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40 years of global environmental assessments: A retrospective analysis

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ABSTRACT

This paper provides a retrospective analysis of global environmental assessment (GEA) processes and their changing character, focus and political context over the past 40 years. We examine how and why elements of organizational design, objectives, and the evolving political landscape have interacted and changed, with a view of informing the design and conduct of future processes. We find that the historical genesis of GEAs is closely connected to the emergence of environmental multilateralism. However, the prevailing conditions and assumptions which originally gave rise to the GEA concept have changed significantly over time, giving rise to an increasing demand for a focus on response options and policies. We also find that the epistemic and process complexity of GEAs has increased substantially, without a corresponding expansion in the magnitude and composition of GEA management teams. We suggest that developing analytical capacities for policy assessment as well as ensuring sufficient resources and tools to manage increasingly complex GEAs is essential to ensure their future relevance and success. This article is part of a special issue on solution-oriented GEAs.

1. Introduction

Future scholars studying global environmental governance are likely to point to the year 2015 as an important milestone in the evolution of multilateralism and international cooperation. On 13 December 2015, 196 governments—despite the exigencies of war and economic and social upheaval—agreed the world's first universal and legally binding climate treaty, the Paris Agreement. The same year also witnessed the adoption of the *2030 Agenda for Sustainable Development*, the global Sustainable Development Goals (SDGs), and the Sendai Framework for Disaster Risk Reduction. Of course, the full, effective and sustained implementation (and enforcement) of these global compacts is far from guaranteed (Tollefson and Weiss, 2015; Aitsi-Selmi et al., 2016; Deacon, 2016; Rogelj et al., 2016; Schleussner et al., 2016). Nonetheless, these multilateral agreements represent a culmination of some forty years of intergovernmental negotiations and remarkable scientific progress (Robbins, 2016; Rogelj and Knutti, 2016; Savaresi, 2016). They also build on a landscape of global environmental assessments (GEAs) that have served to inform, provoke and even shape complex international deliberations (Clark et al., 2006; Jabbour et al., 2012; Kowarsch et al., 2017a,b).

To date over 140 such GEAs have been initiated since their inception 40 years ago.[1] We define GEAs as largescale, highly deliberative processes where experts are convened to distill, synthesize, interpret and organize existing scientific knowledge (on environmental issues) to inform decision-making. Well-designed GEA processes are widely viewed as powerful, legitimate tools with the potential to catalyze cooperation and arrive at consensual evidence-based knowledge (Clark et al., 2006; Rothman et al., 2009; Watson, 2013; Kowarsch et al., 2016). Climate change, stratospheric ozone depletion, and biodiversity loss are among the most iconic examples. For each of these global challenges, a succession of GEAs has provided the scientific foundations and evidentiary basis for multilateral intervention (Watson, 2013). Today, GEAs have become an established feature of the international policy landscape and the global architecture for sustainability governance.

Over a four-decade span, the production of GEAs has given rise to a number of conceptual, normative and institutional obstacles. How to reconcile the vast, sometimes diverging perspectives (and/or vested interests) that different actors bring to bear has been a universal challenge (see Kowarsch et al., 2017b). Hrabanski and Pesche (2015) suggest that the organizational structure of a given GEA is closely linked to the distribution of power and the challenges and balancing acts inherent in the assessment process itself. At the broadest level, the

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[1] The first GEA was the 1977 OECD-led Assessment of Long-Range Transport of Air Pollutants (LRTAP); see Supplementary materials *(Table S1)* for a compressive inventory of GEAs completed to date.

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GEA enterprise has shared a complex, if at times uneasy, coexistence with international negotiations, where scientific debates and political ones, not surprisingly, often overlap and clash.

Amidst the growing presence and prominence of GEAs in high-stakes international affairs, discussions around their future function and utility have emerged. Key actors—within and beyond the assessment communities— question whether GEAs can deliver fit-for-purpose information that can inform decisions on the deployment of effective actions at national and subnational levels. Related concerns over the compatibility (or incompatibility) between existing assessment structures and their capacity to analyze benefits, costs and risks of specific policy options and management alternatives have also surfaced (Creutzig et al., 2012; Rowe et al., 2014; Carraro et al., 2015; von Stechow et al., 2016). These questions have elicited critical thinking on the future role of GEAs. In recent years, scientists and governments alike have engaged in reflective dialogue on potential restructurings and key reform opportunities (e.g., Hulme et al., 2010; Shapiro et al., 2010; IPCC, 2014; Carraro et al., 2015; Victor, 2015; Chan et al., 2016).

Given the changing international environmental governance (IEG) context and the growing complexity in the models of science-policy-society interactions (Buizer et al., 2011; Koetz et al., 2012; Kauffman and Arico, 2014), the GEA enterprise now finds itself at crossroads. Four decades offers a good vantage point to reflect on the broader assessment landscape and to draw from the collective and individual experiences to date. This paper sets out to provide a retrospective analysis of the GEA enterprise and the evolution of assessment approaches with a view of informing future processes.

Most of the reflective scholarship on GEAs and the efficacy of their impacts have focused on understanding the different procedures and means of conduct through which GEA-generated information enters and influences, or fails to influence, decision-making spheres (Rothman et al., 2009; Rowe et al., 2014; Riousset et al., 2017). In other words, 'why', 'how' and 'when' have assessments led to the adoption of political and economic choices, and/or changes in societal behavior that would not otherwise have occurred. These questions remain crucial. However, we believe that they represent only one side of a feedback loop. In this paper, we argue that the relationship between assessment approaches and effectiveness cannot be examined separate from the prevailing political and institutional circumstances in which GEA processes are embedded, and shaped by. A key point of departure for this research, thus, rests on the assertion that shifting international policy contexts in and of themselves, exert influence on how GEA processes evolve.

Building on the seminal body of GEA research that emerged in the early 2000s—pioneered by the *Social Learning Group* and the *GEA Harvard Project*—this work examines how and why elements of organizational design and objectives of GEAs and their evolving political backdrop depend on one another. The discussion presented in this paper draws heavily from a broader interdisciplinary body of work developed through a collaborative research project: *The Future of Global Environmental Assessment Making* (FOGEAM).[2] With reference to that work, we provide evidence to support two key assertions. First, GEA processes have been increasingly hampered by a discernible rise in epistemic and process complexity. Second, the GEA enterprise is undergoing a fundamental reorientation from a focus on problems toward solutions.

