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ANALYSIS
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Key knowledge gaps to achieve global sustainability goals

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Regional and global assessments periodically update what we know, and highlight what remains to be known, about the linkages between people and nature that both define and depend upon the state of the environment. To guide research that better informs policy and practice, we systematically synthesize knowledge gaps from recent assessments of four regions of the globe and three key themes by the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services. We assess their relevance to global sustainability goals and trace their evolution relative to those identified in the Millennium Ecosystem Assessment. We found that global sustainability goals cannot be achieved without improved knowledge on feedbacks between social and ecological systems, effectiveness of governance systems and the influence of institutions on the social distribution of ecosystem services. These top research priorities have persisted for the 14 years since the Millennium Ecosystem Assessment. Our analysis also reveals limited understanding of the role of indigenous and local knowledge in sustaining nature's benefits to people. Our findings contribute to a policy-relevant and solution-oriented agenda for global, long-term social-ecological research.

The future of humanity depends on how we respond to the current social-ecological crisis[1]. Existing paradigms in conservation and sustainability science have informed and influenced large-scale knowledge assessments and policies on the environment. Over the past 60 years, scientific perspectives on the relationship between humanity and nature have gone through four major stages, which Mace in 2014 (ref. [2]) labelled as "nature for itself" (1960s and 1970s); "nature despite people" (1980s and 1990s); "nature for people" (2000–2005); and "nature and people" (2005–present). Each of these phases has been characterized by different environmental policy and management goals, such as those for harvested species shifting from maximum sustained yield of single populations to management of entire ecosystems for resilience[3]. Given the increased demand for policy-relevant knowledge and the epistemic complexity involved in its production, further synthesis and interpretation of large-scale knowledge assessments is needed to distill key findings for policy-makers[4].

In 2005, the Millennium Ecosystem Assessment (MA)[5], with its focus on ecosystem services and human well-being, marked the end of the 'nature for people' phase. It was inspired by previous

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findings on the high value[6] and declining trends[7] of ecosystem services worldwide. The knowledge gaps that it identified were partially responsible for triggering a new push towards greater recognition of the complex, multi-layered interdependencies and feedbacks between people and ecosystems[8]. Most research needs listed by the MA were oriented toward monitoring ecosystems and their processes and services, while others focused on the nature of interactions among drivers of change—which can result in abrupt or nonlinear ecosystem shifts[9]. The MA and the science-policy initiatives that followed (for example, The Economics of Ecosystems and Biodiversity (TEEB)[10] and Mapping and Assessment of Ecosystems and their Services (MAES)[11] in Europe) stimulated rapid progress in scientific understanding of the linkages and feedbacks between people and nature while leaving many important questions unanswered[12]. Since the 2014 publication of Mace's analysis, the nature and people paradigm has changed to reflect the complexities of human societies and their consequences for ecosystems, particularly in relation to topics such as governance, equity, social heterogeneity, resource access and their relationships to environmental sustainability[12].

Each successive period of deepening understanding within environmental science has led to new knowledge, new priorities and new research questions. Identifying and focusing proactively on key research priorities is vital to ensuring that we build the necessary knowledge to respond to emerging social-ecological crises and avoid future problems[12,13]. The Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) assessments offer a unique opportunity to identify and characterize current gaps in our knowledge about the linkages between people and nature, and to profile key areas for future research. Ahead of the recent Global Assessment[14], IPBES published four regional (Africa, Americas, Asia and Pacific, Europe and Central Asia) and three thematic reports (Pollination, Land Degradation and Land Restoration, and Scenarios and Models) between 2016 and 2018. These seven reports provide an up-to-date assessment of what is currently known about biodiversity and ecosystem services with both regional resolution and thematic depth. While numerous knowledge gaps are mentioned in each report and were to a large extent reflected in the recently completed Global Assessment, they have not been systematically synthesized to guide policy-relevant knowledge production and capacity building.

A common conceptual framework that builds on and extends the 'nature and people' paradigm guided the production of all IPBES assessments. It has three distinct features[15] that differentiate it from the conceptual framework used in the MA. First, it stresses that most ecosystem services (referred to as nature's contributions to people—ES/NCP hereafter) depend on the joint contribution of nature and anthropogenic assets, a process known as 'co-production'[16]. Second, it highlights the central role of institutions, governance and other indirect drivers in ES/NCP co-production and distribution[17]. Finally, by recognizing the role of the social construction of knowledge and values, it emphasizes the necessity of integrating multiple scientific disciplines and knowledge systems into assessments of the linkages between people and nature[18].

