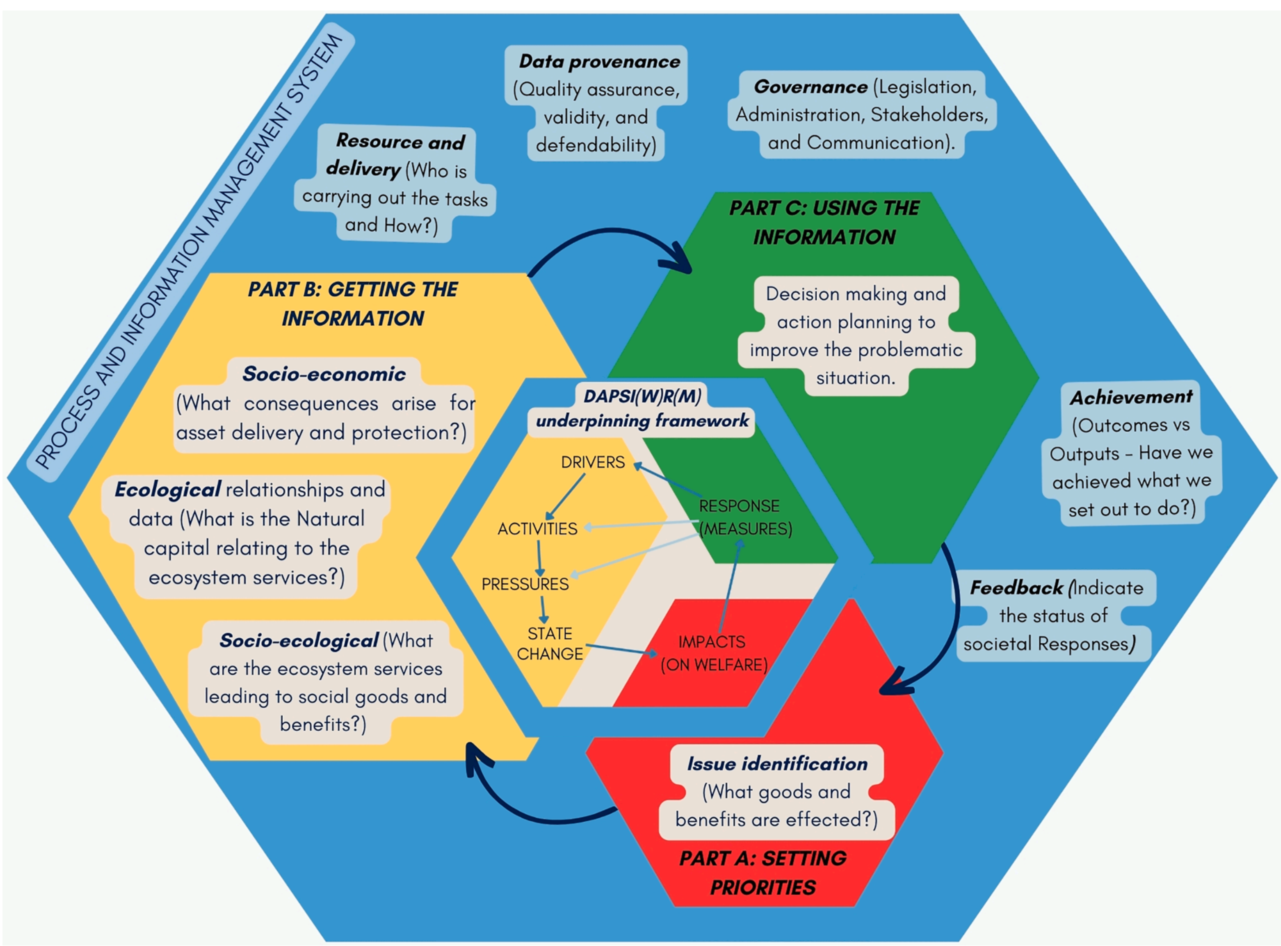

Fig. 2. A schematic representation of the Simple SES approach.

4.3. Managing intersecting social systems and ecological data

To ensure the effective implementation and operationalization of the Simple SES, a robust management system is essential. The Process and Information Management System (PIMS) was developed to manage the collection, storage, and use of both social and ecological data. PIMS integrates key elements of process management, resource management, stakeholder identification and engagement, data provenance, evaluation and governance—most of which are prescribed by the ISA conceptual model. PIMS functions as a guiding tool to ensure that marine ecosystem-based management (EBM) projects are scientifically rigorous, transparent, inclusive and adaptable. As such, establishing PIMS is a critical preliminary step in the Simple SES to provide a strong foundation for analysis and decision-making.