The remainder of the paper is organized as follows. Section 2 describes the materials and the methods employed, including a retrospective analysis of metadata from 20 GEAs spanning 1977 to 2014. Section 3 begins with a contextual narrative summarizing our extensive systematic literature and document review on the historical origins of global environmental assessments. Tracing key developments in the lead up to first-generation assessments (those occurring before 1995), we argue that the genesis of GEAs is closely connected to the birth of environmental multilateralism. We then present and discuss results from various analyses which demonstrate that the prevailing conditions and assumptions which originally gave rise to the GEA concept have changed. Specifically, there is a significant increase in the epistemic and process complexity of GEAs; and a shift in demand for greater emphasis on, and engagement with, the solution-space. Section 4 concludes with reflections and recommendations on how to further develop GEAs to meet future decision-making needs.

2. Methods and materials

Our analysis is based on multiple lines of evidence including interviews, focus group workshops, extensive literature and document review/meta-analysis, and direct GEA experience.[3] Given the socially constructed nature of assessment processes, direct experience serves as both an important mode of learning (challenging preconceptions and deepening understanding) while facilitating direct and unmediated access to process dynamics that are otherwise impossible to document. At the same time, care needs to be taken to control for subjective bias. Our strategy to do so was to collect the empirical data as described below; regularly discuss findings and interpretations within the FOGEAM research team and colleagues at our respective institutions, and other researchers and practitioners at scientific conferences and workshops (see below); and by comprehensively reviewing the GEA literature.

The analysis presented in this paper draws on the results of 99 semi-structured interviews conducted between August 2013 and April 2015. The interviews were carried out with a broad spectrum of GEA stakeholders including authors, advisory experts, reviewers, governmental representatives, and practitioners. Interview candidates were largely drawn from a pool of individuals involved in the production of either the UNEP-led fifth Global Environment Outlook (GEO-5) assessment (n = 73), or the IPCC Fifth Assessment Report, Working Group III: Mitigation of Climate Change (n = 16). The interviews lasted between 20 and 120 min and averaged ~60 min. Where possible, interviews were digitally recorded, with the consent of each interviewee, and transcribed. The interviews were piloted and guided by an interview topic guide organized around eight clustered areas of investigation (see *Supp. Mat. 1.2.2*). The interview transcripts were coded in Max-QDA and analyzed using the Grounded Theory and Constant Comparative techniques (Strauss and Corbin, 1998; Ritchie and Spencer, 2002).

Two focus groups of experts and assessment practitioners in the field of global environmental change convened in October 2013 and September 2015 in Berlin (Germany) provided valuable experiential data, perspectives, and interpretations including feedback on our early research findings; and helped further shape the research design. Focus group discussions are commonly employed for the elicitation of specific refining information and for the generation of experiential data and insights which are more readily gleaned through direct interaction between participants (Morgan, 1996; Krueger and Casey, 2014). The first group consisted of 13 experts from the *Global Environment Outlook* (GEO) community, engaged in a two-day workshop comprising a series of semi-guided discussions on procedural and methodological issues, impact channels, institutional and political contexts, and GEA design options. The participants shared insights on the inner workings of assessment processes including the deeply embedded (and often dismissed) norms and culture, self-perceptions and social dynamics that shape the assessment-making experience. The second focus group brought together 18 distinguished scholars and practitioners, including senior representatives from the science-policy community, to reflect on and deliberate over the challenges and future opportunities of con-

[2] see Editor's Introduction to this Special Issue.

[3] J. Jabbour has been closely involved the coordination of the GEO process and C. Flachsland with IPCC AR5 WGIII.

temporary assessments, and particularly the shift towards solution-orientated processes. These discussions confirmed the direction of our initial findings, and helped to further refine and extend our analysis (see *Supp. Mat. 1.2.3* for further details).

2.1. GEA metadata catalogue, 1977–2014

As described in the introduction to this special issue of *Environmental Science and Policy*, an extensive dataset (or catalogue), bringing together comparable metadata for 20 assessments was developed as a core component of the FOGEAM collaborative research initiative and the analysis presented here (see *Supp. Mat. 1.2.1*). The purpose of the catalogue was to facilitate comparative analysis of key attributes and epistemic properties across a range of largescale GEA processes spanning the period of 1977 to 2014. In this paper, we present results and discuss the analyses of key data derived from the catalogue that highlight the changing character of GEAs and the associated rise in process and epistemic complexity. In particular, this paper presents comparative analyses of the following attributes: respective lengths and scope of GEA reports, references and information sources, composition and distribution of participants, review comments, authorizing mandates, objectives and key messages.

Three selection criteria were employed to evaluate the inclusion of a given assessment: (1) aiming to achieve a representative sample of recurring and non-recurring (or irregular) GEAs; (2) sufficient access to information regarding relevant preparatory and background documentation; and (3) largescale assessments that are 'global' in their scope in terms of thematic and geographic coverage, and participation. We also strove to capture an indicative sample consistent with the relative temporal distribution (frequency) of GEAs published across the 40-year inclusion period. Extensive discussions with the FOGEAM research team and focus-group feedback (as described above) helped inform the criteria and the final selection of GEAs. The ability to satisfy the specific inclusion/exclusion criteria (e.g., access to information) had a major impact on the available sample size.

A broad range of materials and document types were analyzed as part of the data-gathering exercise for developing the GEA metadata catalogue. They include background documents, assessment scoping papers, meeting reports, independent evaluations, authorizing mandates, participants' lists, and crucially, a range of United Nations (UN) documentation including official proceedings of the UN General Assembly, subsidiary organs of the UN or specific UN conferences, UN Resolutions and Decisions of governing bodies and/or subsidiary organs, verbatim or summary records of the meetings, annexes and supplements. Information from national government publications, newspaper articles, peer-reviewed paper, and of course, the assessment publications themselves were also integrated into the GEA catalogue. The development of the catalogue was initiated in March 2013 and completed in July 2016. The processes involved collecting, collating, and integrating data—across numerous heterogeneous sources—coding information, and, where necessary, digitizing selected texts from earlier GEAs (e.g. key messages, assessment objectives etc.). The selection of attributes and the information categories included in the catalogue was informed by the academic literature, specialized reports and independent reviews on assessment practices (e.g., InterAcademy Council's Review of the IPCC), the authors' own personal experiences with GEAs, anecdotal and informal evidence, and a series of exploratory focus-group discussions within the FOGEAM research team, assessment practitioners involved in the October 2013 two-day expert workshop as described above.