After the MA found that more than 60% of ecosystem services around the world were being transformed or degraded[8], ecosystem services were included in the Aichi Biodiversity Targets (ABTs) set by the Convention on Biological Diversity in 2010 to avert biodiversity declines by 2020. Similarly, actions to mitigate the major drivers of biodiversity and ecosystem service loss identified by the MA were formalized in the Sustainable Development Goals (SDGs) set by the United Nations in 2015 to end poverty, protect the planet and ensure prosperity for all by 2030. To date, 163 and 193 countries have, respectively, adopted ABTs and SDGs to guide their policies on biodiversity conservation and sustainable development. Current ABTs will expire in 2020, and new targets set by the Convention on Biological Diversity will be informed by findings from IPBES assessments. Thus, assessing progress from MA to IPBES and revealing knowledge gaps for achieving ABTs and SDGs help to identify critical themes in which further research can contribute most to environmental integrity and social justice, and to which the post-2020 policy agenda should attract action.

Relatively few comparisons of large-scale knowledge assessments have previously been attempted and these have used a variety of approaches, making it difficult to compare results[19]. Here, we systematically synthesize knowledge gaps identified in the four regional and three thematic IPBES assessment reports and analyse their linkages with the IPBES conceptual framework, the ABTs and SDGs, and the research needs identified in the MA. Specifically, we address the following questions: (1) which knowledge gaps prevail across these seven IPBES assessment reports as related to the IPBES conceptual framework? (2) Which clusters of knowledge gaps are most relevant for achieving ABTs and SDGs across regions and themes? And (3), which knowledge gaps identified in the MA persist in the IPBES assessments? By structuring this analysis with the IPBES conceptual framework, systematically synthesizing knowledge gaps into thematic clusters, comparing their policy-relevance across regions and themes and assessing their persistence across assessments, we provide a new and deeper perspective on the linkages between various knowledge gaps and the need and motivation to address each of them. This structured analysis adds critical depth to the recent list of knowledge gaps from the IPBES Global Assessment, and aims to refine its policy relevance by highlighting strategic research directions that can simultaneously tackle multiple interconnected knowledge gaps and support the policy agenda beyond 2020.

Analysis and synthesis of knowledge gaps

The following three sections summarize our findings regarding the three research questions.

Individual knowledge gaps in the IPBES conceptual framework. We identified 708 individual knowledge gaps across the seven IPBES reports (138 in the African report[20], 166 in the Americas report[21], 50 in the Asia and Pacific report[22], 127 in the Europe and Central Asia report[23], 43 in the Pollination report[24], 137 in the Land Degradation and Restoration report[25] and 47 in the Scenarios and Models report[26]; Supplementary Results 1–7). As a result of the expert valuation (see Methods), more than half of these gaps (52%) were considered slightly to extremely relevant in regard to achieving ABTs and SDGs, and thus were categorized as policy relevant. All elements (that is, boxes and arrows) of the IPBES conceptual framework contained knowledge gaps, but the largest numbers related to how human actions directly transform nature and how these transformations in turn influence the co-production of ES/NCP. They are specifically connected in the IPBES conceptual framework along the chain that links direct drivers (375 individual knowledge gaps), their impacts on nature (415), nature (487), nature's contribution to ES/NCP co-production (323) and ES/NCP themselves (393) (Fig. 1 and Supplementary Table 1).

Chances of achieving the ABTs and SDGs will be weakened by gaps in our knowledge of how ES/NCP contribute to a good quality of life, and how changes in quality of life feed back to cause changes in natural systems through institutions, governance and other indirect drivers. The elements of the framework for which more than 75% of individual knowledge gaps are considered policy relevant are connected along the chain that links ES/NCP (78%), its contributions to good quality of life (81%), good quality of life itself (82%), its feedback on institutions, governance and other indirect drivers (79%), institutions, governance and other indirect drivers themselves (92%) and their influence on direct drivers (76%; Fig. 1 and Supplementary Table 1).

