Measuring Nature's Contributions to People – what data do we have?

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Abstract

The concept of Nature's Contributions to People, established by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, extends the ecosystem services approach by acknowledging the many perspectives and world views about human-nature relationships. Quantifying these relationships requires robust data and tools. Using existing databases and artificial intelligence-assisted web searches, this study identifies and evaluates 297 online resources across the 18 categories of Nature's Contributions to People. We assessed these resources based on their functional roles, ranging from Foundational Data Infrastructure to industry- and policy-focused tools, as well as their confidence levels, maturity, and adherence to Findable, Accessible, Interoperable, and Reusable principles. Our mapping reveals data gaps, particularly in material and regulating categories such as energy and regulation of ocean acidification. While Ecosystem Assessment and Modeling Platforms demonstrate high confidence through primary observations, policy and industry-focused tools are less frequent and often rely on inference. Furthermore, categories like pollination and water quality frequently lack spatial and temporal coverage. Network analyses linking these resources to the Kunming-Montreal Global Biodiversity Framework show weak alignment with Goal C and Targets 13, 20, and 23. This indicates that access, benefit-sharing, and distributional dimensions of Nature's Contributions to People may be insufficiently represented. We provide these resources as a modular, expandable database to support bridging the existing data gaps.

Key words: Ecosystem Services, Natures Benefits, Natures Gifts, Natural Capital, Nature Based Solutions

1 Introduction

The broad concept of nature's contributions to people (NCPs; Díaz et al., 2018), that extends the framing of Ecosystem Services (ES), is now being embedded in international policy (Figure 1). The adoption of the Kunming-Montreal Global Biodiversity Framework (KMGBF) has modernized global priorities for conservation, sustainable use, and sharing of the benefits of biodiversity (CBD 2024), with Target 11 specifically mandating the restoration, maintenance, and enhancement of Nature's Contributions to People (NCPs), including ecosystem functions and services. This current framework aims to address the implementation gaps of the previous decade, where progress on ES monitoring remained limited (COPCBD, 2022). Meanwhile the Sustainable Development Goals (SDGs) continue to emphasize the integration of nature into human development, supported through an extensive, multi-level monitoring system (Avtar et al., 2020; Scharlemann et al., 2020). In this contemporary policy context, it is critical to assess our current capacity and identify the data available to measure status and trends in NCPs in support of progress toward global goals and targets, including the SDGs to 2030 and the KMGBF targets to 2030 and goals to 2050 (Figure 1).

Beyond public policy, the private sector is increasingly recognizing the dependency of business operations on nature, through both natural capital assets that can be directly translated into economic value and ESs that, while not always monetized, remain essential

to business performance and resilience (Kurth et al., 2021; Natural Capital Financial Alliance, 2023). Major literature and expert reviews have been undertaken to develop databases of sectoral dependencies on natures, such as those included in the ENCORE and Science Based Targets Network (SBTN) Materiality Screening Tool (Natural Capital Financial Alliance, 2023; Science Based Targets Network, 2026). At the macro-economic level, natural capital accounting approaches have been developed for nations to understand, manage, and monitor their stocks and flows of natural capital and ESs (Ingram et al., 2024).

While ES has been the dominant vernacular, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has developed this conceptual thinking into a broader understanding of NCPs (Díaz et al., 2018). Detailed cross-walking between ES and NCPs has been attempted in recent literature (Kadykalo et al., 2019), and the NCP framing has been utilized in various IPBES assessments. However, the development of the IPBES Monitoring Assessment (IPBES, 2023) and the upcoming second IPBES Global Assessment (IPBES, 2024) creates an urgent need to clarify the conceptual underpinnings of NCPs, the relationship between ES and NCPs (Figure 1), and the knowledge resources that allow links between this framing and international policy and business frameworks.

Apart from older compilations of data related to Aichi Target 14 (Shepherd et al., 2016) and the SDGs (UN, 2023), there is limited available literature on the data resources specifically available for measuring changes across the 18 NCP categories. While the first IPBES Global Assessment synthesized scientific papers to deliver metadata on trends

(Brauman et al., 2020), it did not provide actual data from within databases characterized by time-series and metadata standards.