To the best of our knowledge this is the first attempt to generate such a catalogue of comparable GEA metadata. Not surprisingly, we encountered several challenges in assembling the database, related to the diffusion (and volume) of relevant information and in some cases its limited availability or accessibility. Similarly, issues of confidentiality and restricted disclosure—including intergovernmental deliberations and proceedings—also presented difficulties. In some instances and particularly for the assessments that predate the internet, relevant information (e.g. participant lists, budgets etc.) are poorly documented, if at all. Finally, harmonizing heterogeneous datasets across different assessment processes was also a challenge. These obstacles underscore the inherent difficulties of studying GEA processes and cultivating the reflexivity and deliberative learning that assessment structures require to evolve (Rowe et al., 2014; Shapiro et al., 2010).

3. Results and discussion

The results of our study show that the character and orientation of global environmental assessments (GEAs) has shifted considerably since their inception, and particularly in recent years. We commence our analysis with a discussion of the historical origins and key developments that gave rise to GEAs. We then discuss the nature, importance and implications of these shifts in relation to an evolving international environmental scene and changing political context. Finally, we present and discuss results from various analyses which illustrate a discernible rise in epistemic and process complexity in contemporary assessments; and an increasing emphasis on, and engagement with solutions.

3.1. Tracing the origins and early development of GEAs

In 1972, the United Nations Environment Programme (UNEP) was established as subsidiary organ of the UN General Assembly and given the mandate to facilitate the monitoring, reporting and ongoing assessment of the state of the global environment (Ivanova, 2007). The rise in awareness over largescale environmental phenomena (e.g. ozone depletion, persistent organic pollutants) and the imperative to comprehend the potential consequences and threats to human well-being, alongside the creation of UNEP, resulted in a significant expansion of environmental literacy and multilateralism (Young, 1997; Desai, 2010). Over the 1974-84 decade, the proliferation of global environmental treaties, regimes, and processes catalyzed widespread recognition for international scientific cooperation (Haas, 1992; Desai, 2003). The emerging international environmental governance community sought to evolve a systematic process that could at once harness an international scientific consensus and transcend divergent national allegiances (Jabbour et al., 2012). Scientific panels, expert advisory bodies and similar independent structures began to coalesce around most multilateral environmental processes (Watson, 2005). Putting in place such structures to evaluate and deliver informed collective judgments about the impacts of pervasive environmental problems and the consequences of remedial action (or inaction) became a precondition for negotiating multilateral responses (Morrisette, 1989; Agrawala, 1999; Selin and Eckley, 2003; Mitchell, 2003; Grainger, 2009). The combined efforts to generate an accepted body of scientific knowledge on complex environmental problems to support the legitimatization and edifice of international regimes marked the birth of international scientific knowledge assessments.

The Montreal Protocol[4] was the first instance to institutionalize the concept of scientific assessments in 1987. It adopted a mechanism establishing an independent international group of experts to periodically assess relevant scientific developments and guide policy negotiators in subsequent revisions and adjustments of the treaty (Benedick, 2005). By the late-1980s, coordinated global scientific assessments involving extensive collaborations between large numbers of scientists from various nationalities became a driving force behind international policymaking (Young, 1989). These highly structured social processes—beyond the reports themselves—began to serve as knowledge

[4] The Montreal Protocol on Substances That Deplete the Ozone Layer is a landmark international agreement, originally signed in 1987, designed to protect the stratospheric ozone layer.

intermediaries between science and policy (Farrell and Jäger, 2006). First-generation GEAs helped forge intergovernmental cooperation and an objectively defensible means to arrive at consensus on environmental problems and policy positions that seemed irreconcilable (Mitchell, 2006; Farrell et al., 2001). Over the next decade, various largescale GEAs (notably the IPCC reports) evolved and codified a deliberative consensus-based approach to knowledge production (Goodwin, 2009; Curry and Webster, 2013). By the early-1990s, there was widespread recognition in the international community that the most pervasive environmental issues extended beyond strict geopolitical confines, and could no longer be analyzed or resolved in isolation (Haas, 1990). This thinking gave way to new levels of international dialogue and cooperation, including new roles for international institutions in the production of scientific knowledge on a range of environmental sustainability issues (Raustiala, 1997; Watson, 2005).

The rise in awareness and political attention on the issue of sustainable development catalyzed the 1992 Earth Summit in Rio de Janeiro. The Earth Summit marked the beginning of a ten-year surge in multilateral treaties and new governance structures (Desai, 2003; Elsig et al., 2011). The Earth Summit also brought to light a number of critical implementation challenges for IEG, including uncertainties in scientific knowledge and the need to remove North-South information asymmetries. These challenges reinforced the importance of monitoring, technology transfer and scientific assessments—cornerstones of the Summit's voluntary action plan *Agenda 21*. Beyond a rapid succession of multilateral environmental agreements (MEAs) in the post-Rio period, were increasing appeals from the international science-policy community to redress ongoing deficits of reliable scientific information to support these agreements (Haas et al., 1992; Parson, 1993; Boehmer-Christiansen, 1994; Levy et al., 1995).

3.2. Shifting political and institutional orientations

The environment now represents the second most common area of international rulemaking, only after international trade (Muñoz et al., 2009). Moreover, from being a niche topic, environmental concerns have moved to become an equal and indispensable dimension of sustainable development. Zaccai (2012) describes a series of changes in the constellation of actors, discourses, modes of action, and the nature of problems themselves, that characterize the evolution of the "environmental scene" and to a large extent, shaped the discursive struggle over sustainable development. Building on his analysis, we enumerate an expanded selection of features relevant to the evolving international environmental scene contrasting the pre-sustainable development era with the current situation. These prevailing shifts offer a useful background for examining how GEAs have been influenced by, and responded, to the context in which these have transformations occurred (Table 1).