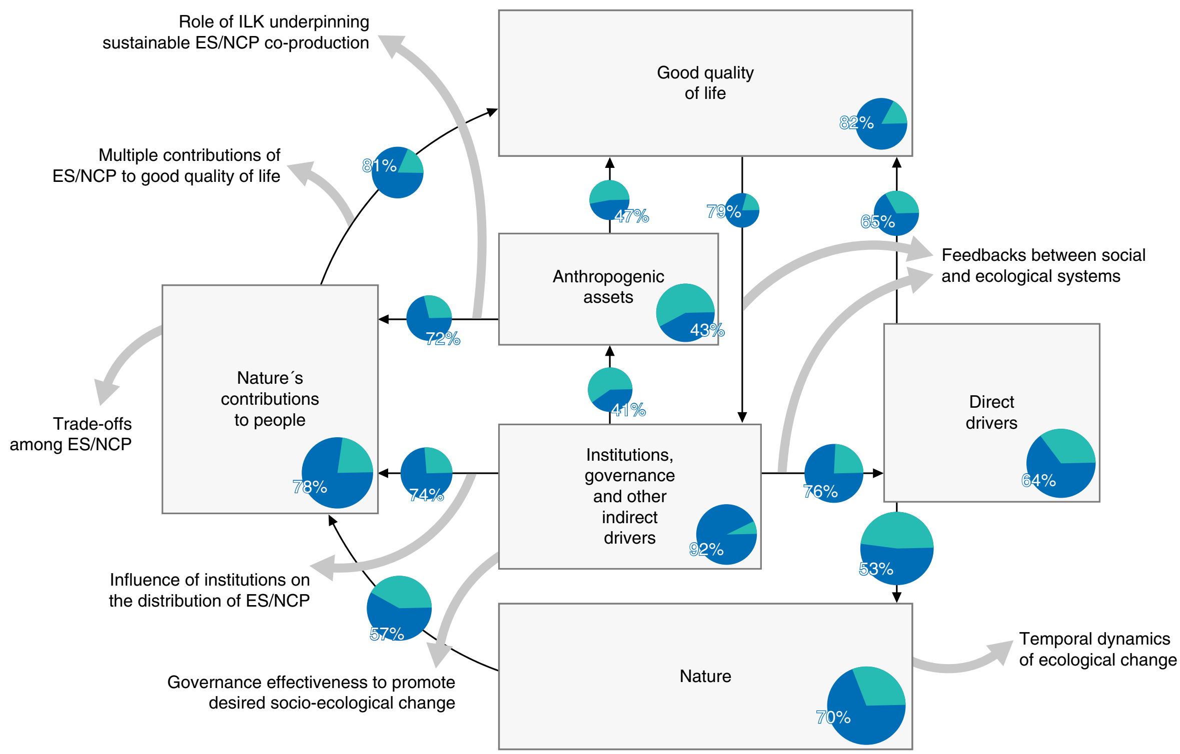

Fig. 1 | Distribution of individual knowledge gaps across the IPBES conceptual framework. Numbers of individual knowledge gaps synthetized from the seven IPBES reports that are associated with each conceptual element (that is, boxes and arrows) of the IPBES conceptual framework. The total number of gaps in each element is indicated by the area of the pie chart, and the number of policy-relevant gaps (that is, those considered slightly to extremely relevant in regard to meeting ABTs and SDGs) by the area of the slice in blue. The top-seven policy-relevant clusters of knowledge gaps are shown in association with particular elements of the IPBES conceptual framework (grey arrows). Figure adapted from ref. [51], PLoS.

Policy relevance of clusters of knowledge gaps. We grouped the 708 individual knowledge gaps into 36 clusters based on their thematic similarities (see Methods). Individual knowledge gaps grouped in seven of these 36 clusters were considered, on average, slightly to extremely relevant for achieving ABTs and SDGs, so these seven clusters were considered policy relevant (Supplementary Table 2). In the following, they are presented in order of their policy relevance and analysed in terms of (1) their relationships with different elements of the IPBES conceptual framework (Fig. 1); (2) their policy relevance in particular regions and/or themes (Supplementary Table 3 and Supplementary Results 9–11); and (3) their relevance for particular policy targets and goals (Supplementary Result 12).

Cluster 1 relates to feedbacks between social and ecological systems. Changes in people's preferences and quality of life influence institutions, governance systems and indirect drivers (for example, consumption patterns) which, in turn, impact direct anthropogenic pressures on natural systems (for example, agricultural production). Gaps identified in the Scenarios and Models report and grouped in this cluster were deemed highly relevant for both ABTs and SDGs—for instance, the need to "identify new methods for incorporating social-ecological feedbacks and how social dynamics shape exposure to hazards and access to ecosystem services"[26]. Increasing understanding of feedbacks between social and ecological systems was considered particularly relevant to designing and implementing effective plans for sustainable production and consumption, and to keep impacts of direct anthropogenic pressures on natural systems well within safe ecological limits (ABT 4).

Cluster 2 relates to trade-offs among ES/NCP, and encompasses gaps in our knowledge of trade-offs in ES/NCP production[27], ES/NCP preferences[28,29] and ES/NCP across space and time[30]. Gaps identified in the Europe and Central Asia report and grouped in this cluster were considered highly relevant for ABTs and SDGs where it is stated, for instance, that "we still have limited understanding of the synergies and trade-offs between biodiversity and ES/NCP, as well as of the spatial distribution of their provision"[23]. Assessing relationships and interactions among multiple ES/NCP in their co-production and social distribution across scales was considered especially important to inform responsible production and consumption decisions, and to prevent unintended consequences from natural resource use (SDG 12).

