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Strengthening the seascape of global environmental assessments to support ocean sustainability

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Ambitious evidence-based policies are urgently needed to redirect mankind's trajectory towards ocean sustainability. While global environmental assessments (GEAs) synthesizing ocean knowledge are multiplying, we must ensure that their processes and outputs are conducive to social legitimacy, scientific credibility, and meet decision-makers' needs. Here, we identify best practices for GEAs to achieve legitimacy, credibility, and salience and develop a framework to evaluate their levels of implementation. We apply this framework to review the processes and outputs of 12 influential reports at the ocean science-policy interface. Credibility best practices were well implemented in GEAs but significant opportunities remain to strengthen legitimacy and salience best practices, notably by increasing stakeholder engagement, diversifying knowledge systems represented, and featuring actionable knowledge for decision-makers. We formulate four recommendations to strengthen the GEA seascape: elevating co-production practices, bridging scales through multi-level approaches, increasing transparency in knowledge choices and gaps, and coordinating assessment processes.

Marine ecosystems and their contributions to people are at increasing risk of collapse[1,2]. Unsustainable uses of the ocean, high-impact land-based activities, and climate change are jeopardizing the health of the ocean and of the entire Earth system. Many initiatives have been deployed to address the historical underrepresentation of the ocean in international policy discussions following increased political recognition that ocean health is necessary to achieve global sustainability and address the climate and biodiversity existential crises[3]. The United Nations (UN) Ocean Decade (2021–2030), the Sustainable Development Goal (SDG) 14 dedicated to Life Below Water, the 30 × 30 conservation target by the Kunming-Montreal Global Biodiversity Framework, and the recently concluded High Seas treaty under the UN Convention on the Law of the Sea are all encouraging milestones demonstrating a growing shared awareness and political will to achieve ocean sustainability.

Achieving transformative action – i.e., radical shifts in social, political, and economic systems - toward sustainability depends on a set of complex and interconnected factors including political will, societal incentives, shifts in shared narratives and values, and the deliberate reconfiguration of governance structures[4–6]. Requirements to achieve a sustainable transition include effective two-way communication between scientists, decision-makers and stakeholders[7,8]. This need led to the establishment of knowledge-exchange interfaces aiming at assembling available scientific information to provide policy-relevant knowledge while accounting for different viewpoints, societal values, and uncertainty[9]. Such science-policy interfaces have taken diverse shapes, including scientific advisory bodies, standardized impacts assessments, and large-scale integrated scientific assessments[9,10]. Unlike other knowledge-exchange strategies, integrated scientific assessments are often linked to intergovernmental frameworks, synthesize knowledge at the global or supra-national scale, and their scope is typically mandated or endorsed by governing bodies (e.g., United Nations General Assembly)[9]. Science-policy interfaces dedicated to global environmental challenges have been primarily supported by Global Environmental Assessments (GEAs), which are large-scale deliberative processes through which experts synthesize and organize existing knowledge on environmental issues to inform evidenced-based decision-making[11]. Among GEAs, assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental

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Science-Policy Platform of Biodiversity and Ecosystem Services (IPBES) have become references to inform climate and biodiversity loss mitigation policies. However, ocean-related challenges have historically been underrepresented in these assessments and the mandates of ocean-focused assessments often limited to a narrow geographic or thematic scope, such as the fishery sector or marine pollution impacts. To provide a more comprehensive representation of the ocean's state, the UN Regular Process was established in 2010 to conduct the World Ocean Assessment (WOA) series[12], now approaching its third assessment cycle. A decade later, the publication of the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) by the IPCC[2] represented another landmark in moving the ocean forward in the climate agenda, in particular by initiating the formal ocean dialogue in the UN Framework Convention on Climate Change. While the increasing number of ocean knowledge syntheses is encouraging, it remains crucial to ensure that their underlying processes, methods, and outputs serve to maximize their effectiveness.

The effectiveness of GEAs can be defined as the extent to which GEAs wield influence on political decisions and in turn on societal and environmental transformations towards sustainability[13,14]. The effectiveness of GEAs depends on external factors - such as political will and resource constraints - and on internal factors - such as the processes, methods, and scope of the assessment, which determine their perceived legitimacy, credibility, and salience[15–17]. While a direct measure of the influence of GEAs on society is extremely challenging[13,18], an abundant literature has identified best practices[15,16,19] that contribute towards effectiveness and that are more readily measurable than effectiveness itself[13,15–17,19]. Further, critical reviews of GEAs have evaluated the implementation of some best practices in both ocean-focused assessments[12,20] and Earth-system assessments, in particular those produced by the IPBES and IPCC[21,22]. However, previous reviews have typically focused on a subset of best practices within a single or a subset of ocean-focused assessments, which does not provide a comprehensive outlook on the strengths and weaknesses of the GEA seascape as a whole (i.e., the combination of assessments synthesizing ocean knowledge to inform policymaking). Furthermore, while it is recognized that gaps exist in the ocean knowledge covered by the GEA seascape[23], no systematic review of ocean knowledge covered by GEAs has been performed.

The aim of this study is to evaluate the implementation of best practices and the coverage of ocean knowledge in global ocean assessments. Specifically, we aim at answering the following research questions: (1) what are recognized best practices of legitimacy, credibility, and salience for GEAs?; (2) are these best practices implemented in the processes and outputs of GEAs?; (3) how is ocean knowledge covered across the GEA seascape?; and (4) in light of these results, how can future GEAs be improved to better support ocean sustainability? To answer these questions, we develop a standardized framework to assess the implementation of 26 best practices for legitimacy, credibility, and salience in GEAs, based on best practices identified from scientific and institutional literature. We then score the implementation of these best practices across 12 influential GEAs at the ocean science-policy interfaces to provide a critical outlook of the strengths and weaknesses of processes underlying the GEA seascape. Lastly, we evaluate the coverage of ocean knowledge across GEAs to identify content gaps that could be developed in future assessments, as well as content redundancies that represent opportunities for coordination between assessment processes. We supplement our findings with insights from interviewees with long-standing experience at ocean science-policy interfaces and highlight four opportunities to strengthen future assessment cycles.

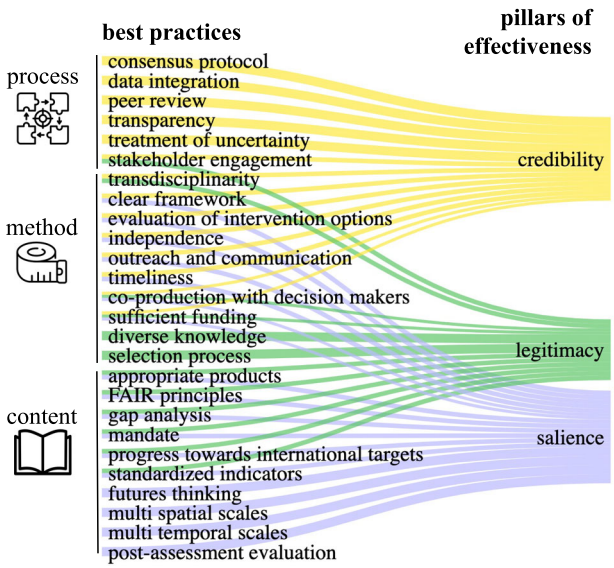

Fig. 1 | Best practices contributing to the legitimacy, credibility, and salience of Global Environmental Assessments. Links connecting best practices to two (resp. three) pillars of effectiveness are twice (resp. three-fold) thinner than links connecting best practices to a single pillar. Definitions of best practices are provided in Supplementary Table S2.