The most demanding issues on today's IEG agenda are characterized by highly dynamic patterns of causality and complex interactions between environmental drivers and pressures (Jabbour and Hunsberger, 2014). Regarding key actors, roles and dominant modalities for action, the emphasis has shifted away from a pure focus on the state, towards wider stakeholder engagement, shared responsibility and collaborative private-public actions (Lozano, 2012). A similar shift has occurred at the science-policy-society interface with a move towards greater inclusivity, and efforts to transcend traditional reductionist approaches (Vogel et al., 2007; Wesselink et al., 2013). This thinking has influenced the direction of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and other recent GEAs efforts (e.g. GEO-6) to institutionalize synergies across knowledge systems by introducing a series of functioning mechanisms and procedures (Tengö et al., 2014; Perrings et al., 2011).

Many of the transformations reflected in Table 1 manifested in the deliberations on the 2030 Agenda and the SGD framework, in contrast to the expired Millennium Development Goals (MDGs). For example, the SDGs reflect a more balanced and integrated treatment of the global environment and the imperative to address both social and environmental inequalities (Martinez and Mueller, 2015). Regarding environmental sustainability, the SDGs place greater importance on the need to promote equitable access to increasingly scarce resources and energy, and to minimize the vulnerability of the poor. In this regard, debates were centered on how existing international agreements can address equitable, inclusive low-carbon growth. A similar discourse-shift is reflected in the narratives of many recent GEAs that call attention to the notion that the science of global environmental change can no longer be divorced from fundamental issues of fairness, equity and social justice (e.g. Green Economy, 2011; GEO-5, 2012; IPCC, 2014). Another important difference between the MDGs and the SDGs–bearing witness to the evolution of geopolitics and the environmental scene—is that emerging economies and lower-income countries, created the impetus for the 2030 Agenda and were deeply involved its formulation. This resulted in an SDG framework that better reflects the principles of universality and accountability, while respecting the need for adaptability. This is a drastic shift from the pre-sustainable development era, and even the 1990s, when northern economies dominated most multilateral fora including IEG, while low and middle income states (i.e. G-77) and the BRICs (Brazil, Russia, India and China) had much less political, economic and scientific clout (Papa and Gleason, 2012). Investments in technology and scientific research in the global south are accelerating at a rapid pace. It comes as little surprise, therefore, that developing-country[5] participation rates in GEAs have experienced a 10-fold increase ($>$ 250% proportionally) from 1977 to 2014. The enhanced involvement and greater influence that middle and low-income countries have acquired, as a result, could mean more legitimacy and impact for the SDGs, and similarly, the future uptake of GEA findings − particularly in countries facing lower scientific capacity and limited data flows.

While important advances in bringing international treaties and related aspects of IEG into a more coherent and stable institutional framework have taken place, the current constellation of MEAs—the international legal basis for cooperation—has become increasingly complex and disconnected from GEA processes (Rothman et al., 2009). The historical function and objectives of first-generation GEAs (occurring before 1990) were comparatively narrower in scope, and could thus uphold a stronger coupling with existing policy-relevant structures and international regimes. Selin and Eckly (2003) describe how the GEAs on persistent organic pollutants (POPs) from the mid-1980s possessed more fluid boundaries between science and policy and were directed at a "specific context of policy application, with mutual construction and evolution of scientific and policy agendas" (2003:21). Consequently, these first-generation GEAs, which they describe as expressions of 'regulatory science' played a prominent role in establishing POPs as an issue of international concern, and influencing intergovernmental deliberations on their management and mitigation. Findings generated from the chronology of GEAs titled *Scientific Assessment of Ozone Depletion*—the reoccurring assessment process mandated by the Montreal Protocol (Article 6)—have not only informed deliberations of the 'Conference of Parties' to the MEA, but have provided the scientific and evidentiary basis for seven crucial amendments to the Protocol since its inception (e.g. accelerating phase-out schedules), including the most recent Kigali Amendment on hydrofluorocarbons. In this view, early GEAs played a more explicit role in framing relevant environment issues around problems and building the necessary consensual knowledge and international cooperation—at a time when the underlying problems were uncertain and governments were selective and reticent on specific multilateral commitments.

Much has changed since the inception of GEAs forty year ago. The

[5] Including low- and lower-middle-income economies as defined by the World Bank classification lists.

Table 1
Figurative representation for the evolution of international environmental scene.
(Adapted from Zaccai, 2012).

Selected features of the environmental scene		Pre-sustainable development era (1970s and 1980)	Current situation (last ten years)
1.	Iconic policy instruments	Command and control instruments (e.g. *Montreal Protocol*)	Economic/market-based instruments (e.g. *The Paris Agreement*)
2.	Key actor(s) relied on	Predominantly Government (*heavy reliance on public sector*)	Mix of Government and Stakeholders (*growing role for non-state actors*)
3.	Dominant modalities of action/implementation	Emphasis on industrial sectors; technology-driven interventions (*e.g. agricultural intensification*)	Working with industry and consumers, through technology, innovation, finance (e.g. *renewable energy incentives*)
4.	Knowledge about the Environment	Superficial, or limited to specialists in a narrower range of fields	Extensive, mainstreamed, diffused in many realms of society
5.	Information, data and knowledge management	Limited public access, expensive, inadequate or highly propriety national data flows	Proliferation of digital, open access data platforms and networks;
6.	Main disciplines; fields of scientific engagement	Predominantly natural science researchers; observational sciences (*chemistry, biology and physics*)	Trans-disciplinary research; integrated approaches; projections and futures (*social, natural, economic and holistic)*
7.	Iconic environmental problems; most urgent	Wastes, water pollution (*easier to define/narrower point sources*)	Climate change, loss of biodiversity (*more complex and diffuse*)
8.	Main actors/regions seen to be drivers of adverse change	Industries, production patters OECD (*United States*)	Consumers, consumption patters Emerging economies (*China, Brazil*)
9.	Social equity issues and environmental equality	Superficial, or neglected concerns (*peripheral to mainstream debate*)	Key goal of many environmental policies (*core aspect of 2030 Agenda and SDGs*)

political setting for the environment, including institutional contexts and the international governance architecture that GEAs are operating in, while more robust and more empowered, is now subject to a variety of challenges including but not limited to a separation of political ambition (or will) and the means of implementation (Aitsi-Selmi et al., 2016; Deacon, 2016; Rogelj et al., 2016; Schleussner et al., 2016). As the political context has evolved, our analysis indicates that the prevailing conditions and assumptions that gave rise to the GEA concept have also shifted. In the following sections (3.3 and 3.4) we present and discuss results that demonstrate a significant increase in the epistemic and process complexity of GEAs; and an increasing demand for greater emphasis on, and engagement with, the solution-space.