Given the importance for NCPs to be measured, monitored, and modeled for future trends, this paper presents a broad-ranging assessment of available NCP information and data sources at national to global scales. We aim to support the delivery of intergovernmental assessments and policy processes, while also taking a step toward fully operational data that can be used for national government and business-level decision-making. To address this, we present the quality of currently located data, highlight the major data gaps, and propose pathways for how these monitoring needs might be filled. We furthermore present the data in an easily accessible User Interface (UI) to allow shareability and usability by different end-user groups.

2. Methods

Our goal was to systematically assess and map online resources using a comprehensive framework to determine resource relevance for monitoring the 18 NCPs defined by Diaz et al. (2019). To maximize the coverage of our global online search we developed a sequential and modular resource assessment protocol (Supplements_S1; NCP_DMR) that we used in GeminiAI (v2.5 Pro) to make the search and subsequent information extraction as repeatable and standardized (Haddaway et al., 2022) as possible, while aiming to reduce reviewer and collection bias (Arias et al., 2023; Haddaway et al., 2022).

We included three guiding principles to assure the scientific robustness of the assessment, applied to data extraction and scoring (Figure 2). All scores, classifications or

justifications done by GeminiAI had to be based on explicit and verifiable evidence directly extracted from the assessed NCP resource (Primacy of explicit evidence, Principle 1), with evidence being retained in the form of meta-data (Haddaway et al., 2022). Principle 2, mandate for conservative inference, builds on Principle 1, having GeminiAI assign the more conservative score or classification in cases of ambiguous or incomplete information. We chose this precautionary approach to reduce overestimation of resource relevance, with large language models (LLM) being prone to overconfidence (Wen et al., 2024) which ultimately could reduce the overall NCP assessment quality as well as end-user application.

Finally, we included the requirement for treating the absence information as evidence of absence in our context to further reduce the chance for creating ambiguous NCP records. This step aims to account for tendencies in LLMs to pass down inference bias in sequential applications (Principle 3, Absence of evidence as justified inference; (Kirsten et al., 2025; Wen et al., 2024).

2.1 Gemini AI resource search and meta-data retention

We provided GeminiAI with the necessary background information on NCPs, using the deep search option for advanced information processing and retrieval (Xu & Peng, 2025). Post-background information acquisition, GeminiAI was instructed to collect all possible online resources pertaining to NCPs and their stable URLs, using snowballing, given the fact that for a global resource search we did not start with a traditional database search (Wohlin, 2014; Wohlin et al., 2022). The resource search was conducted between September 1st and September 3rd, 2025, and resulted in 324 suggested online resources

relating to NCPs across all six official languages of IPBES (Arabic, Chinese, English, French, Russian, and Spanish; Figure 2).

In step one of the resource evaluation, duplicates, resources out of scope (e.g. purely informational value), or those with broken or non-functioning URLs, were removed (Data_NCP; Figure 3). The remaining 251 resources were assigned to one of four foundational categories, relating to their potential role for monitoring NPCs as well as targeted end-users (Foundational Data Infrastructure (FDI); Ecosystem Assessment and Modeling Platform (EAMP); Policy, Planning and Finance Mechanism (PPFM); Business and Industry-Focused Tool (BIFT)). Base resource information was extracted in step two to ensure transparency according to Principle 1 (e.g. resource name, URL; Figure 3; Supplements_S1; NCP_DMR).

2.2 Information criteria

All information criteria used for NCP resource information extraction found in steps three to six were based on the official definition found in peer reviewed literature or provider resources to further reduce LLM bias or ambiguity. A justification was mandatory for every score or assignment in accordance with the guiding principles.

2.2.1 NCP categories

NCP classifications were assigned to each of the 251 NCP resources based on Diaz et al's definitions for each of the 18 NCPs categories and 3 NCP category division (regulating 1-10, material 11-14, non-material 15-17), with NCP 18, maintenance of options, generally being associated with all three categories. NCP category assignment was complemented by a

confidence score from 1 to 3 (0 meaning absence of an NCP category as the default score (Díaz et al., 2018)). Confidence scores of 1 (Plausible Inference from a Widely Accepted Proxy) indicate that an NCP assignment was based on the resource providing proxy data for a specific NCP. A confidence score of 2 (direct foundational data) indicates that the resource does not explicitly name the NCP in question but provides foundational data that can be used for monitoring the NCP. Confidence scores of 3 were used for cases of Explicit Evidence, with the resource stating the provision of monitoring data for an NCP e.g. through a dedicated indicator or data product (Figure 3; Supplements_S1; NCP_DMR).