Effective communication and stakeholder engagement are essential for the operational success of any SES framework. The importance of stakeholder inclusion and data provenance, as highlighted by frameworks such as SAF, IEA, and ESF and ISA, is central to the Simple SES. This framework emphasises empowering citizens to engage in conservation efforts [77] and ensuring integrated governance across sectors and levels [16]. While the complexity of communicating data across different governance structures poses a challenge [16], the Simple SES addresses this by incorporating principles such as the ten-tenets of sustainable management; these emphasise effective communication and cultural inclusivity, as well as ecological, economic, technological, societal, legal, administrative, political and ethical aspects [78]. By tailoring communication strategies to different stakeholders, the Simple SES aims to mitigate these challenges and facilitate successful implementation.

The SWOT analysis identified that SES frameworks must operate effectively in both data-rich and data-poor environments. The DAPSI(W)R(M) framework requires either extensive data for science-based management decisions or, in the absence of such data, an expert-judgement approach. The Simple SES leverages Systems tools from frameworks such as the SAF to improve data collection efficiency, particularly in data-poor areas, by identifying the minimum necessary data and highlighting knowledge gaps through the DAPSI(W)R(M) structure. The ultimate objective of the Simple SES is to develop management response measures that are accepted by decision-makers and translated into effective policies and regulations, aligning with the broader vision of sustainable marine management. Within the PIMS, outcome and process evaluation prompts are embedded to ensure continuous reflection on whether objectives have been achieved, how stakeholders were engaged, and lessons learned for future processes.

4.4. Complementary tools for implementing the SES

The implementation of the Simple SES relies on complementary analytical tools, such as Causal Loop Diagrams (CLDs) and Behaviour Over Time (BOT) graphs. These tools, originating in Systems Thinking [79], enable the analysis and understanding of complex interactions within marine systems.

BOT graphs are used to analyse the dynamic (temporal) behaviour of key system elements [80]. Rather than focusing on precise values, BOT graphs represent trends and changes in variables, making them qualitative and semi-quantitative tools. In the Simple SES approach, BOT graphs are developed for indicators required for each element in the DAPSI(W)R(M) framework (e.g. indicators for pressures, changes to the ecology and changes to societal goods and benefits). By illustrating historical trends and identifying system behaviours—such as growth, decline, or equilibrium—these graphs provide insight into causal relationships and potential time delays within the system. BOT graphs also highlight data needs and inform dynamic hypotheses, making them an appropriate tool for SES analysis [80].

CLDs are qualitative visual tools that map key system variables and the causal relationships between them. They are crucial for fostering a shared understanding among practitioners and stakeholders of system structures and behaviours. In the Simple SES approach, CLDs are constructed based on the DAPSI(W)R(M) elements identified in BOT graphs. Arrows indicate causal theories of relationships, with positive (+) or negative (-) signs denoting the nature of the influence [81–83]. Feedback loops, either reinforcing (growth or decline) or balancing (stability), can be identified, aiding in system complexity analysis, the identification of leverage points (i.e. points/elements in a system where management interventions would be impactful), and the evaluation of management strategies. These diagrams are intended to be developed using participatory methods and refined through stakeholder validation.

The operationalisation of the Simple SES requires consideration of nested scales, as highlighted in both the SWOT analysis and within EA Principles. Systems concepts, together with examples from other frameworks, support the inclusion of multiple levels (local, regional, national, global) in the analysis. For example, local overfishing may be driven by international market demands, necessitating responses across different scales—local (e.g., community-based regulations), regional (e.g., collaborative efforts between countries), and global (e.g., international agreements) [16]. The incorporation of scalability highlights the importance of recognising both internal (endogenic) and external (exogenic) pressures. The Simple SES approach consistently accounts for these pressures by embedding considerations of system scale and external factors throughout its use.

Fundamentally, the proposed approach aims to include diverse perspectives in the analysis, enhancing its comprehensiveness and relevance. Such engagement is instrumental in validating the research findings and ensuring that the analysis encapsulates a broad spectrum of viewpoints. Although the start and end dates are necessary for applying the SES, it is emphasised that this approach benefits from an iterative and circular process. Fig. 3 illustrates the operationalised schematic of the Simple SES, which follows an anticlockwise progression within the DAPSI(W)R(M) framework. This layout encourages starting the analysis with elements closest to system users, such as impacts on welfare, and progressing through a causal linkage chain. This anticlockwise application facilitates a systematic understanding, beginning with elements directly affected by or impactful to stakeholders, and building towards a holistic view of the entire SES.