3.3. Rising epistemic and process complexity

The most obvious attribute-change in GEAs over the last four decades concerns both the depth and breadth of their contents. Across all assessment processes examined, GEAs have consistently become increasingly voluminous reports. Successive iterations of IPCC reports, for example, have experienced a nearly fivefold increase in length since their inception, despite efforts to set page limits. The *Fifth* and latest IPCC assessment (across three volumes) totals over 4300 pages, 60 chapters, and 16 annexes totaling approximately 3.26 million words. To put this in perspective, it would take the average person nearly eight uninterrupted work-weeks to read the report, never mind digest or comprehend the material. The Global Environment Outlook (GEO) series and the supporting material produced alongside its underlying assessments have increased four and 7-fold respectively from 1997 to 2015.

These changes reflect the impacts of a rise in epistemic complexity. This trend is manifested, in part, by a dramatic increase in the number of relevant publications that assessments draw upon. As illustrated in Fig. 1, comparing the number of source materials used in the five iterations of the GEO and IPCC reports, reveals seven and 13-fold increases respectively, from the first reports to the most recent; with the latest IPCC report containing nearly 31,300 citations. Conversely, the first IPCC assessment included only 2284 citations. In addition to this massive upsurge in the number of source materials used, more crucially, the citation-to-content ratio (i.e. the average number of citations per page), has also increased from 2.1 to 5.6 for GEO and from 2.5 to 6.9 for the IPCC assessments. In contrast, of the first-generation GEAs examined (predating 1995), the average citation-to-content ratio was 1.7:1. These results are consistent with recent bibliometric studies that highlight the exponential growth of relevant peer-reviewed literature since inception of the IPCC, where in 2015 alone, more articles were published (> 30,000) than the entire 12-year period between the first and third assessment reports (Minx et al., 2017). The rapid advancements in environmental science and global-change research in recent years, compounded by the increasingly multiscalar and multidimensional nature of relevant information, has served to complicate what was already an inherently demanding and complex task for GEA experts.

In addition to the substantial increase in scientific publications, the magnitude and complexity of the assessment task has also been exacerbated by significantly greater demands and rising expectations. Our results indicate that GEAs have experienced a significant expansion in their substantive and operational scope in the last decade. A broadening of thematic coverage, for example, is evident if one compares earlier assessments (e.g. LRTAP, 1977 or Atmospheric Ozone, 1985) that dealt with more narrowly defined environmental problems, compared with more recent GEAs (e.g. IPCC and GEO) that encompass much more diffuse, interrelated and multi-factorial issues (Flachsland et al., 2015; OECD, 2015; Minx et al., 2017; Riousset et al., 2017).

This is manifest in the sharp rise in the number of individual objectives per assessment, and the number (and range) of specific framing questions that assessments are expected to address (Fig. 2). More crucially, of the 20 GEAs analyzed in our database, there was no evidence of deliberate prioritization or ranking of such objectives in any one of them; thus, leaving their relative importance open for interpretation. Eleven interview respondents made reference to this theme. One of the interviewees stated, for example, that the widening the scope of attention with no clear alignment to the prevailing GEA storyline "*diminishes the intensity of analyses and creates confusion and friction among* [*experts*]" while exposing the assessment processes to be diverted by peripheral issues (December 2013; L5). Another respondent described feeling overwhelmed by *"the mystification of purpose [of the GEA]"* resulting from *"mission-creep and [this] gradual shift in emphasis [in the course of production]"* (September 2014; LL2). In the absence of specific guidance or stricter measures on the development of GEA objectives, assessment processes are at risk of being overwhelmed by their own mandates and unwieldy bulk.

Another important trend contributing to the rise in process and epistemic complexity of GEAs is the sharp increase in the number of