Cluster 3 relates to the influence of institutions on the social distribution of ES/NCP. Gaps identified in the Land Degradation and Land Restoration assessment and grouped in this cluster were deemed highly relevant for ABTs as, for instance, it is stated there that "a better understanding is required of how diverse stakeholder interests and influences affect the distribution of flows of ecosystems and services amongst society members"[25]. The identification of institutional arrangements and governance systems that foster equity in ES/NCP distribution was considered key knowledge for promoting healthy lives for people (SDG 3).

Cluster 4 relates to the role of indigenous and local knowledge (ILK) in underpinning sustainable ES/NCP co-production. Gaps identified in the Asia and Pacific assessment and grouped in this cluster were considered highly relevant for ABTs and SDGs where it is stated, for instance, that "the amount of information within traditional knowledge is (…) largely underknown to developing or underdeveloped countries"[22]. Addressing this knowledge gap was considered a fundamental step towards integrating indigenous peoples and local communities into innovative strategies for adapting and mitigating environmental change (ABT 18), among many other goals.

Cluster 5 relates to the effectiveness of governance systems to promote desired socio-ecological change. Gaps identified in the African assessment and grouped in this cluster were considered highly relevant for ABTs, where it is stated, for instance, that "indicators are lacking for monitoring and evaluating mainstreaming effectiveness for biodiversity, ecosystem services, poverty alleviation and development outcomes"[20]. Improving our knowledge of the costs and benefits of alternative governance systems was considered critical to inform decisions and policies that, for instance, reform incentives that are harmful to biodiversity and put in place those that enhance it (ABT 3).

Cluster 6 relates to the multiple contributions of ES/NCP to good quality of life. Quality of life is value-based and context-dependent: it encompasses multiple dimensions (for example, health, education, spiritual satisfaction) that depend on multiple ES/NCP[17]. Gaps identified in the Pollination assessment and grouped in this cluster were deemed highly relevant for ABTs as, for instance, "existing studies of the economic value of pollination have not accounted for non-monetary aspects of economies, particularly the assets that form the basis of rural economies"[24]. The assessment of this multidimensionality was considered particularly important to reveal and raise awareness about the multiple values of biodiversity (ABT 1) and integrate this into development planning and national accounting (ABT 2).

Cluster 7 relates to the temporal dynamics of ecological change, which reflect how ecosystems and their ES/NCP respond to multiple interacting indirect and direct drivers across time, often in a nonlinear fashion, leading to irreversible ecological and social change[9]. Gaps identified in the Americas assessment and grouped in this cluster were considered highly relevant for ABTs and SDGs where it is stated, for instance, that "monitoring programs of biodiversity and ecosystem services need to be extended beyond conservation areas"[21]. Maintaining and upgrading environmental research networks to monitor long-term trends in key ecological and social processes was deemed necessary to produce knowledge relevant for building resilience against desertification and climate change (ABT 15) and, more generally, to halt land degradation and biodiversity loss (SDG 15).

Importance of clusters of knowledge gaps in MA and IPBES. The top-seven policy-relevant clusters of knowledge gaps differ in their ubiquity across the seven IPBES assessment reports (Fig. 2 and Supplementary Table 4). The most ubiquitous clusters mentioned in all seven reports, and very frequently in more than four of them, are those related to the role of ILK underpinning sustainable ES/NCP co-production and to governance effectiveness in promoting desired socio-ecological change (Clusters 4 and 5 above, respectively). Clusters 5 and 1 (feedbacks between social and ecological systems) are frequently mentioned in the Land Degradation and Land Restoration, and Scenarios and Models reports, reflecting the value of these types of knowledge for understanding complex social-ecological dynamics. Cluster 3 (influence of institutions on the social distribution of ES/NCP) is frequently mentioned in the Americas and African reports, where social inequality and poverty are associated with conflicts around access to and control of ES/NCP. The least ubiquitous cluster is Cluster 7 (temporal dynamics of ecological change), which is mentioned in five out of seven reports.

Fourteen years ago, the MA identified knowledge gaps about biodiversity and ecosystem services that were subsequently synthesized and qualitatively prioritized[6,16]. The change in importance of knowledge gap clusters between the MA and IPBES assessments shows different trends for the top-seven policy-relevant clusters (Fig. 2). Key gaps related to feedbacks and governance (Clusters 1 and 5) have persisted for 14 years, having been ascribed high importance in the MA and being also highly ubiquitous across IPBES assessments. In contrast, key gaps related to the temporal dynamics of ecological change (Cluster 7) appeared to have been partially addressed between assessments, as their importance has decreased over time. Finally, the role of ILK in underpinning sustainable ES/NCP co-production (Cluster 4) increased in importance from the MA to IPBES assessment, as IPBES has prominently promoted 'weaving' different knowledge systems to develop effective responses to environmental change[18].