2.2.2 KMGBF indicators

In step four, resources were assessed for policy relevance against the KMGBF goals and targets (Hughes & Grumbine, 2023; UNWCMC, 2025). This step was designed to identify resources that can directly support implementation and reporting obligations as well as provide a first indicator for potential for cross-operability of an NCP resource base. Using the binary (Yes/No) scoring protocol, a 'Yes' score was assigned only if the resource provided data or tools that directly mapped to a KMGBF goal or target and subsequently indicators (UNEP-WCMC, 2025). 'No' was the default score.

2.2.3 Resource maturity

We used 12 maturity criteria for GeminiAI (Supplements_S1; NCP_DMR) across four foundational resource maturity pillars; Data availability and quality (DAQ; (Adepoju et al., 2022; Ferretti, 2011)), Monitoring infrastructure (MI; (Adepoju et al., 2022; Sparrow et al., 2020)); Analytical capacity for indicators (ACI; (Schmeller et al., 2018; Tallis et al., 2012)) and Governance and human capacity (GHC; (Harris & Browning, 2013; Tallis et al., 2012))

to assess how ready the reviewed NCP resources are for use as well as their long-term stability and coverage. Each criterion was scored 0-3 based on a detailed rubric (Supplements_S1; NCP_DMR), with '0' assigned as the default if no information was found.

2.2.4 FAIR principle

In step six, a technical audit of each resource's alignment with the FAIR (Findable, Accessible, Interoperable, Reusable) Guiding Principles was conducted. Using the binary (Yes/No) scoring protocol, a 'Yes' score was assigned only if explicit, verifiable evidence of implementation was found (e.g., a data license page). 'No' was the default score if no such documentation was located.

2.2.5 Manual checks and accessibility

The sequence concluded with step seven, a mandatory self-audit by GeminiAI to ensure protocol adherence. This final quality check confirmed that all required fields were complete, all scores (NCP, KMGBF, Maturity, FAIR) included the required justifications, and that the three Guiding Principles were consistently applied before the record for each resource was finalized.

2.3 Data analyses

To map the distribution, coverage, and interoperability of resource capabilities, we employed a single network coincidence analysis using the netCoin R package (Escobar & Martinez-Uribe, 2020). This methodology is designed to assess the structure and degree to which different attributes, or events, tend to co-occur within a defined set of scenarios. For this analysis, each online resource evaluated was treated as a unique scenario.

The events (nodes) mapped within these scenarios were the 18 individual NCPs and the KMGBF headline indicators. From our reviewed data, a bimodal incidence matrix (0/1) was constructed, linking each resource (scenario) to all its associated NCPs and KMGBF indicators (events). This matrix was then projected into a single unimodal coincidence network to visualize significant relationships ($p < 0.05$) between the events themselves.

We then analyzed this unified network to identify key patterns, including mapping the frequency of each NCP and KMGBF indicator, assessing node connectivity (degree) to identify hubs, and quantifying the statistical significance of connection strength between any two attributes (e.g., NCP-to-NCP or NCP-to-KMGBF) using Haberman's adjusted residuals (Escobar & Martinez-Uribe, 2020). This approach provides an intuitive, visual assessment of which NCPs are frequently covered together and simultaneously maps the realized interoperability between NCPs and the KMGBF indicators, identifying structural linkages within the monitoring resource landscape.

2.3.1 GAP analyses

To conduct a traceable gap analysis, we used a "Gap Profile" for each of the 18 NCPs. This approach calculates 10 distinct gap metrics and one cross operability score, allowing for the diagnosis of specific monitoring weaknesses and strengths rather than relying on a single, composite score.

Core coverage was assessed with two metrics. The Relative Coverage Gap calculated as $Gap_{Coverage} = 1 - (n_i/n_{max})$ measures an NCP's coverage (n_i) against the maximum observed resource coverage for any single NCP (n_{max}) across the four functional

categories. This metric identifies gaps relative to the resources best-covered area. The **Confidence Gap**, $Gap_{Confidence} = 1 - (\bar{C}_i/3)$, measures whether this coverage across functional categories is based on direct evidence (Score 3) or weaker, inferential links (Score 1), based on the average confidence score ($\bar{C}_i$) for that NCP.