The PIMS provides the foundational support throughout this process. Represented by bidirectional arrows, the PIMS ensures that information flows continuously across all stages of analysis, serving both as a central reference point and as a governance system that interweaves through the entire SES framework. This structure allows the PIMS to support iterative learning and real-time adjustments, reinforcing the adaptive

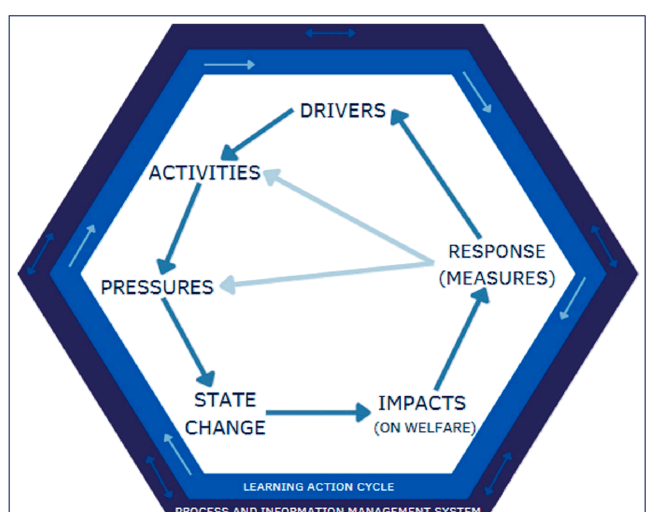

Fig. 3. The Operationalised Simple Social-Ecological Systems Framework.

nature of the Simple SES.

5. Concluding remarks

While the simple SES based on the ISA provides a foundation for analysing and understanding complex marine social-ecological systems, it is not without limitations. By supplementing ISA with key elements from the SAF, SESF, EF, and tools from Systems Thinking, this has resulted in a more comprehensive and effective approach to managing the complexities of marine systems and tackling cause-consequence-response relationships. The approach is considered here to offer a meaningful pathway for designing management measures based on better-informed decision-making. However, the further practical operationalisation and testing of this approach are crucial to understand its strengths and limitations. Increased understanding of SES management and further evolution to a salient approach may aid practitioners in understanding and managing complex and adaptive marine systems.

This study rigorously examined nine SES frameworks, reflecting current practices in the literature. While there may be other approaches not identified in this review, the authors consider that the frameworks analysed represent exemplars of the progress made in SES literature. Through a SWOT analysis of these frameworks, we highlight the value of SES approaches for marine management. Strengths common across the frameworks include holism, adaptation, cross-scalability and interconnectedness—qualities that align with EA principles, such as Principle 3, which emphasises considering the effects of activities on adjacent ecosystems [43]. The practical application of these frameworks offers valuable guidance for marine managers aiming to implement holistic and well-informed decision-making processes. The Simple SES approach aspires to provide a useable and comprehensive understanding of marine systems, their behaviour and the interactions between environmental managers and society. Furthermore, this review contributes to the literature by identifying concepts which aspire to improve EBM uptake in the context of sustainable marine management. Building on the foundational work of Ostrom [41], Berkes and Folke [30] and Holling [45], together with insights from marine management projects such as the SAF, the Simple SES integrates lessons learned from operationalising SES frameworks. This analysis fills an important gap by providing an up-to-date, focused comparison of SES frameworks specifically tailored for marine ecosystems and EBM objectives.

In conclusion, this review presents a Simple SES framework for enabling the practical implementation of holistic EBM in marine systems. It also identifies trade-offs that must be considered to fully operationalise SES frameworks in various marine management contexts.

This study is a contributor to the efforts of increased uptake of EBM by the EU and UKRI-funded Horizon Europe project Marine SABRES (Marine Systems Approaches for Biodiversity Resilience and Ecosystem Sustainability [84], see https://www.marinesabres.eu/). Further work is now operationalising and applying it in geographical case studies.

Contributions

GS undertook the literature review study, the SWOT analysis and writing of this paper. AG and JA reviewed the literature review study and developed the structure and approach of the review. AG and JA conceptualised the initial Simple SES approach and structure, created the PIMS framework and models in Figs. 2 and 3. AG, JA, and GS all contributed to the operationalisation of the Simple SES approach resulting from this study. As the originator of the original ISA, ME was not involved in the SWOT analysis but was responsible for the motivation for the study, reviewed the literature review study and contributed to writing this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100476.

Data availability

No data was used for the research described in the article.

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