Discussion

Our synthesis of the knowledge gaps identified in IPBES assessments shows how the broader agenda of sustainability science is changing. Like the MA before them, the IPBES assessments lay out scientific needs for a new phase in environmental science. We might call this 'people in nature', following Berkes[31], who used the phrase to highlight the importance of values and institutions for ecosystem sustainability. Relative to the 'people and nature' phase that followed the MA[2], this new phase is defined by a stronger recognition of the co-production of ecosystem services by people and nature, and the relevance of societal dynamics and structure to environmental governance and management. These evolving research priorities are reflected in the shifts that we have documented in identified knowledge gaps, which relate to changes in scientific perspectives and policy goals. For example, the much greater attention afforded to indigenous and local knowledge in the seven IPBES assessments (that is, Cluster 4) is the result of increasing recognition in the scientific community of ES/NCP co-production. It is also derived from an explicit consideration in ABTs (ABTs 14 and 18) of the importance of understanding how different human societies create and assign values to ES/NCP. Similarly, the consistent emphasis across IPBES assessments on the role of institutions in the distribution of ES/NCP (that is, Cluster 3) reflects the higher relevance ascribed in SDGs (SDG 1) to the fundamental influence of social differences in resource access on the vulnerability of the poor[4]. Such shifts in research priorities show the influence of policy goals on the focus of knowledge assessments, and highlights the importance of synthesizing knowledge gaps that emerge from these assessments to define future policy goals. Just as the MA and other large-scale knowledge assessments informed the ABTs and SDGs, there is an opportunity for IPBES to inform the post-2020 policy agenda.

Evolving research priorities are also reflected in the global-level knowledge gaps identified in the summary for policy-makers of the IPBES Global Assessment[14]. Given the recent completion of this assessment, a systematic and structured synthesis like ours is yet to be undertaken. Most knowledge gaps identified by the Global Assessment relate to the basic knowledge and tools needed to address the policy-relevant knowledge gaps identified here. For example, the need for "integrated scenarios and modelling" listed in the Global Assessment will contribute, if addressed, to fill knowledge gaps about feedbacks between social and ecological systems, identified here as persistent and policy-relevant. However, knowledge gaps identified here are not so much about the functioning of social-ecological systems but about the governance of these systems, particularly about the quest for environmental governance arrangements that are effective (Cluster 5), equitable and just (Clusters 2 and 3), inclusive (Cluster 4) and promote good quality of life (Cluster 6). Our rigorous analysis provides a complementary perspective on the linkages between the IPBES framework´s elements and a wide spectrum of policy targets and goals, as recommended by the Global Assessment. In addition, the regional resolution of our detailed analysis addresses the Global Assessment's recommendation to assess the uneven geographical distribution of knowledge gaps.

There are many reasons why research priorities might have evolved as they have done. Technological advances in Earth system platforms (for example, satellite remote sensing, improved climate data), capacity for data processing and tools for modelling and