To assess resource quality with traceability, disaggregated **Maturity Gaps** were calculated. Scores for the four maturity pillars (*P*) and their subcategories (e.g. DAQ1, DAQ2…); Data Availability/Quality (DAQ), Monitoring Infrastructure (MI), Analytical Capacity (ACI), and Governance/Human Capacity (GHC), were averaged from relevant resources ($\bar{S}_{P,i}$) and inverted to identify specific failures using the formula $Gap_{Maturity(P)} = 1 - (\overline{S_{P,i}}/3)$.

Similarly, **FAIR Gaps** were formed by the four pillars (*F*) and their subcategories (e.g. F1, F2…); (Findable, Accessible, Interoperable, Reusable). These are calculated as the inverted percentage of covering resources (n_i) that meet a given pillar's principles ($R_{F,i}$), using the formula $Gap_{FAIR(F)} = 1 - (R_{F,i}/n_i)$. This pinpoints specific usability failures, such as a lack of persistent identifiers ('F' Gap) or clear data licenses ('R' Gap).

2.3.2 KMGBF crosswalk

Each significant ($p < 0.05$) NCP to KMGBF target link from the network and all associated resources were assessed using a standardized crosswalk framework (Table 2). Evaluation was conducted across four evidence dimensions: context, data and trends, drivers, and options. Context assessed whether resources articulated a conceptual or analytical

framework linking changes in the NCP to Target-relevant outcomes. Data and trends assessed whether resources provided indicators, time-series data, or monitoring approaches capturing Target-relevant change mediated by the NCP. Drivers assessed whether resources analyzed causal mechanisms linking drivers of biodiversity change to Target performance through the NCP. Options assessed whether resources identified actionable interventions for which monitoring the NCP directly supports evaluation of progress toward the Target or Goal (Table 2).

For each NCP–Target pair (e.g. NCP 2 linked to Target 6 = 6 resources), the collective resource set was scored independently for each dimension using a three-point ordinal scale, where scores of 3 indicated robust evidence, 2 indicated partial or fragmented evidence, and 1 indicated weak or no meaningful coverage. Scores were assigned at the resource-set level. Definitions of KMGBF Targets and Goals followed the official descriptions provided by the KMGBF Indicator Knowledge Platform (CBD, 2026; UNWCMC, 2025). Mean NCP to KMGBF target or goal scores crosswalk connections across context, data and trends, drivers and options were translated to weak (1-1.66), Moderate (1.67-2.33) and strong (2.34-3) to identify broad gaps.

3 Results

Most of the 251 assessed resources provided potential data and information on non-material NCPs (linked to n = 232 resources; range 1-3 NCPs per resource) and regulating NCPs (linked to n = 212 resources; range 1-9 NCPs per resource), followed by material NCPs (linked to n = 151 resources; range 1-4 NCPs per resource; Figure 3). NCP distribution within those three broad categories was uneven, mainly covering a few specific NCPs

(Figure 3). The most common NCP (Table S1) was NCP15 (Learning and inspiration; n=226), followed by NCP18 (Maintenance of options; n=187), NCP1 (Habitat creation and maintenance; n=167) and NCP 12 (Food and feed; n=103). The least covered NCPs (Table S1) were NCP2 (Pollination and dispersal of seeds; n=15); NCP17 (Supporting identities; n=15); NCP5 (Regulation of hazards and extreme events; n=9) and NCP11 (Energy; n=8). Most of the synthesized resources were FDI resources (n= 143). 51 resources were PPFM and 49 resources were EAMP. BIFT were only associated with 8 of the 251 resources (NCP_data.xlsx).

KMGBF goals and targets that the resources potentially also provide information on (Figure 3) were mainly Goal A (elements of biodiversity and species protection/ ecosystem extent; n=97) and Target 10 (agricultural production; n=39) and in relation to Goal A, Target 21 (indicator on biodiversity information; n=35; Table S1). Goal C on monetary and nonmonetary benefits through access and benefit sharing instruments had the fewest cross-operability potential with the assessed NCP resources (n=6), as well as its associated indicators under Target 13 (C1 and C2 indicators; n=8). Other low frequency targets were Target 23 (n=6) and Target 20 (n=5).