Results

Best practices for the legitimacy, credibility, and salience of GEAs

We pooled the 92 recommendations identified from five key institutional and scientific publications[20,24–27] (see Methods and Supplementary Table S1) into 26 non-redundant and exhaustive best practice categories (Fig. 1, Supplementary Table S2) that contribute towards the three pillars of GEA effectiveness: legitimacy, credibility, and salience (Fig. 1). While some best practices related to a single pillar of effectiveness, several related to two or all three pillars. Best practices supporting the legitimacy of an assessment, i.e., the perception that the assessment process is fair and impartial[28], were primarily linked to features of the assessments' process, such as the level of co-production with decision-makers, the level of engagement with diverse knowledge-holders, and the independence of the expert committee (Fig. 1). Best practices supporting the credibility of an assessment, i.e., the perception by the relevant expert communities that the evidence presented is trustworthy and technically correct, were primarily related to the rigor of the knowledge synthesis, such as the treatment of uncertainty, protocols to address lack of consensus, and external peer-review by independent experts (Fig. 1). Lastly, best practices supporting the salience of an assessment were primarily related to the relevance and timeliness of the knowledge presented with regard to stakeholders' needs and agency[29]. Best practices supporting salience included the synthesis of knowledge that is spatially and temporally relevant to decision-making processes, critical evaluations of intervention options, and the presentation of knowledge in a digestible format for decision-makers (Fig. 1).

The GEA seascape: a patchwork of ocean knowledge syntheses

We reviewed recent (post 2018) environmental reports produced to inform science-policy interfaces at the global scale (hereafter GEAs) and synthesizing knowledge either on the ocean or on the entire Earth-system. For recurring assessments, we only reviewed the most recent publication of the series. The 12 GEAs that matched these criteria (see Methods for more details on selection criteria) varied strongly in their scope, total length (number of pages), and publication periodicity (Fig. 2). Five of these assessments were predominantly ocean-focused, among which three (the WOA II, the State of the Ocean Report - StoR, and the State of the Ocean Fisheries and Aquaculture - SOFIA) were part of publication cycles. The other seven assessments focused on the entire Earth-system. Six of them were part of publication cycles with periodicities ranging from one to six years. The proportion of Earth-system assessments dedicated to ocean knowledge (see "Ocean-related content of assessments" in Methods) varied between ~5% (Global Resource Outlook, GRO) and 50% (IPCC AR6). Apart from the WOA II and the State of the Ocean Report (StOR) which had a broad scope, GEAs focused on a specific activity sector (e.g., fisheries or mining) or a specific existential threat (e.g., climate change or biodiversity erosion).

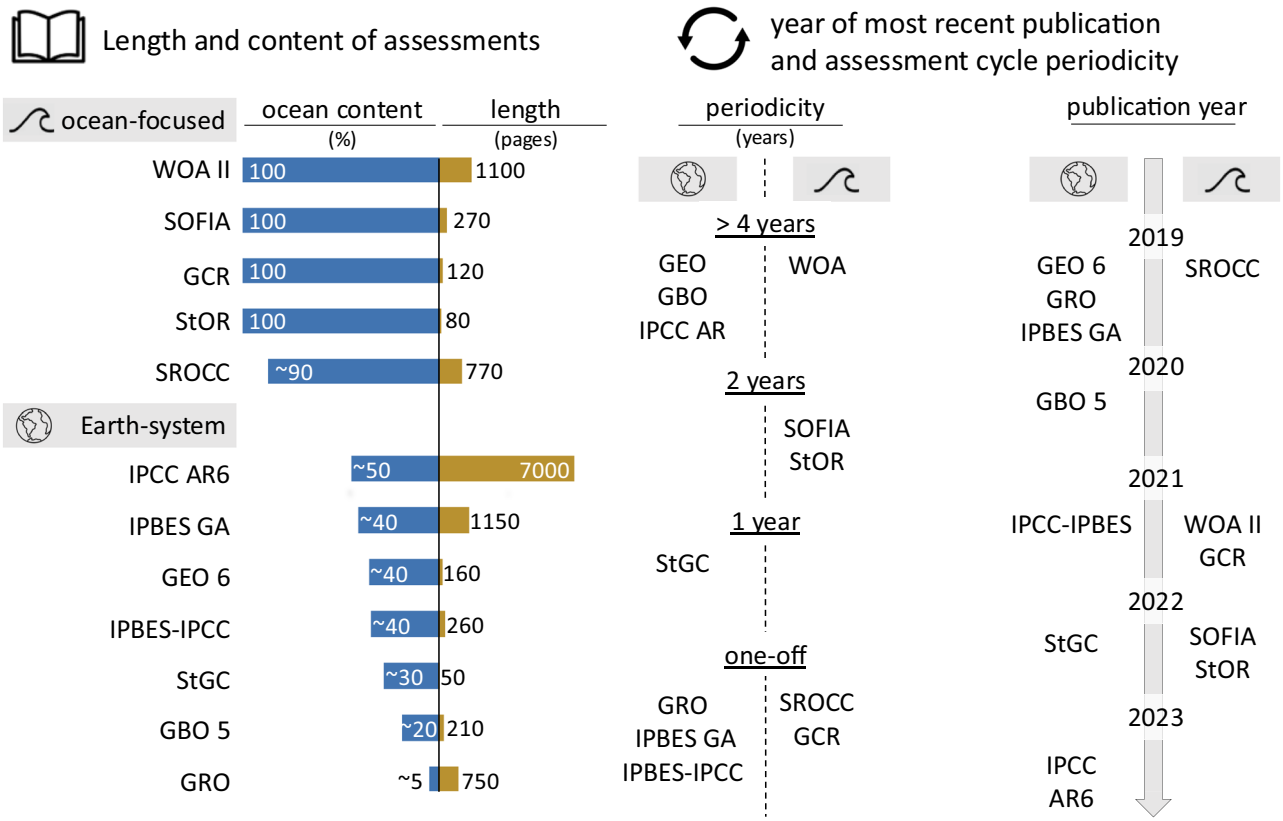

Fig. 2 | Profiles of global environmental assessments reviewed. Proportion of content (% pages) dedicated to ocean knowledge and total length (in pages) of assessments (left panel), periodicity of assessments' publication (central panel), and year of their latest publication (right panel). Wave icons denote ocean-focused assessments, while earth icons denote Earth-system assessments. Assessment acronyms stand for the following: Global Environmental Outlook (GEO), Global Biodiversity Outlook (GBO), World Ocean Assessment (WOA), Assessment Report (AR), Special Report on Ocean and Cryosphere in a Changing Climate (SROCC), State of the Ocean Fisheries and Aquaculture (SOFIA), State of the Ocean Report (StOR), Global Coastal Resources (GCR), the State of the Global Climate (StGC), Global Resource Outlook (GRO), Global Assessment Report on Biodiversity and Ecosystem Services global (IPBES GA) and IPBES-IPCC co-sponsored workshop report on Biodiversity and Climate Change (IPBES-IPCC).