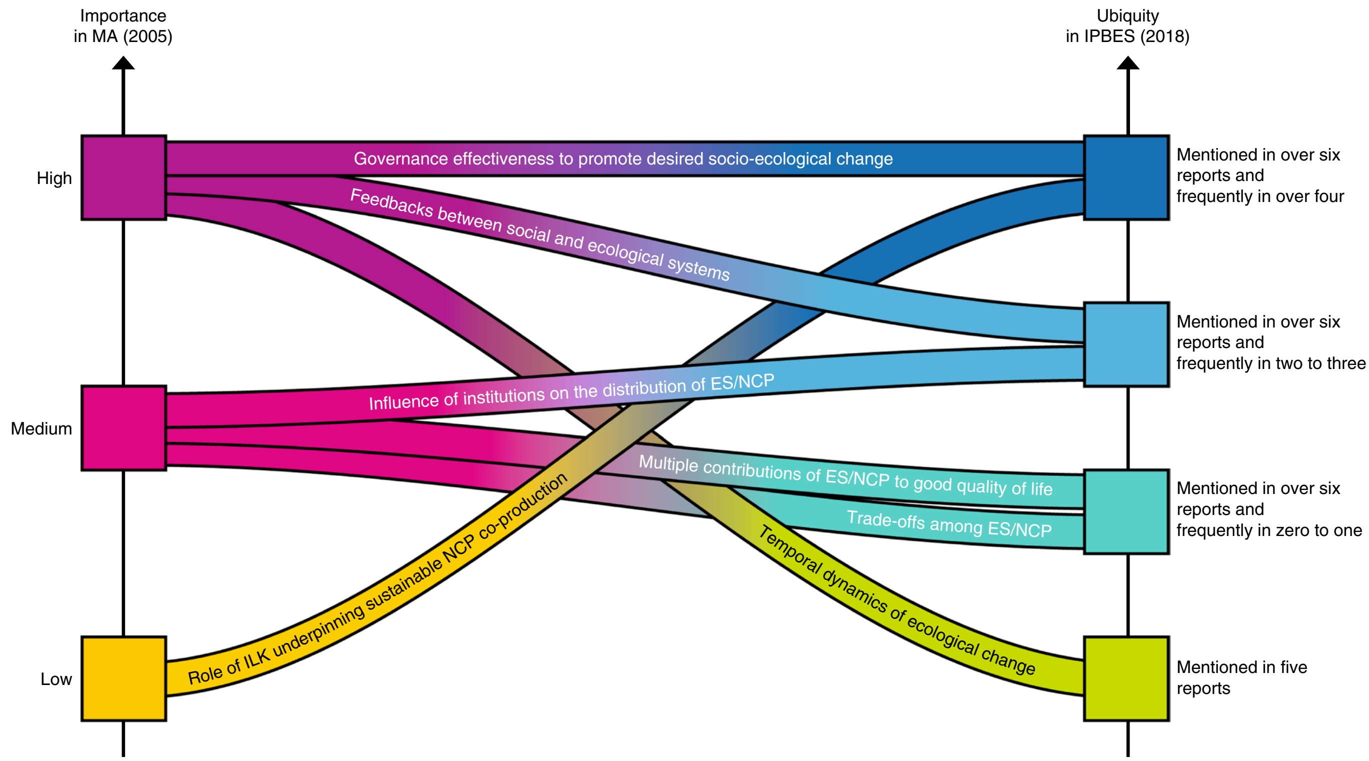

Fig. 2 | Evolution of key knowledge gaps from MA to IPBES. Change in the importance for ecosystem sustainability of the top-seven policy-relevant knowledge gap clusters between MA[5] (left axis) and the seven regional and thematic assessments reports by IPBES[20–26] (right axis).

scenario simulation have supported progress in understanding the temporal dynamics of ecological change[32,33] and trade-offs among ES/NCP[34]. Changes in societal values, including those of scientists, also drive shifts in research agendas by influencing funding strategies and engagement in science-policy platforms such as IPBES. For example, growing interest in how institutions and socio-ecological dynamics relate to equity and justice may result in further changes in research priorities.

Our mapping of policy-relevant knowledge gap clusters in the IPBES conceptual framework identifies essential linkages among these gaps. For example, monitoring the temporal dynamics of ecological change (Cluster 7) is fundamental to proper diagnosis of trade-offs among ES/NCP (Cluster 2) and in the detection of feedbacks between social and ecological change (Cluster 1). Local understandings of how people resolve trade-offs among ES/NCP (Cluster 2) and achieve its sustainable co-production (Cluster 4) are critical to understanding and managing feedbacks (Cluster 1). In addition, integrated valuation of the multiple contributions of ES/NCP to good quality of life (Cluster 6) is needed to design effective governance systems (Cluster 5) and institutional arrangements that ensure a fair distribution of ES/NCP among social groups (Cluster 3). The explicit consideration of these linkages in the design and implementation of research projects and programmes increases their potential impact on policy and cost effectiveness by capturing critical interactions between people and nature and tracing the linkages between ecosystems and ES/NCP, human behaviour and its impacts on nature, and the capacity of social-ecological systems to ensure the sustainable co-production and fair distribution of ES/NCP.

Our synthesis and prioritization of knowledge gap clusters show that improving our understanding of feedbacks between social and ecological systems, of governance effectiveness and of the influence of institutions on ES/NCP distribution is critical for achieving ABTs and SDGs, while our comparison to knowledge gaps after the MA indicates that these gaps have persisted as top research priorities for at least the last 14 years (Figs. 1 and 2). In addition, mapping clusters in the IPBES framework shows that these three knowledge gaps are related to conceptual elements at the core of the framework, highlighting the interconnected and persistent gaps in our knowledge about the links among institutions, governance and other indirect drivers, ES/NCP and good quality of life, and their feedbacks (Fig. 1). All IPBES reports, and most recently the Global Assessment, recognize the limited success of recent social and political dynamics for tackling these interconnected and persistent gaps. Such persistence is likely to impede the progress that is urgently required to achieve sustainable and equitable governance solutions. The identification of persistent gaps helps in understanding why certain targets have not been met and how to frame post-2020 targets. Keeping ubiquitous (for example, Cluster 4) and persistent (for example, Clusters 1, 3 and 5) gap themes in globally agreed policy targets might attract action and motivate countries to address these gaps, as happened in the past. For example, ABT 11 and 14 on ecosystem services led the European Union to translate the targets into actions, with Action 5 of Target 2 of the EU Biodiversity Strategy instructing member states to map and value ecosystem services in their national territories following the formation of MAES[11]. Nevertheless, resolving this knowledge deficit is a necessary but insufficient condition for meeting policy goals and targets, since knowledge gaps lead to inaction when combined with institutions, power and values that lock decisions required for transformation[35].