Local connectivity, which identifies high-degree NCPs (nodes) that co-occur frequently with others was analyzed ($p<0.05$ (Table S2); Figure 3; Table S1). For NCPs, the highest local connectivity was observed for NCP4 (Regulation of climate) connecting to 16 other NCPs and KMGBF goals and targets and freshwater related NCP7 (Regulation of freshwater and coastal water quality; v=12), and NCP6 (Regulation of freshwater quantity, location and timing; v=12) followed by NCPs18 (Maintenance of options), 8 (Formation,

protection and decontamination of soils and sediments) and 9 (Regulation of hazards and extreme events), all with 10 connections.

3.1 NCP coverage gaps

Coverage gaps measured on a scale of 0 to 1, with larger values indicating larger gaps, within functional categories were comparable across most of the 18 NCP classes, reflecting most of findings from the general frequency distribution under 3.1. Complete coverage gaps were mostly recorded for BIFT resources, with NCPs 5, 9, 11, 14, 16 and 17 being absent. BIFT resources within their functional category focused on information and data on regulating NCPs in addition to Food and feed (NCP 12); Learning and inspiration (NCP 15) and Maintenance of options (NCP 18; Figure 4a; Table S3). NCPs 11 (Energy) and 5 (Regulation of ocean acidification) were furthermore not recorded for EAMP resources (Figure 4a; Table S3), with EAMP NCP resource gaps being evenly distributed across regulating, material and non-material NCPs (Figure 4a; Table S3). Across those categories, EAMP resources showed large gaps >0.9 for NCPs 2 (Pollination and dispersal of seeds and other propagules), 10 Regulation of detrimental organisms and biological processes), 14 (Medical, biochemical and genetic resources) and 17 (Supporting identities). Large gaps for FDI resources were predominantly present for regulating NCPs (NCP 2, 3, 5, 9, 10) as well as for NCP 11 and NCP 17, with most information focussing on NCP1 (Habitat creation and maintenance) and material NCPs (Figure 4a; Table S3). Regulating NCPs also had the most gaps (>0.9) associated with them for PPFM resources (NPCs 2, 3, 5, 10) as well as NCPs 11 and 13. Within functional category coverage gaps support the overall frequency findings from 3.1 with resources within the four functional categories providing information and

data on few often overlapping broader NCPs, like NCPs 1 (Habitat creation and maintenance), 4 (Regulation of climate), 12 (Food and feed), 15 (Learning and inspiration) and 18 (Maintenance of future options), with certain coverage nuances within functional categories.

3.2 NCP confidence gaps

Confidence gaps, measured on a scale of 0 to 1 with larger values indicating a greater reliance on inference over explicit data, varied distinctly across the four functional categories (Figure 4b; Table S4). Complete confidence gaps (data absence) naturally were the same as under coverage. BIFT resources recorded the only instance of perfect explicit coverage (0) for Regulation of detrimental organisms (NCP 10). However, BIFT resources also exhibited the largest confidence gaps (>0.65) for critical regulating services, specifically Pollination (NCP 2), Regulation of air quality (NCP 3), and Regulation of water quality (NCP 7). EAMP resources consistently provided the most explicit data, recording the lowest confidence gaps for Pollination (NCP 2; 0.08), Materials (NCP 13; 0.14), and Regulation of hazards (NCP 9; 0.16). Like BIFT, EAMP resources lacked data for NCP 5 and NCP 11. EAMP gaps were otherwise evenly distributed but generally remained below 0.30, suggesting a strong adherence to primary observation. FDI and PPFM functioned as stabilizing categories with no complete data gaps but higher average inference. FDI resources showed gaps for Habitat creation (NCP 1; 0.43) and Energy (NCP 11; 0.44). PPFM resources displayed a homogenized gap distribution, clustering between 0.33 and 0.45 across regulating and material NCPs. A cross-category comparison (Figure 4b; Table S4)

shows lower confidence for Pollination (NCP 2) and Water Quality (NCP 7) as data moves from EAMP (0.08; 0.17) to BIFT (0.67; 0.67).

3.3 Resource maturity and FAIR adherence

The assessment of resource readiness (Maturity) showed that Monitoring Infrastructure (MI) and Analytical Capacity for Indicators (ACI) were the most driving factors for higher gap scores (Figure 5a; Table S5). Monitoring Infrastructure (MI) showed the highest gap scores, with the highest average gap of 0.34. This score was driven by indicator MI2 (Remote sensing application; 0.64), suggesting that most resources do not use or provide remote sensing data. ACI represented the second-largest barrier (0.21), with higher gap scores in ACI1 (Methodological sophistication; 0.40). Conversely, Governance and Human Capacity (GHC) displayed the highest level of maturity with a minimal gap of 0.09, followed closely by Data Availability/Quality (DAQ) at 0.12.