Implementation of best practices in GEAs

We developed standardized criteria (Supplementary Table S2) to score the level of implementation (0 - absent, 1- partial, or 2 - complete) of the 26 best practices related to legitimacy, credibility, and salience that we identified, and evaluated their level of implementation in the 12 GEAs reviewed. We found that GEAs scored highest in the implementation of credibility best practices, followed by legitimacy best practices, while they scored the lowest in the implementation of salience best practices (Fig. 3). Weaknesses of the GEA seascape identified by interviewees were also predominantly linked to salience (58% of mentions, Fig. 4).

Credibility best practices were the most broadly implemented across the GEA seascape, for both Earth-system and ocean-focused assessment. Peer-review processes, transdisciplinarity among experts, well-defined framework, and ongoing sources of funding were found in almost all assessments reviewed (Fig. 3). Credibility best practices that were only partially implemented or absent from GEA processes included the presence of a consensus protocol, the performance of a post-assessment evaluation, and the use of a standardized confidence language to indicate the level of evidence and uncertainty of the knowledge presented.

The most widely implemented legitimacy best practices were FAIR (findable, accessible, interoperable, and reusable) principles for data used in assessments, legitimate mandates, engagement with decision-makers, and transparency on internal governance mechanisms. Multiple legitimacy best practices were implemented in less than half of the GEAs evaluated, such as diversifying knowledge systems considered in assessments, increasing stakeholder engagement, fostering independence of expert committees, and selecting experts transparently. With the exception of the SROCC, ocean-focused assessments had lower implementation levels of legitimacy best practices than Earth-system assessments (Fig. 3).

We found that the salience pillar offers the largest opportunity for improving the implementation of best practices (Fig. 3). Salience best practices that were most widely implemented included timeliness (i.e., the respect of the GEA's publication timeline and the synthesis of up-to-date information), the use of standardized indicators to document the state of the ocean, and the presence of gap analyses (i.e., information on which fields require further scientific or policy development). By contrast, the inclusion of future scenarios at multiple temporal scales (near-, medium-, and long-term) and of intervention options at multiple spatial scales (local, regional, and global) were rarely implemented. Most GEAs provided partial or no synthesis of intervention options, which were often limited to anecdotal case studies as opposed to systematic comparisons of outcomes across multiple options. Further documentation on the progress made towards international targets, such as the SDG 14 or the Aichi Targets, and on how different interventions could contribute to these targets, could also increase the policy relevance of assessments. Lastly, apart from the SOFIA, futures thinking was either absent or restricted to predictions of physicochemical variables in ocean-focused assessments, despite the recognized importance of developing shared common visions and pathways for sustainability transformations[30–32].

Gaps and redundancies in the coverage of ocean environmental knowledge

We evaluated the coverage of ocean environmental knowledge across the GEA seascape to identify well-covered themes and those that could benefit

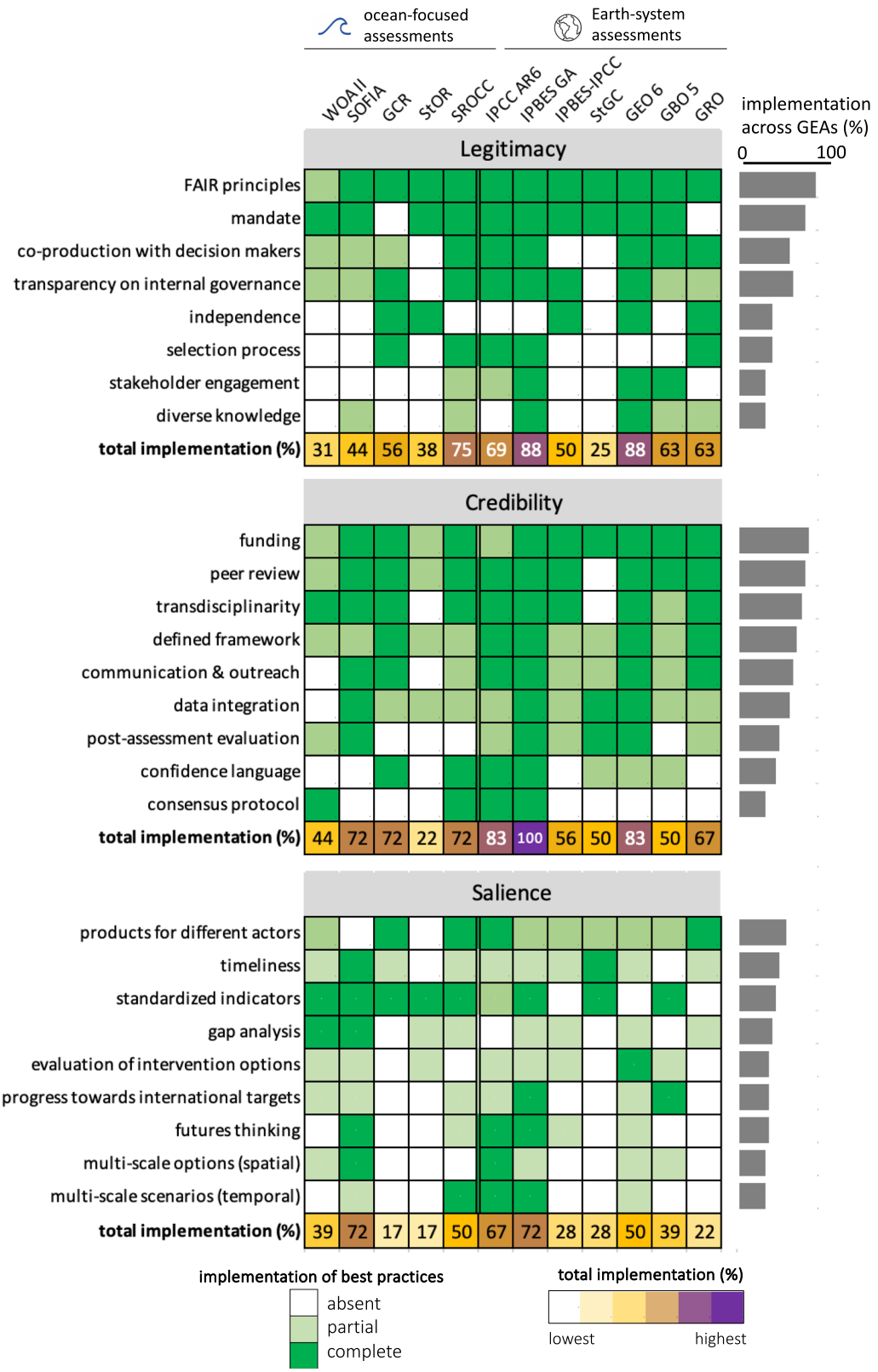

Fig. 3 | Level of implementation of legitimacy, credibility, and salience best practices in GEAs. Colors (white to dark green) denote the level of implementation of best practices in individual assessments (absent to complete). Total implementation (%) denotes the total level of implementation of best practices across a given pillar of effectiveness. Gray bars to the right indicate the level of implementation of a given best practice across assessments evaluated. Levels of implementation were determined from multiple sources of information including GEA content, GEA websites, and literature on GEAs (see Supplementary Data S1).