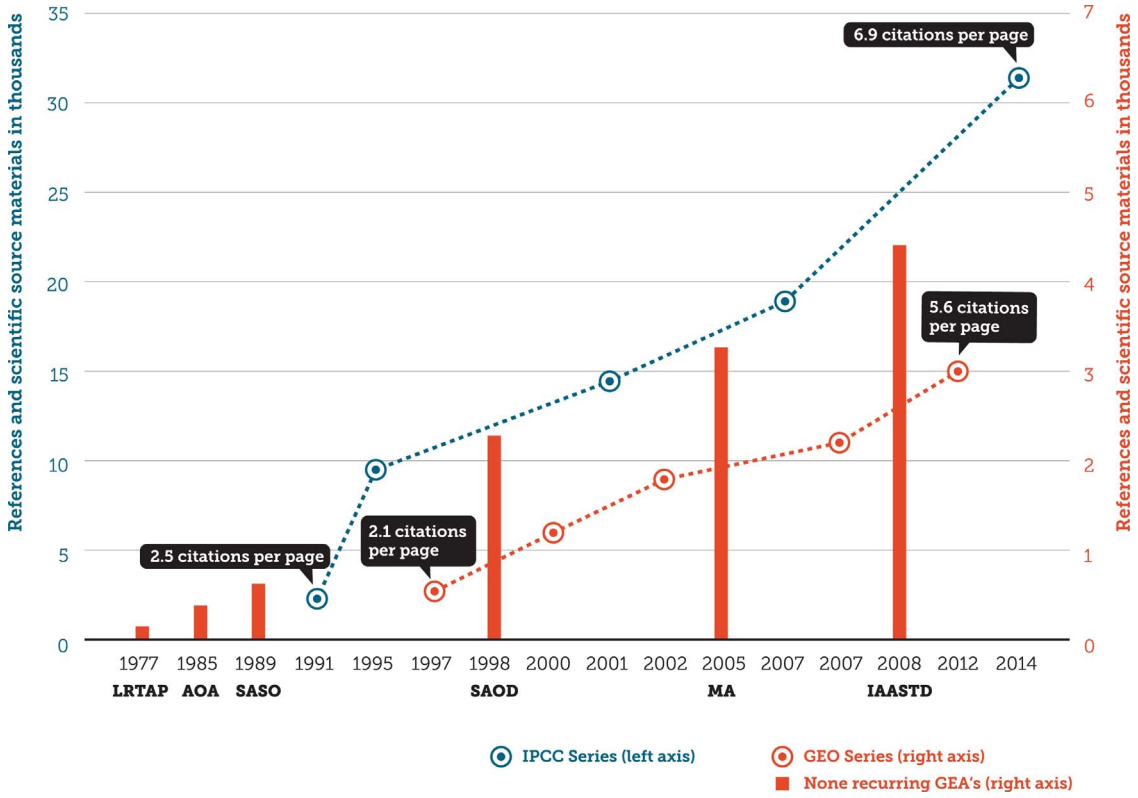

Fig. 1. Trends in the number and proportion of source materials used (i.e., average citations per page expressed as a ratio) in two recurring assessments: the GEO series (right axis), and the IPCC series (left axis) over five successive iterations; as well as six nonrecurring GEAs assessments (right axis).

participants actively engaged in producing a given assessment. We observe parallel shifts in the type and distribution of stakeholders and their respective roles. The GEO and IPCC recurring assessment processes, as well as six non-recurring GEAs examined (spanning 1977 to 2014) have experienced a significant rise in the number of authors and 'expert' contributors over their evolution. In the case of GEO, the segment of participants effectively responsible for content-development rose from 186 individuals in the first GEO (1997), to 863 in GEO-5 (2012) and well over 1000 experts for GEO-6 (*forthcoming*). For the IPCC, a total of 607 authors and expert contributors were involved in delivering the first assessment in 1990, compared with 2330 individuals for fifth assessment report delivered in 2013–2014. If one considers the full spectrum of stakeholders involved in the development and production of the latest GEO and IPCC assessments (i.e. expert advisors, reviewers, government representatives, production staff, editorial teams, technical support) the number of participants rises to 2018 and 4905 respectively. Considering that the first GEA in 1977 (LRTAP) comprised of fewer than 80 individuals, contemporary GEAs have become enormously more complex, resource-intensive processes to coordinate. The complexity of interconnections—interpersonal, group

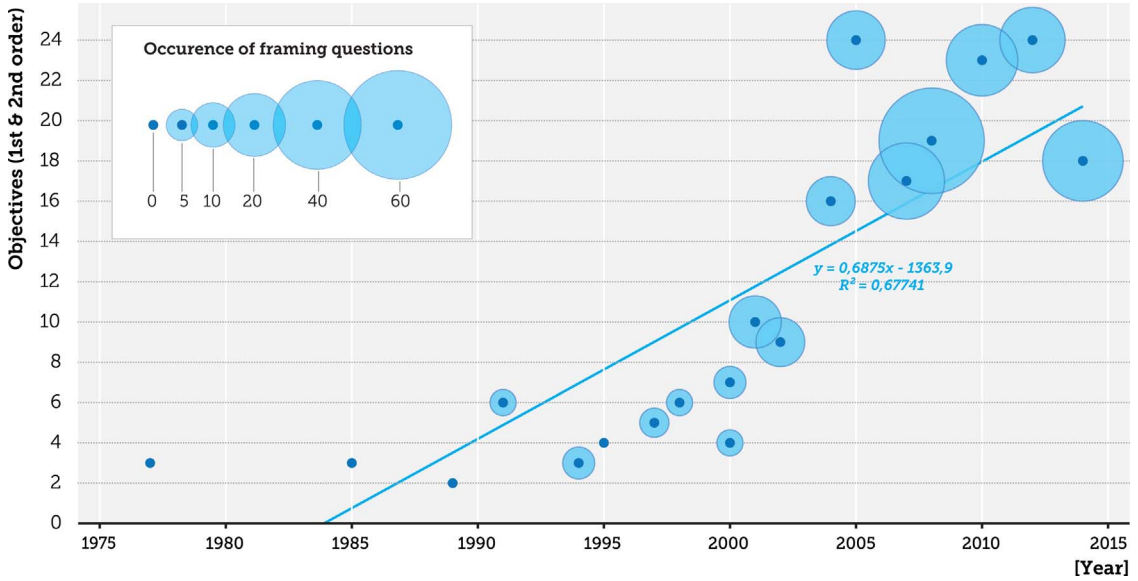

Fig. 2. Broadening in the extent and scope of assessment objectives of GEAs, 1977–2014; the relative size of data points represents the occurrence of additional framing questions. (See Supp. Mat. 1.2.4 for further details).