The FAIR gap analysis, based on presence absence data identified Findability as the most urgent usability bottleneck with an average gap of 0.38 (Figure 5b; Table S6). Large gaps in F1 ((Meta)data are assigned a globally unique and persistent identifier; 0.72) and consequently F3 (Metadata clearly and explicitly include the identifier of the data they describe; 0.71) highlight issues with persistent identifiers and metadata linking. Accessibility also presented a hurdle (0.32), particularly regarding indicator A1.2 (The protocol allows for an authentication and authorisation procedure, where necessary; 0.66). In contrast, the resources demonstrated robust performance in Reusability (lowest gap: 0.05) and Interoperability (0.11). Collectively, these findings suggest a landscape where

resources are effectively licensed and governed for reuse yet remain largely inaccessible and unmonitored due to potentially gaps in findability and infrastructure.

3.4 KMGBF Crosswalk

The network analysis identified 54 significant connections between NCP-related resources and potential monitoring information for KMGBF goals and targets (Table S2; Figure 3). These links spanned four goals (A, B, C, and D) and 14 targets (Targets 2, 3, 5, 6, 7, 8, 9, 10, 12, 15, 18, 21, 22, and 23). Connections between NCPs and KMGBF goals and targets based on the network analysis show that resources addressing a given NCP tend to contain information relevant to specific KMGBF goals or targets; connection strength reflects how well this information can be cross walked across key monitoring aspects (context, data and trends, drivers, and options), or whether these components are missing (Table 3; Table S7).

Across all linkages, the strongest connections between NCP resources and KMGBF goals and targets were associated with data and trends (n = 25; 46.3% of strong connections) and context (n = 11; 20.4%). In contrast, drivers (n = 2; 3.7%) and options (n = 3; 5.6%) exhibited few strong connections and were dominated by weak linkages, with more than 50% of connections classified as weak for both aspects (Table 3).

The strongest complete linkages were observed between ‘Materials, companionship and labor’ (NCP13) and ‘Adequate means of implementation of the KMGBF’ (Goal D); between NCP13 and ‘Businesses assess, disclose and reduce biodiversity-related risks and negative impacts’ (Target 15); and between ‘Maintenance of options’ (NCP18) and ‘Conserve 30% of land, waters and seas’ (Target 3; Table 3).

In contrast, several NCP–target and NCP–goal combinations exhibited consistently weak linkages. These included ‘Pollination and dispersal of seeds’ (NCP2) and ‘Reduce the Introduction of invasive alien species by 50% and minimize their impact’ (Target 6); ‘Regulation of air quality’ (NCP3) and both ‘Restore 30% of all degraded ecosystems’ (Target 2) and ‘Reduce pollution to levels that are not harmful to biodiversity’ (Target 7), as well as ‘Enhance green spaces and urban planning for human well-being and biodiversity’ (Target 12; Table 3).

Weak associations were also observed between ‘Regulation of freshwater quantity, location and timing’ (NCP6) and ‘Biodiversity and NCPs are sustainably used and managed’ (Goal B), as well as Target 2. Similarly weak linkages were identified between ‘Medicinal, biochemical, and genetic resources’ (NCP14) and both ‘The integrity, connectivity, genetic diversity and resilience of all ecosystems are maintained, enhanced, or restored’ (Goal A) and ‘Benefit sharing of genetic resources and traditional knowledge associated with genetic resources’ (Goal C), as well as Target 6 (Table 3). Finally, ‘Physical and psychological experiences’ (NCP16) and ‘Manage wild species sustainably to benefit people’ (Target 9), along with Supporting identities (NCP17) and both Goal B and Target 3, were weakly linked across all four analytical aspects (Table 3; Table S7).