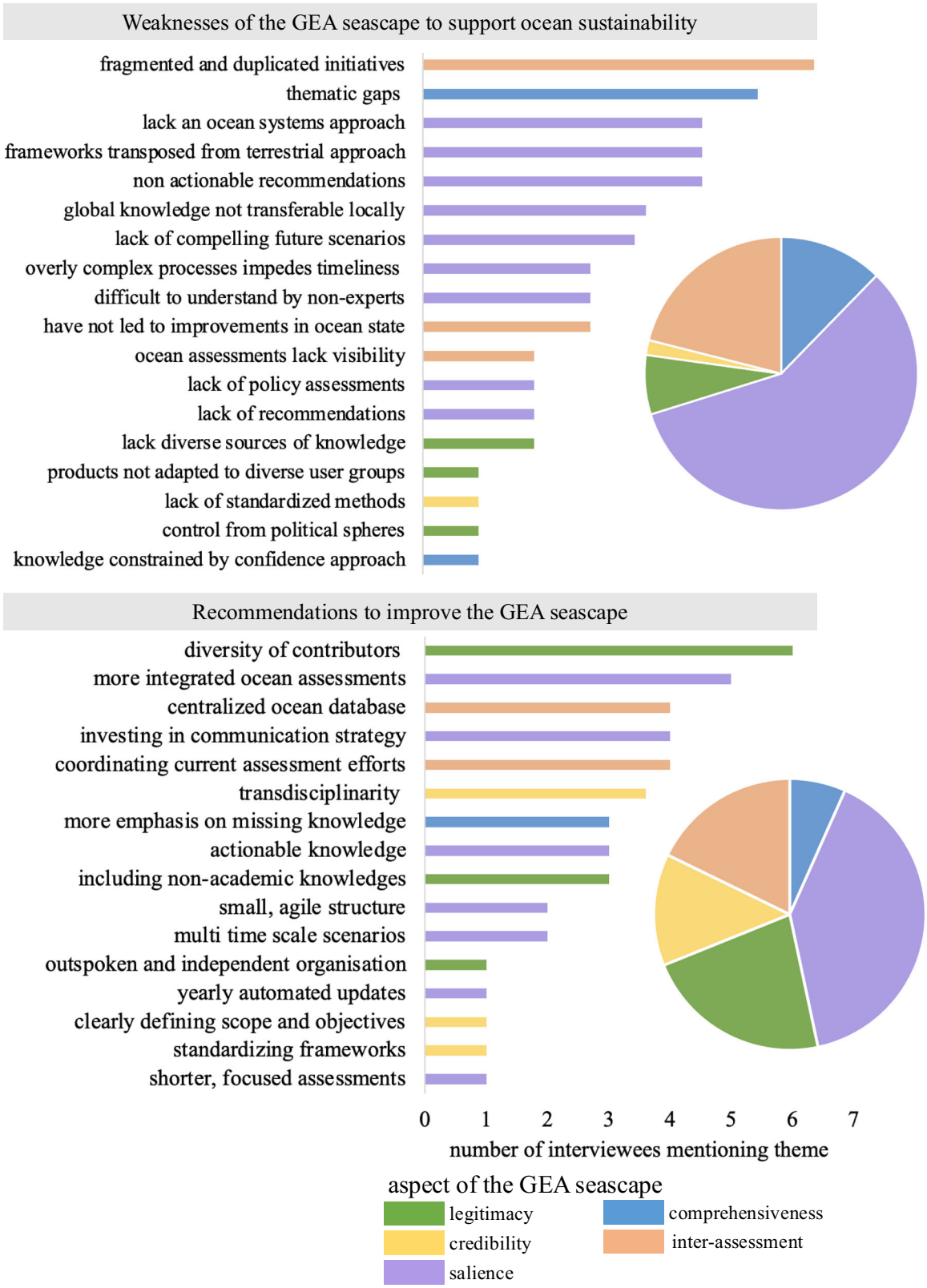

Fig. 4 | Weaknesses of (top panel) and recommendations for (bottom panel) the GEA seascape identified by interviewees. Colors indicate the pillar of effectiveness that the weakness or recommendation relates to. The "inter-assessment" category refers to weaknesses or recommendations beyond the scope of individual GEAs, at the scale of the GEA seascape as a whole.

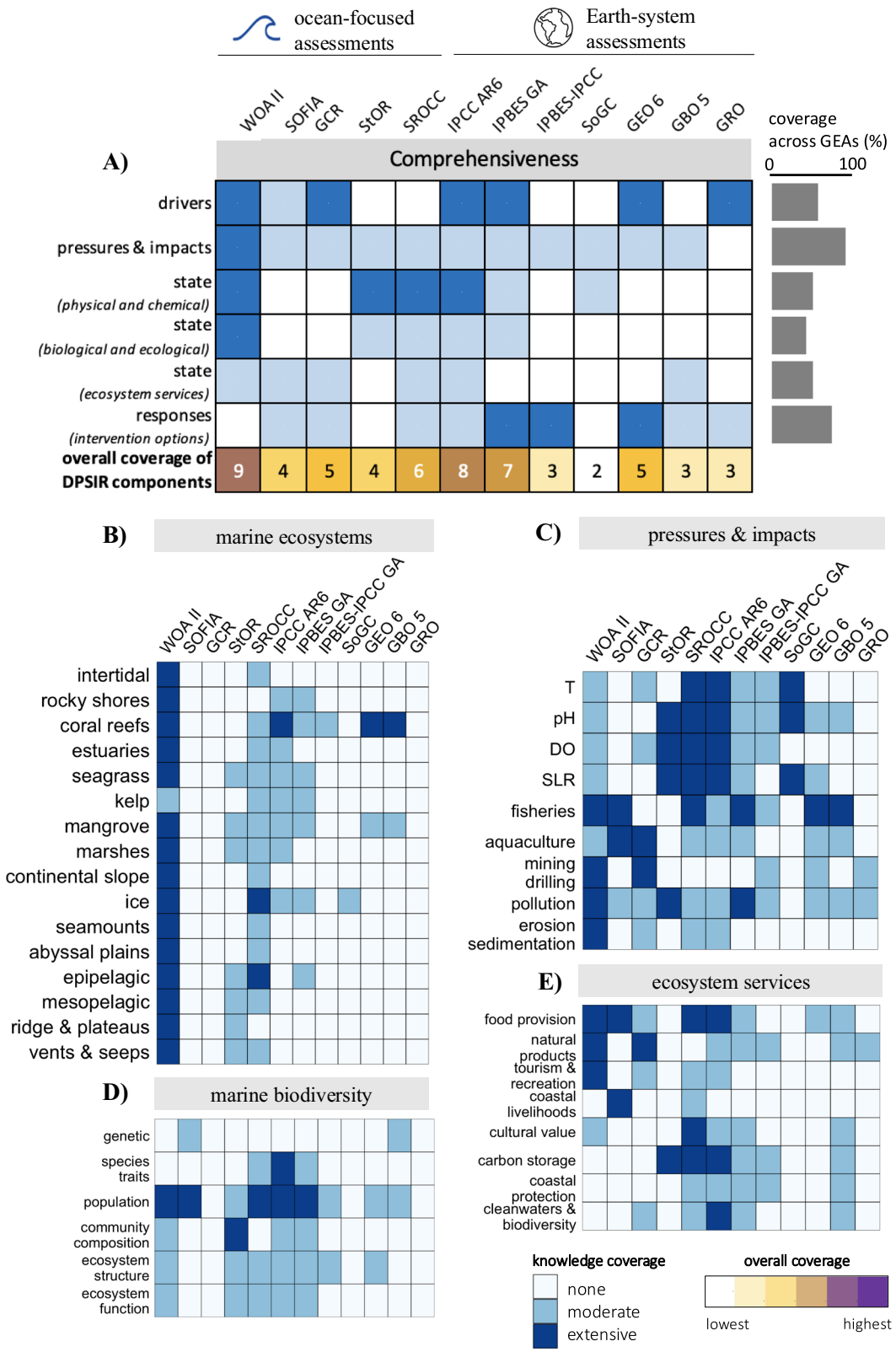

Fig. 5 | Coverage of ocean environmental knowledge by the GEA seascape. Coverage of environmental knowledge was evaluated for each assessment across components of the DPSIR framework (**A**), across marine ecosystems (**B**), across types of pressures and impacts (**C**), across scales of the marine environment (**D**), and across ecosystem services (**E**). Bars to the right of panel (**A**) indicate the level of coverage of DPSIR components across all reports evaluated. Colors (white to dark blue) denote the coverage level of environmental knowledge in individual assessments (none to extensive). Acronyms refer to temperature (T), dissolved oxygen (DO), sea level rise (SLR). Knowledge coverage was determined by reviewing the content of GEAs.