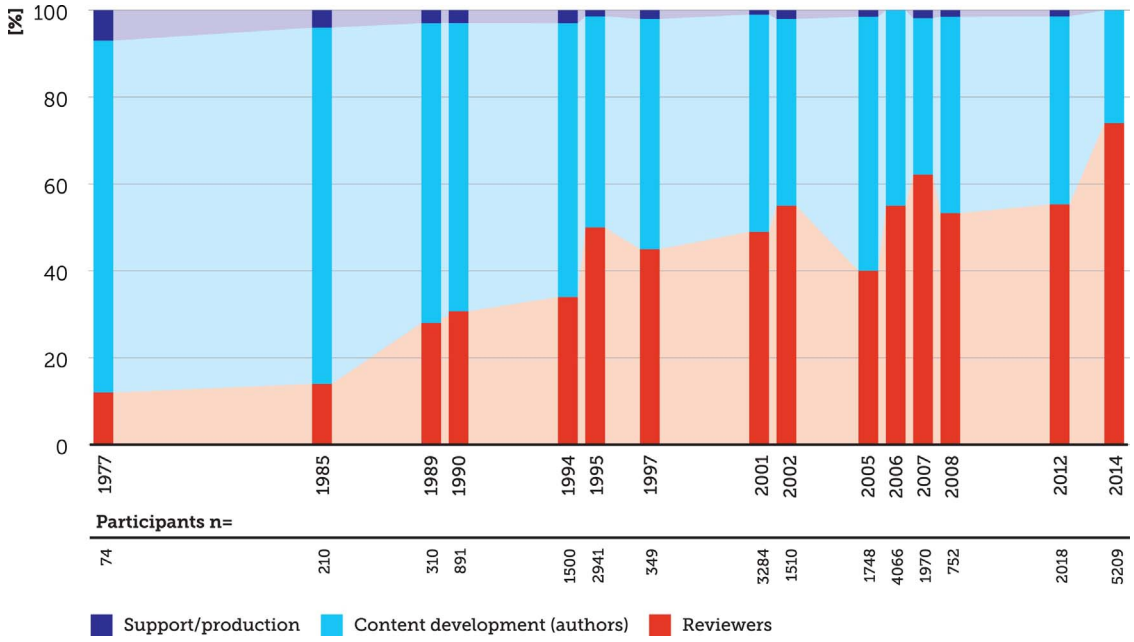

Fig. 3. Reviewers as a percentage of total GEA participants (N = 15; from 1977 to 2014).

and institutional dynamics—brought about by interfacing hundreds (sometimes thousands) of actors towards a process of 'negotiated' knowledge production remains poorly understood (Wesselink et al., 2013). This is complicated by the heightened sensitivity to the concerns of political neutrality, particularly given the shift to solution-oriented analyses (see Section 3.3), which has increased GEAs' exposure to divergent viewpoints requiring active management (Kowarsch et al., 2017a,b).

Despite the exponential rise in GEA participants and the increase in process complexity, interestingly, the administrative structures of GEAs (i.e. management/production support staff) have diminished or remained largely unchanged over time. These actors, who typically belong to the boundary organizations facilitating a given GEA, play an important coordination and knowledge-intermediary role (Jones et al., 2012; Huitema and Turnhout, 2009). For first-generation assessments, production support, on average, accounted for approximately 6% of the total pool of GEA participants. More recently, this segment has been reduced to less than 2% (e.g. GEO-5, MA, IPCC and IAASTD). This difference is not trivial, given the additional burden of responsibility these actors face in having to manage the procedural and organizational structures that can handle the vastness and diversity of inputs, data-flows, contributions and critical reviews. Rigorous multi-stage review processes, for example, which comprise more stringent protocols for ensuring transparency and scientific credibly (Shapiro et al., 2010), have become far more onerous exercises to coordinate. Assessment processes have also experienced a substantial increase in the proportion of reviewers engaged in GEAs in the last four decades (Fig. 3). For the most recent GEAs examined (those occurring in the last 10 years), reviewers constituted the largest segment of stakeholders involved (between 40 and 63%). This has led to a commensurate increase in the number of revisions requested of author teams. In the latest IPCC assessment, the total number review comments that draft manuscripts received and dealt with (across all working groups), was in the order of 143,000. Similarly, the number of review comments in the GEO process has increased 6-fold from 3893 (GEO-3; 2002) to 23,772 (GEO-5; 2012).

3.4. The shift to solutions-oriented assessments

We find that contemporary assessments put increasing emphasis on considering future outlooks, response strategies, action-oriented narratives, and to varying degrees, public policy analysis relative to analyzing the biophysical and ecological problems underlying global environmental challenges. This is reflected in both the institutional objectives and the actual content in the underlying reports. In the case of the IPCC, its new Chair has declared explicitly that 'the next cycle of assessments should be more focused on opportunities and solutions' (Tollefson, 2015).

While some of these variants and attribute-shifts have been institutionalized in the authorizing mandates and formal objectives of GEAs, others remain much harder to quantify. Our analysis of core GEA messages articulated in the summaries or stand-alone key messages pooled from eight GEAs[6] published between 1985 and 2012 reveals a ten-fold and eight-fold increase in the use of the terms *"political action"* and *"policy response(s)"* respectively. Similarly, the use of the word *"solutions"* in the GEO assessment series reports has risen consistently with nine instances in GEO-1, to 99 instances in GEO-5. Quantitative text analyses of 320 source materials[7] of four GEAs[8] from 1985, 1995, 2008, and 2012, reveals an increasing reliance on solution-focused information with 0%, 12%, 47% and 55% respectively. Similar trends are occurring in other assessment-related fields, for example, environmental risk assessment. Finkel (2011) describes evidence for an emerging reversal in the functional and conceptual practice of traditional risk assessment; where the focus has shifted away from dissecting problems, and increasingly towards evaluating management pathways and tangible solutions to mitigate risks.

Our results also indicate an increasing demand by decision-makers and scholars for solutions-oriented GEAs. A review of the authorizing mandates of contemporary GEAs (e.g. Table 2) and subsequent experimental approaches and design-innovations introduced suggest growing demand for policy analysis and more integrative response options. An analysis of the recent IPCC reform debate explicates this desired shift and the call for more explicit and meaningful assessments of possible

[6] Atmospheric Ozone, 1985; Scientific Assessment of Stratospheric Ozone, 1989; Global Biodiversity Assessment, 1995; Global Environment Outlook (GEO-1), 1997; GEO-2, 2000; GEO-3, 2002; GEO-4, 2007; IAASTD, 2008; GEO-5, 2012

[7] 'Source materials' refers to all sources of information and data used in the report including scientific peer-reviewed papers, as well as scientific research reports and materials produced by organizations and governments cited in the GEAs examined.

[8] Atmospheric Ozone, 1985; Global Biodiversity Assessment, 1995; IAASTD, 2008; GEO-5, 2012.

Table 2
Examples of authorizing mandates of recent GEAs that exhibit a focus on solution analysis.