5 Discussion

Our goal was to map available NCP data sources and online data systems and categorise these according to the kinds of NCP data they deliver. This has also facilitated an analysis of gaps in the available NCP data landscape, and the degree to which available data meets best practice standards. One of our main conclusions is that although there are significant

sources of relevant data, much more would need to be done to achieve full coverage of data at national to global scales for all categories of NCP. By mapping available data sources and data systems we are also better able to understand the challenges faced by countries reporting on progress towards Target 11 of the KMGBF which focuses on restoring, maintaining and enhancing NCPs, as captured in our crosswalk (CBD, 2026). Across all the KMGBF indicators there seems to be limited availability of operational measures related to NCPs. It remains to be seen how governments will report against Target 11 in their 7th national reports and the synthesis that will be delivered by CBD COP17 as the "global report of collective progress" (CBD, 2025). To support countries with this task we have made publicly available the database of resources we gathered for this analysis.

5.1 What are the main gaps and how can we close them?

Our findings show an uneven distribution of information across the 18 NCP classes, characterized by both frequency and confidence gaps. In terms of frequency, resources are skewed toward non-material and regulating services, with NCP15 (Learning and inspiration) and NCP18 (Maintenance of options) being the most documented, while other categories such as NCP11 (Energy) and NCP5 (Regulation of ocean acidification) remain under-represented. This uneven information landscape has important implications for decision-making and the implementation of the KMGBF. While learning and inspiration are comparatively well represented, several regulating and material NCPs that are central to hazard and climate risk management, as well as sustainable production, exhibit pronounced coverage gaps, specifically NCPs 2, 3, 5, 9, 10, 11, 14, and 17.

The confidence gaps further highlight a qualitative disparity in the evidence base. While certain functional categories like EAMP demonstrate high confidence through primary observation, others, particularly BIFT, rely more on inference (Avtar et al., 2020; Biber, 2013; Sparrow et al., 2020). This results in data-poor scenarios or gaps in spatial and temporal coverage for services like pollination (NCP2) and water quality (NCP7), where the reliance on indirect data leads to lower reliability in global monitoring efforts (Kremen et al., 2011; Sprague et al., 2017). Most current resources are categorized as FDI, with far fewer policy/planning mechanisms or business tools available (Grêt-Regamey et al., 2017; Havas et al., 2014). Consequently, even when data exists within FDI or EAMP systems, it is often not translated into the specific formats, tools, and indicators required by decision-makers (Bitoun et al., 2022). Furthermore, weak alignment with KMGBF Goal C and Targets 13, 20, and 23 indicates that access, benefit-sharing, and the distributional dimensions of NCPs are poorly operationalized in existing datasets (Ruan et al., 2024; von Wettberg & Khoury, 2022).

Closing these identified gaps requires a shift from passive data collection to active, cross-sectoral integration. While foundational data is growing, its application for actionable policy, specifically regarding "Options" and "Drivers", remains a significant bottleneck. Addressing this requires an increased strategic focus on infrastructure, sector-specific engagement, and the democratization of the evidence base (Edens et al., 2022; Schmeller et al., 2017; Sterner & Elliott, 2024).

First, the "findability" and technical maturity of existing resources must be modernized. High gap scores in Monitoring Infrastructure (MI) and FAIR principles,

particularly regarding persistent identifiers and remote sensing integration, suggest that much existing knowledge remains invisible for global indicators (Bumberger et al., 2025; Sterner & Elliott, 2024). Data coordinators should prioritize standardized metadata protocols and unique identifiers (Crystal-Ornelas et al., 2022). Integrating remote sensing applications into EAMP systems is essential to bridge the "confidence gap," providing the spatially explicit observations needed for under-reported services like pollination and water quality (Glassic et al., 2024; Gonzales et al., 2022; Yang et al., 2022).

Second, the low presence of BIFT across critical NCP categories presents an opportunity to close the "Drivers" gap. Business materiality tools like ENCORE and SBTN materiality screening sector tool rely on NCP data to help companies assess and manage their environmental dependencies. Because industry activities are primary drivers of biodiversity loss, the overall lack of available tools for NCPs related to energy and hazards could hinder the ability to assess risks or disclose impacts under KMGBF Target 15, with current strong links being limited to NCP 13 (Medicinal resources). Closing this requires the co-development of tools, that translate complex ecological data into industry-standard metrics, ensuring non-material and regulating NCPs are weighted equally alongside material commodities in corporate reporting (Brander et al., 2024; Grunewald et al., 2024a; Liu et al., 2025). For instance, The System of Environmental-Economic Accounting (SEEA) is an initiative for countries to place the environment on equal footing with other aspects of the economy.