from additional reporting to inform the complex challenges faced by decision- and policymakers. To do so, we developed knowledge categories based on the components of the Drivers-Pressures-State–Impacts-Responses (DPSIR) framework[33], including ecosystem services[34]. We chose the DSPIR framework because it is among the most broadly recognized policy-oriented framework that promotes a holistic, systems-approach representation of sustainability challenges[35,36] altough different frameworks and knowledge categories could be adopted. While our review of best practices encompassed environmental, social, and policy considerations, we restricted our review of ocean knowledge covered in GEA to environmental themes as our review focused on environmental assessments.

We found that the most documented DPSIR components in GEAs were marine pressures and intervention options (corresponding to the "response" component of the DPSIR framework, Fig. 5A). Drivers of ocean change were either extensively covered (e.g., WOA II, Global Coastal Resources) or not covered at all (e.g., SROCC). The biological and ecological state of the ocean (e.g., community composition and ecosystem structure) was covered by fewer assessments and was not as thoroughly documented as physical and chemical ocean variables. Overall, the WOA II featured the most comprehensive coverage of ocean environmental knowledge across DPSIR components (Fig. 5A), although it did not cover intervention options and only partially documented marine ecosystem services. The next most comprehensive assessments regarding ocean environmental knowledge were Earth-system assessments, such as the IPCC AR6 and the IPBES global assessments.

We assessed the coverage by GEAs of different marine ecosystems, ecosystem services[37], marine pressures[38], and of different features of marine biodiversity, from genetic to ecosystem functions[39]. We found that the coverage of these features was fragmented and uneven, with some features covered in multiple assessments, and others not covered in any (Fig. 5B–E). This observation was also formulated by interviewees ($n = 21$, Fig. 4), who stated that the main weaknesses of the GEA seascape were fragmented and duplicated initiatives ($n = 7$ statements) and thematic gaps ($n = 6$). Only the WOA II and the SROCC documented the state of all major marine ecosystems (extensively and partially, respectively), while most GEAs primarily focused on coastal ecosystems, in particular coral reefs and mangroves, or did not provide information on ecosystems' state (Fig. 5B). The state of the ocean's health was documented predominantly through a limited number of population- and ecosystem-level metrics, such as abundance, range shift or extent (Fig. 5D). By contrast, less than three GEAs synthesized knowledge on the state and trends of marine genetic diversity or of species traits. Ecosystem services were the least documented features and were mostly restricted to extractive uses such as food provision and natural products (Fig. 5E). Services that are not as easily quantifiable in economic terms, such as the support of coastal livelihoods, intrinsic and cultural values, tourism and recreation activities supported by a healthy ocean were mentioned in five or fewer assessments. All main marine pressures were documented by at least one GEA, but few GEAs extensively documented several pressures, reflecting the sectorial-driven mandates of assessments. The SOFIA extensively focused on fisheries and aquaculture; the GCR on aquaculture, mining, and drilling; while the IPCC AR6, SROCC, StGC, and StOR primarily focused on climatic pressures (Fig. 5C). The WOA II was the only assessment that covered all types of pressures, but with a lower emphasis on climatic pressures.

Discussion

Global sustainability targets provide a collective lighthouse to guide humanity towards sustainability. GEAs play a crucial role in synthesizing global knowledge on the state of the ocean, presenting intervention options to policymakers to achieve sustainability targets, and evaluating the progress made towards these targets. Global targets require translation into local policies and implementation, the achievement of which is shaped not only by global scientific endeavors such as GEAs but also by societal priorities, differentiated capacities, socioeconomic realities, and geopolitics. Notwithstanding, GEAs provide synthesized knowledge on the Earth's systems designed to support decision-making across scales and as such should be credible, legitimate, and salient.

Using a standardized framework to evaluate the implementation of legitimacy, credibility, and salience best practices in GEAs, we identified features that should be strengthened across the methods, process, and content of GEAs. We found that the GEA that provides the most comprehensive coverage of ocean knowledge, WOA II, is one of the assessments that would most benefit from the development of legitimacy and salience best practices. Previous evaluations have also highlighted the limited capacity of the WOA process to support efforts towards SDG 14[12]. While the WOA II achieved important improvements relative to the WOA I, these observations likely contribute to the WOA series still being overshadowed, even in the ocean sphere, by Earth-system assessments like the IPCC and the IPBES[12]. At minima, strengthening the GEA seascape requires the reinvigoration of existing assessment processes through co-production with decision-makers, inclusion of diverse knowledge systems, and broader stakeholder engagement. Previous frameworks developed by Earth-system GEAs to develop knowledge co-production, multilevel approaches, and futures thinking is available to guide future WOAs in this regard. In parallel, setting up a new boundary-spanner mechanism for ocean sustainability[40] to strengthen ocean science-policy-society interfaces through an inclusive, action-oriented, and demand-driven approach, such as the emerging International Platform for Ocean Sustainability, has been identified as an avenue to consolidate and perpetuate the UN Ocean Decade goals[31,41,42].

Building upon the findings of this study, we formulate four recommendations to strengthen the GEA seascape: elevating co-production practices, bridging scales through multi-level approaches, increasing transparency in knowledge choices and gaps, and coordinating assessment processes.

Recommendation 1: Elevating co-production practices within GEA processes

Ocean-focused assessments could increase their legitimacy by developing weakly-implemented legitimacy best practices, including co-production with decision-makers, engagement with stakeholders, and integration of diverse knowledge systems. Such co-production processes are essential to promote trust and ownership of GEAs' outputs amongst ocean stakeholders, foster a shared understanding of environmental issues, tailor context-relevant recommendations, and in turn ensure that the scope of assessments and policy endeavors are coordinated[7,29,43,44]. The prioritization of scientific knowledge over Indigenous and local knowledge still dominates the GEA modus operandi[45]. While recent efforts, notably by the IPBES[46,47], have aimed at developing inclusive frameworks that represent diverse sources of knowledge in assessments, much criticism remains on the limited representation of non-Western knowledge systems, values, and worldviews in GEAs, IPBES alike[48,49]. Improving current frameworks could be achieved by implementing principles of 'knowledge-weaving,' a process that expands the current emphasis on knowledge synthesis to embrace other tasks such as mobilization, translation, negotiation, and application[50]. This process goes beyond integration by fostering an intertwining of insights while respecting the uniqueness of each knowledge system[51].