GEA	Year	Mandated solution-oriented objective	Design innovation
TEEB-D1	2010	*"Identification of opportunities for action, such as applying new or reforming existing policy tools"*	Applying new economical valuation methodologies
GEO-5	2012	*". analysis of case studies of policy options, that incorporates environmental, economic, social and scientific data and information and their indicative costs & benefits to identify promising policy options."*	Assessing progress against internationally agreed goals and objectives
IPBES	2012	*"supports policy formulation and implementation by identifying policy-relevant tools and methodologies, such as those arising from assessments…"*	Conceptual Framework explicitly includes co-design and multiple knowledge systems

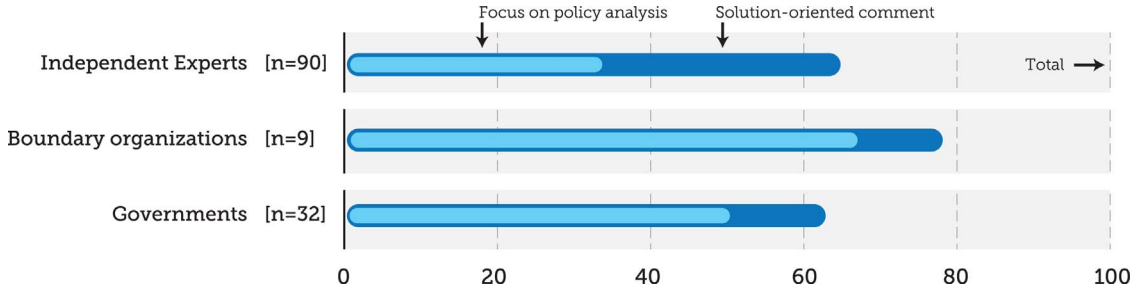

Fig. 4. Results of a 2014 survey on IPCC reforms illustrate the increased demand for solution-oriented assessments (across three GEA actor groups) with an emphasis on actionable knowledge and means of implementation, (n = 131).

solutions and action-oriented knowledge in GEAs (Fig. 4). Of the 32 government responses submitted to a 2014 IPCC survey on the future work of the Panel, 20 (62%) indicated the need for greater emphasis on response options including more explicit assessments of policies. The survey, which invited inputs on both the IPCC's future reports and the structure and modus operandi for producing the assessments, elicited nearly 100 different recommendations, representing 72% of the total respondents (across various actor groups), were aligned with a solution-orientation shift. These results are consistent with similar findings from the independent evaluation of the fourth GEO assessment (UNEP, 2009; Koetz et al., 2012), and the more recent evaluation of the fifth GEO (Rowe et al., 2014), which describe explicit changes in the demand for and supply of information that better supports 'policy options', and not only 'problem identification'.

Taken together, the emphasis of solution- and policy-orientation of GEAs in a changing political context (Sections 3.1 and 3.2) has led many experts to postulate that GEAs are and should increasingly focus on exploring solutions to global environmental problems (Edenhofer and Kowarsch, 2015; Carraro et al., 2015; Bulkeley and Kok, 2016; Kowarsch, 2016; Le Quéré and Minns, 2016; Beck and Mahony, 2017; Kowarsch et al., 2017a,b).

4. Conclusions

The objective of this study was to provide a retrospective analysis of the GEA enterprise and the coevolving context in which assessment processes are embedded. Our results demonstrate that the prevailing conditions and assumptions which originally gave rise to the GEA concept have changed significantly since the mid-1970s when GEAs were conceived.

Arguably responding to these changes in the IEG context of GEAs, there has been a shift in demand for greater emphasis on, and engagement with, the solution-space. At the same time, GEAs have experienced a perceivable increase in epistemic and process complexity. As a result, knowledge producers and boundary institutions facilitating these highly complex deliberative processes are expected to address and manage an ever-expanding and increasingly inter- and trans-disciplinary knowledge base, extraordinarily large numbers of participants who represent increasingly diverse and diffuse actor-groups, more varied spatial, time and institutional scales, and new dynamics between the scientific and policy spheres.

One possibility for responding to these challenges is to advance a new generation of tools, models and frameworks better able to assemble, streamline, manage and integrate information, including those generated through different paradigms, to better support policy-relevant analysis (e.g., Minx et al., 2017; Flachsland et al., 2015). One option that is currently being explored at UN Environment is to adapt aspects of integrated assessment processes to more networked, dynamic and inclusive knowledge generation through the use of digital-based knowledge platforms (e.g., Environment Live). Such efforts promise to enable better organization of information and streamlining of data flows, and provide GEAs with a vehicle for promoting open access, inclusivity and a more reflexive approach towards knowledge provisioning. Also, responses to the challenges stemming from increasingly complex process management requirements (Carraro et al., 2015) might include the provision of adequate GEA management resources (e.g. operating budgets, number of dedicated staff) and capacities (e.g. ensuring skills upgrading and training of GEA practitioners and support staff, including in the area of policy assessment). Finally, some have suggested deliberately scaling-back the complexity of GEAs in terms of a proliferation of their objectives, and instead focusing on shorter and more targeted products and processes (Hulme, 2010).

Ultimately, as our retrospective analysis has shown, for GEAs to be effective, assessment processes themselves must change over time, and there are no one-size fits all analogs. GEAs must therefore be reflexive and respond to context-specific demands for knowledge. This is particularly pertinent in the new global setting for sustainability governance, where many of the SDGs will be attainable only if the environmental knowledge production community together with the GEA enterprise, can effectively contribute to their realization, and is transformed by them (Nossum, 2017).

It appears that global environmental assessment processes are at a crossroads: On the one hand, they could continue down the path of predominantly focused problem analysis and remain reticent to fully engage with the solution space. In that case, their future relevance to policy is at risk of diminishing gradually over time. On the other hand, assessment processes could increasingly engage with a complex solution space, and strive to develop and cultivate a widely accepted set of methods and tools to do so in a way that informs evidence-based policymaking by rigorously synthesizing and assessing available research. Reflecting on the first 40 years of GEAs and the current international governance context, we believe that the latter option deserves more practical and theoretical consideration, including in policy research as well as in the empirical literature analyzing GEAs. Our hope is that more future research will be dedicated to this field.

Conflicts of interest

Given J.J's double role as (1) lead author of this article and (2) guest editor of the special issue, peer review of this article was handled independently of the guest editors and their research teams by the Editor-in-Chief.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2017.05.001.

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