These policy-relevant gaps may have been persistent over the years because of their complex, multi-scalar and wicked nature that requires truly interdisciplinary research to capture critical interactions between people and nature, and to take advantage of the linkages among gaps[2]. Although current research on ES/NCP has become more interdisciplinary[36], it is still evolving[37]. Several ongoing initiatives promise to address the interconnected and persistent knowledge gaps identified here. Long-term social-ecological platforms that network trans-disciplinary, place-based research can track the temporal dynamics of trade-offs among ES/NCP, and detect feedbacks between social and ecological systems[38–41]. Analytical approaches that disaggregate social heterogeneity of the focal and its teleconnected systems can capture differences in access to ES/NCP and assess the causes and consequences of their unequal distribution across social actors[42] and spatial scales[43]. Research programmes with a focus on social learning and governance for transformation explicitly deal with science–policy–society interactions and provide conceptual and methodological tools to evaluate the processes and outcomes of alternative response options[44,45]. Although initiatives to co-produce knowledge through collaboration among ILK-holders, scientists of different disciplines and practitioners face epistemological and methodological challenges[46–48], such programmes are suited to uncover the types of environmental cognitions, social relationships and ecosystem management practices that underpin the sustainable co-production of ES/NCP[49,50]. Future national and international research agendas need to recognize the new epistemologies, and associated capacities and resource requirements, in bold and well-supported initiatives that build the science needed to address the critical issues of societal transformation raised by all IPBES assessments and that will be at the core of IPBES's newly approved second work programme.

Methods

For each IPBES report, a minimum of three co-authors independently identified and listed the individual knowledge gaps explicitly or implicitly reported in each assessment (Supplementary Fig. 1). The co-authors that analysed each particular IPBES report were experts in the region or theme assessed in that particular report, and some were actually authors of the report. A knowledge gap was defined as a piece of knowledge, information or data that is absent, insufficient or unavailable. For each individual knowledge gap identified and listed, each co-author used collectively agreed criteria to (1) establish its association with each of the 16 elements (boxes and arrows) of the IPBES conceptual framework using a binary scale (0, not associated; 1, associated) and (2) score its relevance for achieving each of the 20 ABTs and each of the 17 SDGs using a five-point Likert scale (1, not relevant at all; 2, slightly relevant; 3, somewhat relevant; 4, highly relevant; 5, extremely relevant).

The criteria used for establishing knowledge gap associations with elements of the IPBES conceptual framework, and for scoring knowledge gap relevance for ABTs and SDGs, were discussed and agreed by all co-authors during two meetings. In the first meeting, co-authors designed a methodological approach for identifying and scoring knowledge gaps. After this meeting, all co-authors identified and scored a standard report, the Scenarios and Models assessment. The lead authors assessed scorer reliability and provided feedback, which was discussed during the second meeting to standardize the scoring criteria. Each co-author then proceeded to identify and score knowledge gaps for a report independently.

We produced 29 independent assessments of the identity, associations with elements of IPBES conceptual framework and relevance for ABTs and SDGs of individual knowledge gaps across the seven IPBES reports ($n=4$ for Africa, $n=5$ for the Americas, $n=3$ for Asia and Pacific, $n=5$ for Europe and Central Asia, $n=5$ for Pollination, $n=4$ for Land Degradation and Land Restoration and $n=3$ for Scenarios and Models). We compared the assessments independently produced by multiple co-authors for the same report, and assessed the level of agreement among co-authors. We did this by calculating Kendall's concordance coefficient. W, in Statistical Package for the Social Sciences for every case in which different co-authors scored the relevance for ABTs and SDGs of the same individual knowledge gap. This coefficient was >0.7 in all these cases, which indicates a reasonable to high level of agreement among co-authors in their scores, reflecting that the scoring criteria were effectively standardized in initial meetings. Therefore, we confidently averaged the relevance scores of duplicated gaps across co-authors and generated one consolidated assessment of knowledge gaps per report. The consolidated assessments of knowledge gaps per report are available in Supplementary Results 1–7.