Recommendation 2: Bridging temporal and spatial scales through multi-level approaches

GEAs have shifted over the past decade from a focus on environmental problems to policy solutions[11,52]. However, we found that intervention options are mostly formulated at a global, long-term scale, which is not sufficient to guide shorter-term, context-specific challenges faced by decision-makers[53]. Part of this mismatch is inevitable because of the inherent discrepancy between the timescale of decision makers, dictated by political mandates, and the timescales required for transformational policies to yield noticeable benefits. Nevertheless, the actionability of recommendations could be improved by promoting continuous interactions between GEA actors and relevant institutions and stakeholders across scales[43,54]. This could be achieved by implementing multilevel approaches, including knowledge-brokering - i.e., translating research findings into practical

insights for practitioners[55] - and boundary-spanning -i.e., creating spaces where science and policy can co-produce knowledge[56]. Incorporating case studies to illustrate how global intervention options can be scaled down to local contexts and developing companion assessments to supplement GEAs, such as the IPBES regional assessments, represent feasible options to bridge the gap between the scale of GEAs and that of policymakers. While such efforts are being developed by the IPBES and GEO series, they remain to be developed by most ocean-focused assessments including the WOA series. Collaboration with well-established regional management and reporting systems, such as the UNEP Regional Seas Program or Regional Fisheries Management Organizations, could offer an excellent starting point to develop a cross-scale and multilevel framework for ocean-focused assessments.

Recommendation 3: Making knowledge choices transparent and knowledge gaps explicit

The disparate coverage of marine ecosystems, pressures, services, and scales at which biodiversity is considered reflects the availability of scientific knowledge but also institution-driven knowledge choices that define the thematic scope of GEAs[21,57]. While we do not suggest that GEAs should follow the DPSIR framework or cover each of its components, ensuring that DPSIR components are covered at least once across the GEA seascape holds value because many decision-making frameworks rely on a combination of DPSIR components. Similarly, while an even documentation of all marine ecosystems, pressures, and services might not be the best approach to inform ocean sustainability, more reflexivity and transparency on why some topics benefit from greater coverage than others is warranted. This is particularly important given that available scientific knowledge can reflect thematic biases within scientific fields[58] or inequities in research capacity between the Global North and South[59,60] rather than the knowledge priorities to inform ocean sustainability. Furthermore, understudied fields and high uncertainty topics can be those for which most guidance is needed, as illustrated by ongoing debates on deep-sea mining[61,62], which contrast with the low coverage of deep-sea knowledge across the GEA seascape (Fig. 5B). As a result, tailoring the breadth of thematic sections in GEAs based on available scientific knowledge might not be desirable. Striving towards greater representativeness of all topics across the GEA seascape, including clear statements of knowledge gaps when the latter prevent information synthesis, could contribute to a broader consideration of marine challenges in the policy arena and highlight understudied fields that should constitute priorities for future research efforts. Lastly, greater transparency and reflection on the institutional knowledge practices that shape how and which types of ocean knowledge is synthesized is required to identify and address current epistemological biases and bolster legitimacy[21,63].

Recommendation 4: Optimizing coordination between assessments

In addition to the best practices that we identified as holding important potential to improve the legitimacy, credibility, and salience of GEAs, the effectiveness of the ocean-reporting system can also be enhanced by the implementation of inter-assessment features, as highlighted by interviewed experts. Indeed, the ocean is a complex and highly connected system, in which environmental and human pressures act synergistically rather than independently[64]. While ocean governance systems are characterized by siloed mechanisms that restrict the scope of action of decision-makers, providing a holistic representation of the ocean's state, processes, and threats remains fundamental to inform sustainability interventions and foster more integrated ocean management approaches[65,66]. Developing capacity for knowledge co-production between sectorial governance systems could also serve as a unique opportunity for exchanges and coordination between these fragmented mechanisms[67]. As such, promoting exchanges between assessment processes that focus on single pressures (e.g., fishing for SOFIA and climate for IPCC) could enable more integrated representations of ocean challenges and better inform on the co-benefits and trade-offs of intervention options across sectors. (Fig. 4). The outcomes of the workshop co-led by the IPCC and IPBES[68] is a great example of such effort and would be beneficial to reproduce between ocean-focused assessment processes[65,66].

Coordinating efforts between assessment processes could also serve to rationalize existing ocean-knowledge reporting efforts and decrease the strain exerted on limited financial and human resources[11]. While redundancies in topics covered by GEAs hold inherent value to build consensus and assert the robustness of evidence, streamlining the syntheses of topics covered in multiple assessments could allow to transfer resources towards implementing best practices or developing topics currently underrepresented (Fig. 5). For example, knowledge synthesis performed on the state of fisheries by the SOFIA could be fed into the fisheries section of the WOA series. Lastly, coordination between terrestrial- and ocean-focused assessments would enable to better account for the complexity and interconnectedness of processes at the planetary scale.

This study is not immune to some of the weaknesses identified in the GEA seascape. The literature and the frameworks it builds upon reflect Western worldviews that dominate both scientific and institutional publications[69]. Additionally, in order to produce a three-tier scoring system for the implementation of best practices, we selected measurable criteria based on publicly available information that cannot capture the full complexity of nuanced best practices such as stakeholder engagement. We recognize that as a result, some scoring criteria partly overlapped, were at times difficult to decide upon, or simplified the reality. Lastly, while we strived at representing a gender- and sectoral-balanced composition among the science-policy actors we interviewed, interviewees were predominantly from the Global North. While we believe the overarching strength, weaknesses, and recommendations identified in this study are robust to these limitations, the exact scoring and ranking of assessments can be improved and are now open to scrutiny.

The UN Decade of Ocean Science for Sustainable Development is committed to reversing the deterioration of ocean health, with a focus on developing ocean science that can support nations in achieving ocean sustainability. This involves filling knowledge gaps, making ocean science more actionable, diversifying knowledge representations, and strengthening ocean science-policy-society interfaces. While recent initiatives have increased the visibility of ocean knowledge within GEAs, our study highlights the important opportunities that remain to strengthen the legitimacy and salience of the GEA seascape. Reinforcing the implementation of best practices such as stakeholder engagement, diversity of knowledge represented, and synthesizing actionable knowledge for decision-makers, including multi-scale intervention options and evaluation of progress towards international targets, represent important pathways towards enhanced legitimacy and salience. We recommend that GEAs elevate co-production processes, bridge spatial and temporal scales through multilevel approaches, increase the transparency of knowledge choices and gaps, and develop coordination between assessments to rationalize efforts and provide a more holistic representation of planetary processes and challenges. Many of the weaknesses of GEAs reflect systemic shortfalls and as such, our recommendations can be transferred to improve the effectiveness and equity of other knowledge-exchange interfaces and more broadly of ocean governance and research practices[10,59,70]. This includes diversifying the institutions and countries partaking in knowledge production[70], ensuring that benefits and costs of ocean governance are shared equitably[71,72], integrating local and Indigenous knowledge in scientific frameworks, and fostering inclusive knowledge co-production strategies throughout the scoping, study, and delivery phases of research[7]. These insights are not just academic observations, they are urgent calls for action. Effective reporting systems are required to meet the UN Decade's goals but also to pave the way for sustainable ocean governance beyond 2030.

Methods

Our study is based on the review of recent global environmental assessments (GEAs) focusing either exclusively on marine systems or on the entire Earth-system. We complemented this GEA review with insights from interviewees working at science-policy interfaces. This approach has been broadly used in previous GEA evaluation studies[8].

General framework

The framework of this study builds upon a methodology developed in collaboration with the Directorate-General for Maritime Affairs and Fisheries (DG MARE) of the European Union (EU) as part of the Feasibility Study for the Establishment of an International Panel for Ocean Sustainability[40]. The Feasibility Study was commissioned by the European Union to evaluate the need to establish a new reporting system in support of ocean sustainability. The Feasibility Study was conducted by reviewing existing reporting systems, collecting insights from actors at the science-policy interface, and organizing workshops to understand needs and perceptions of diverse stakeholders[41]. The present study builds upon the GEAs reviewed and the interviews conducted for the Feasibility Study to answer the following research questions: (1) what are recognized best practices of legitimacy, credibility, and salience for GEAs to support ocean sustainability?; (2) to what extent are these best practices implemented in the processes, methods, and outputs of recent GEAs?; (3) what is the coverage of major environmental knowledge themes by the GEA seascape?; and (4) what are key levers to strengthen the capacity of GEAs to support ocean sustainability? The methods used in the Feasibility Study, including the list of best practices and ocean environmental themes evaluated, the terminology used, the measure of the implementation level of best practices were fully revised to design this present publication. This was done to adapt the methodology to the specific research questions raised in this study and to reflect the inputs from co-authors and collaborators that did not participate in the Feasibility Study. Importantly, the Feasibility Study included the review of a broader set of science-policy tools, including policy briefs published by NGOs, data portals (e.g., the Ocean Health Index), and methodology documents (e.g., the Global Manual on Measuring SDG 14 by the UNEP). The difficulties in comparing the processes and methods of such diverse tools led us to narrow the scope of the Feasibility Study to focus specifically on GEAs for the present publication. Additionally, insights gained by authors throughout the review of GEAs and interviews conducted for the Feasibility Study led to a change in the number (23–26) and in the grouping of best practices reviewed. For example, one of the best practices in the Feasibility Study was "measure of progress towards SDG 14", which we broadened in this study to "measure of progress towards international targets". Lastly, no explicit list of criteria had been develop in the Feasibility Study to measure the level of implementation of best practices in GEAs, leading to qualitative comparisons only.

Selection of reports reviewed

We reviewed reports meeting the following criteria as of June 2023: (1) published since 2018; (2) performed at a global scale (regional assessments were excluded, as well as reports focusing on specific types of marine ecosystems); (3) synthesizing knowledge on the state of the ocean, with a primary focus on environmental knowledge (e.g., assessments from the High Level Panel for a Sustainable Ocean Economy were not reviewed as they primarily focus on the economic and social pillar of sustainability); (4) produced by science-policy organizations or processes; (5) summarizing knowledge in a single publication product (we did not review products from organizations publishing many different specialized reports, such as those produced by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) and (6) most recently published in the case of recurring assessments (e.g., we only reviewed the SOFIA assessment published in 2022, although yearly assessments were published between 2018 and 2022). This screening process resulted in the retention of 12 reports:

- Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6). All three working groups were reviewed jointly.
- Special Report on the Ocean and Cryosphere in a Changing Climate[2]
- Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services[73]
- Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change[68]
- The Second World Ocean Assessment[74]
- Global Resources Outlook[75]
- Governing Coastal Resources[76]
- The State of World Fisheries and Aquaculture. Towards Blue Transformation[77]
- Global Environmental Outlook 6: Healthy Planet, Healthy People[78]
- State of the Global Climate 2022[79]
- Global Biodiversity Outlook 5[80]
- State of the Ocean Report, pilot edition[81].

Although the scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change is not strictly speaking a GEA, we used this terminology to designate all reports reviewed in this study for ease of language and because they all have a global scope, focus on environmental knowledge, and were produced to inform the science-policy interface.

Ocean-related content of assessments

The proportion of GEA content dedicated to ocean knowledge was calculated by dividing the number of pages dedicated to coastal or marine topics by the total number of pages dedicated to marine, coastal, terrestrial or freshwater topics. Pages dedicated to cross-cutting themes such as drivers of changes were excluded from this calculation as they relate to the Earth-system as a whole. In the case of GEA that adopted an integrated approach, with terrestrial and marine topics interwoven within each section, we used the proportion of marine topics represented within tables, figures, and lists of each section. The sections, tables, figures used to determine the proportion of ocean-related content for each GEA is detailed in supporting files available on the Zenodo repository associated to this publication (see Data Availability statement).

Legitimacy, credibility, and salience best practices

We based our framework of GEA best practices on the three established pillars of GEA effectiveness: salience, credibility and legitimacy[15,82]. Salience refers to the relevance and timeliness of the knowledge presented with regard to stakeholders' needs and agency. Legitimacy refers to the fairness and impartiality of GEAs as judged by users and stakeholders, and credibility refers to the technical quality of information as perceived by the relevant expert communities. Legitimacy and credibility are enabling pillars to achieve relevancy and depend on characteristics of the assessment production process such as inclusivity, transdisciplinarity, FAIR principles, and transparency.

To evaluate GEAs against each of these pillars, we developed a list of best practices characterizing the process, methods and outputs of GEAs. We identified best practices based on five key scientific publications and institutional reports formulating recommendations for GEAs between 2007 and 2021[20,24–27]. These key publications were identified from the combined expertise of the authors of this study and of members of the EU DG MARE. From these five publications, we identified a total of 92 explicitly listed recommendations for GEAs. These recommendations were based on diverse types of evidence, including expert opinion, systematic reviews, theoretical analyses, and operational research. We then grouped these recommendations into best practice categories. For example, "clear goals and definitions" and "clear strategic framing" were grouped into a "defined framework" category. Multiple categorizations of best practices were tested until authors reached consensus on the non-redundancy and the exhaustivity of best practice categories. The final categorization resulted in 26 best practice categories. While alternative categorization could have been elaborated to group best practices, the one we propose holds the quality of being non-redundant, near-exhaustive, and of consolidating best practices into a reasonable number of categories without being over-simplistic. Recommendations identified from key publications and how each one was associated to a best practice category is described in Supplementary Table S1.

Scoring implementation levels of best practices

We developed a three-level scoring system to quantify the level of implementation of best practices in GEAs: no implementation (score 0), partial

implementation (score 1), or complete implementation (score 2). For example, for the "peer review" best practice, a score of 0 was attributed if no peer review of the GEA was conducted, a score of 1 was attributed if a peer review was conducted, but not by an external body, and a score of 2 was attributed if an external, independent body conducted the peer review. We then summed scores across best practices related to a given pillar of effectiveness to obtain an overall score for the level of implementation of legitimacy, credibility, and salience best practices in GEAs. Total implementation (%) were obtained by dividing overall scores by the maximal score possible if all best practices were fully implemented. For best practices that relate to multiple pillars of effectiveness (Fig. 1), we attributed the pillar that most directly related to that best practice according to the literature. For the few best practices that were particularly difficult to relate to a single pillar (e.g., transdisciplinarity), we tested the effect of pillar reallocation and did not find any major changes in the findings of this study (i.e., which pillars were weakest and strongest).