We assessed the policy relevance of each knowledge gap based on its relevance to achieving ABTs and SDGs. The rationale behind this criterion is that ABTs and SDGs have guided the definition of policy objectives in the numerous countries signing the CBD 2011–2020 Strategic Plan for Biodiversity and the UN 2030 Agenda for Sustainable Development, as well as in public and private organizations across the globe. Thus, despite not being policies per se, ABTs and SDGs encompass a set of policy objectives that have been extensively adopted to formulate national policies. A knowledge gap was deemed policy relevant if the average relevance scores across both ABTs and SDGs were >2, which means that it was considered slightly to extremely relevant for achieving ABTs and SDGs. Supplementary Results 1–7 show the mean relevance scores for ABTs and SDGs for each of the 708 individual gaps identified in the seven reports.

To assess the prevalence of knowledge gaps across IPBES reports in relation to the IPBES conceptual framework (research question 1), we counted the total number of individual knowledge gaps, and of policy-relevant individual knowledge gaps, associated with each of the 16 elements (that is, concepts and their linkages) of the IPBES conceptual framework. We calculated the percentage of policy-relevant knowledge gaps for each element of the IPBES conceptual framework as: (number of policy-relevant individual knowledge gaps associated with element i/total number of individual knowledge gaps associated with element i) × 100 = (percentage of policy-relevant individual knowledge gaps associated with element i) (Supplementary Table 1). Supplementary Result 8 shows the total number of individual knowledge gaps associated with each element of the IPBES conceptual framework in each of the seven reports.

To assess the policy relevance of knowledge gap clusters (research question 2), we first grouped the 708 individual knowledge gaps into 36 clusters of knowledge gaps by coding them and iteratively pairing those with similar codes until reaching a reasonable number of homogeneous clusters. The lead author coded each of the 708 individual knowledge gaps with a set of codes (as large as necessary) that captured the thematic complexity of each piece of knowledge. The codes employed to describe gaps related to concepts and themes commonly used in the literature about biodiversity, ecosystem services and human well-being, which was the raw material used by IPBES authors to assess knowledge (and knowledge gaps). For each gap, the codes were ordered from that capturing the most central/principal theme to that capturing the most peripheral/subordinate. When a gap was described by a set of codes containing themes related to different clusters, it was assigned to the cluster related to the most central theme—that is, that captured by the higher-order code. The resulting clusters were discussed among lead authors and adjusted accordingly to increase consistency. We previously tested alternative methods for clustering text, such as latent semantic analysis, but the one employed here yielded the most meaningful results because a substantial level of abstraction was needed to describe 708 individual gaps using a combination of relatively few concepts and themes. We aimed to reach a meaningful synthesis of knowledge gaps more than an optimal clustering solution; different clustering results can be obtained with the same dataset using other conceptual frameworks and methodological procedures. For each of the resulting 36 knowledge gap clusters, we averaged mean relevance scores for ABTs and SDGs across individual knowledge gaps belonging to the same cluster. Based on the mean relevance score for each cluster, we ranked the 36 knowledge gap clusters and identified that seven of them presented mean relevance scores >2 (that is, were considered slightly to extremely relevant both for achieving ABTs and SDGs), and were thus categorized as policy relevant (Supplementary Table 2). Supplementary Results 9–11 show the mean relevance scores for ABTs and SDGs of the knowledge gap clusters identified in the seven reports.

To compare the knowledge gaps identified in IPBES to those identified in the MA in terms of their importance (research question 3), we first assessed the ubiquity (that is, proxy for importance) of the seven policy-relevant knowledge gap clusters across IPBES reports. For each cluster, we counted the number of times that individual knowledge gaps grouped there were mentioned in each report. We considered that a knowledge gap cluster was mentioned frequently in a report if its individual knowledge gaps were mentioned five or more times in that report. The higher the number of reports in which the cluster was just 'mentioned' (that is, only once) or 'mentioned frequently' (that is, five or more times), the higher its ubiquity across IPBES reports (Supplementary Table 4). Second, we identified the knowledge gaps described as important in the qualitative synthesis and prioritization of research needs undertaken after the MA by refs. [8,9]. We then evaluated persistence by comparing its importance in the MA and its ubiquity across IPBES reports. The higher the importance of a knowledge gap in the MA and its ubiquity across IPBES reports, the higher its persistence across assessments.

Data availability

Descriptive statistics of the raw dataset are available in the Supplementary Information.

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Author contributions

M.E.M. and N.P.-H. designed the study, analysed data and coordinated tasks. L.E., E.B., S.L. and G.S.C. contributed to task coordination. B.L. and E.O.-R. contributed to figure design and preparation. All co-authors contributed to data preparation and manuscript writing.

Competing interests

The authors declare no competing interests.

Additional information

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