Criteria used to evaluate the level of implementation of all best practices are detailed in Supplementary Table 2. J.J. and T.B.R. gathered the information used to score the level of implementation of best practices from multiple sources, including within published GEAs, on the website of GEAs, in publication describing / commenting GEAs, in institutional reports, and through interviews with actors directly engaged with the GEA process in question. The source of information used to score the implementation level of best practices in each GEA is detailed in files available on the Zenodo repository associated to this publication (see Data Availability statement).

Comprehensiveness of GEAs on ocean knowledge

We evaluated the comprehensiveness of GEAs on ocean knowledge based on the components of the Driver-Pressure-State-Impact-Responses (DPSIR) framework. We only reviewed the coverage of knowledge related to the environmental pillar of sustainability since the assessments we evaluated were primarily environmental assessments. Drivers evaluated were based on the three main drivers detailed in GEO 6[78]: population, economic development, and technology. Ecosystem services considered were based on the Ocean Health Index[37]: food provision, natural products, carbon storage, coastal protection, tourism and recreation, coastal livelihoods, sense of place/cultural value, clean waters and biodiversity. Scales of biological diversity considered were based on Essential Biodiversity Variables: genetic composition, species populations (abundance and distributions), species traits (phenology), community composition (e.g., taxonomic diversity), ecosystem structure (e.g., complexity, extent), and ecosystem function (e.g., nutrient retention, energy cycling). This framework was adopted as it does not rely on a specific list of indicators, which varies between different typologies (e.g., Essential Ocean Variables, Essential Climate Variables) but rather promotes the evaluation of different scales of biodiversity, with each playing an essential role towards ecosystem health. Marine ecosystems considered were based from those listed in Halpern et al.[83] and in the WOA II[74]: intertidal zone; biogenic, sandy and rocky reefs; tropical coral reefs; estuaries and deltas; seagrass meadows; kelp forests; mangroves; salt marshes; continental slopes and canyons; high-latitude ice; seamounts and pinnacles; abyssal plains; epipelagic; mesopelagic; ridges, plateaus and trenches; hydrothermal vents and cold seeps. Human pressures considered were adapted from Halpern et al.[38]: climate change pressures (warming, acidification, deoxygenation, sea level rise), fisheries and harvests (artisanal, commercial), aquaculture, pollution (organic, nutrient, solid waste, noise), erosion and sedimentation, mining and oil exploitation. Responses considered were adapted from the framework developed in the Chapter 22 of GEO 6: climate change mitigation, climate change adaptation, mitigation of pollution, sustainable fisheries management, protection of marine ecosystems, mining regulations.

For each of these sub topics, we ranked the comprehensiveness of GEAs from 0 to 2:

0 – if the topic was not mentioned or restricted to a brief mention;

1 – if the topic benefited from a synthesis but without spatial and/or temporal trends;

2 – if the topic benefited from a synthesis including spatial and temporal trends.

Interviews of stakeholders

We conducted 21 interviews with stakeholders that have direct experience with GEA processes, either through active involvement (co-chair, lead authors) in their conception or through engagement at the science-policy interface.

We selected interviewees with the goal of (1) capturing the perspective of experts directly involved with the GEA processes reviewed in this study, (2) capturing the perspectives of ocean science-policy experts from the scientific arena, policymaking arena, and the civil society (3) achieving a balanced representation of genders, and (4) representing experts from different continents. Given these criteria, interviewees were selected based on authors' knowledge of leading actors in GEA processes, which was complemented by identification of contact through web searches. Additional interviewees were recommended by the Maritime Affairs and Fisheries European Commission, who helped co-design a preliminary framework of this study (see *General Framework*). We contacted 25 potential interviewees and 21 accepted to participate in this study. Two of the interviewees were subsequently invited to become co-authors of this study (FG and HOP) because of their manifested interest and their life-long involvement in GEA processes which we believe would enhance the quality and relevance of the study. FG and HOP did not participate in data collection nor data analysis to avoid biases and their contribution focused on the contextualization of findings (see Authors Contributions Statement).

Interviewees were 52% female and came from nine different countries across Europe, North America, and Africa. Ten interviewees were scientists working at the science-policy interface, 7 worked as policymakers, 2 worked in the civil society, 1 was a politician and 1 was a strategic consultant for policymakers. Apart from scientific and civil society institutions, interviewees were active members of the European Commission ($n = 6$), the IPCC ($n = 3$), the IRP ($n = 1$), the UNEP ($n = 1$), GESAMP ($n = 1$), the High Level Panel ($n = 1$), the IPBES ($n = 1$), and the WOA ($n = 1$). The list of interviewees, the GEA processes they have been involved in and their institution of attachment, as well as their genders and the country they represent can be found in Supplementary Table 3.

Semi-structured interviews were conducted remotely between January and March 2023 by T.B-R. and lasted for ~50 min on average. Interviews were structured around four themes: (1) strength and weakness of GEAs towards ocean sustainability; (2) strength and weakness of GEAs at the science-policy interface; (3) measurement of GEA's effectiveness; (4) recommendations on the development and positioning of a potential IPOS in the GEA seascape. Interviews were also used to complement our GEA review with information we could not find on processes (e.g., tools used to engage stakeholders, breadth of policymaker consultation to define the scope of GEAs…). The exact questions structuring interviews can be found in Supplementary Table 4. Interviews were recorded with the consent of interviewees and transcribed using Happy Scribe software. All interviews complied with the General Data Protection Regulation (GDPR) of the European Union. An information sheet detailing the background, objectives, and content of the interviews, as well as what the information collected from the interviews would be used for, were shared and signed by interviewees ahead of scheduling an interview time. The template information sheet is available on the Zenodo repository associated with this publication. All interviewees consented to be recorded and to have interviews contribute towards the findings of this study. Interviewees all accepted for their names to appear in this study but statements were anonymized to respect the wish of some interviewees. As such we do not specify which interviewee expressed which opinions.

J.J. and T.B-R identified and coded unique themes in the recommendations and weaknesses cited by interviewees. *We considered each theme as 'mentioned' or 'not mentioned' by a given interviewee and gave the same weight to themes mentioned once and those mentioned repeatedly."* We ensured consistency in the themes coded by the two authors by conducting a

joint review and annotation of the first ten interviews. J.J. then coded the remaining 11 interviews. For each theme identified, supporting quotations from the associated interview were extracted and compiled in an Excel sheet to allow for subsequent coding verifications. Once the remaining 11 interviews were annotated and assigned to themes, theme attributions were screened by T.B-R. Once consensus between the two coders on theme categories and theme attributions was achieved, we calculated the number of interviewees referring to a given theme to obtain the total number of mentions per theme. Lastly, J.J. and T.B-R linked themes to legitimacy, credibility, salience, comprehensiveness, or inter-assessment features with consultation of L.G., F.G., and J.C.

Data availability

Scores attributed to rank levels of implementation of best practices for each assessment, as well as to evaluate the comprehensiveness of assessments are publicly available in the online Zenodo repository, under the DOI: 10.5281/zenodo.11490999. All global environmental assessments reviewed in this study are available in open access on the website of their institution. To maintain the anonymity of interviewees, full transcriptions of interviews are not publicly available. However, quotations from interviews used to code themes can be shared upon request.

Code availability

No code or mathematical algorithm was used to produce results of this study.

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Author contributions

T.B.R. and J.J. developed the framework of the study. T.B.R. and J.J. conducted the review of assessments. J.J. analyzed the data and produced the figures. J.J. and T.B.R. wrote the manuscript text, with contributions from H.O.P., F.G., J.C., and L.G. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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