Finally, the low scores in "Options" and "Drivers" linkages suggest that current resources provide the "what" (trends) but not necessarily the "how" (policy solutions). To

address low cross-operability and weak linkages in restoration (Target 2) and pollution (Target 7), the resource base must become an open, living ecosystem. By utilizing interactive tools like the NCP Resource Explorer, users can identify gaps in real-time. This modular approach encourages the submission of locally produced resources, ensuring the crosswalk evolves to reflect the diverse ways human well-being is linked to biodiversity while addressing the limitations of the current database (Brondízio et al., 2021; Tallis et al., 2012). Addressing these critical gaps is essential to enable NCP evidence to effectively support global policy and finance decisions.

5.2 Limitations and the use of an open resource base and UI

Despite its systematic approach, this assessment has several limitations that reflect both data availability and the broader context of NCP knowledge production. The review process tends to primarily capture resources that are visible at regional to global scales and accessible through established publication and reporting channels, while smaller, locally produced, or practice-based resources, often highly relevant for NCP assessment and monitoring for local end-users, are likely underrepresented, even when using the snowball approach (Cámara-Leret & Dennehy, 2019; Urbina-Cardona et al., 2023). This bias may disproportionately affect NCPs that are strongly place-based or context-specific, particularly those associated with Indigenous and local knowledge systems. Non-material NCPs were found to be the most common, NCP 15 (learning and inspiration). Non-material NCPs are often lacking in standardized indicators and monitoring data (Huynh et al., 2022; McElwee, 2021), with available data often qualitative, which may be challenging to detect trends. While we tried to address this through different iterations of the analysis, as well

as additional human controls, a high presence of this NCP persisted in the results. This might reflect issues with the definition for non-material NCPs, in particular NCP 15.

Furthermore, the compiled dataset contains more informational value than could be fully captured by our analyses. For example, Target 11 of the KMGBF aims to restore, maintain, and enhance NCPs. Given that our assessment focused explicitly on NCP-related resources, one might expect a strong linkage between these resources and Target 11. However, Target 11 does not appear in the crosswalk table. This is because our analysis identifies only statistically significant links between specific NCP classes and individual Targets or Goals. Target 11 is broadly relevant across all NCP classes and therefore does not emerge as a distinct or significant association with any single NCP category. This example illustrates how methodological choices influence the interpretation of linkages and highlights the need to consider such nuances when evaluating the full informational value of the resource base.

Language coverage remains imperfect, as resources in languages outside the official IPBES languages were not systematically captured, which constrains the representation of NCP-related knowledge across regions. Beyond coverage, linguistic, societal and cultural differences also affect interpretation, as key NCP concepts, especially relational values and culturally embedded contributions, cannot always be translated across contexts or languages without loss of meaning or nuance (Amano et al., 2023; Peter et al., 2022). This challenge is particularly relevant for NCPs linked to identity and social relations, where meaning is often conveyed through culturally specific terms

and narratives. Addressing these limitations requires targeted capacity-building efforts to support multilingual participation and contextual interpretation (Ziervogel et al., 2022).

To address these limitations, the offered resource database aims to be extensible and open source, allowing users to submit additional resources that can be integrated through standardized categories and assessment scores, thereby supporting the development of a living database that improves over time. An open, community-driven approach that enables resource submissions in diverse languages and contexts is therefore essential to ensure more equitable representation and to strengthen resource relevance and usability for end-users as seen in other platforms and data systems (Bumberger et al., 2025; Ladouceur et al., 2022). Central to this approach is the integration of a dedicated User Interface (UI; NCP_resource_explorer.html; NCP_resource_explorer_guide.pdf) and interactive network tools. By utilizing the netCoin package, the resource base provides interactive HTML-based network visualizations that provide a User Interface (UI) accessible to any user (Escobar & Martinez-Uribe, 2020). This platform moves beyond static data by employing tags to allow for targeted searches, highlighting featured resources, and offering an interactive way to explore the network. Crucially, this interface hosts the NCP to KMGBF crosswalk matrix, allowing users to gain a comprehensive overview of individual resources and visualize the significant links to KMGBF targets. By providing the resources in a more intuitive and interactive manner with a searchable UI, the resource base can become a modular tool that facilitates a more transparent and user-friendly exploration of the evidence base for NCPs.

5.3 Sustainable development goals and future assessments

While the primary focus of this mapping exercise is the link between NCPs and the KMGBF, the results could also carry weight for other international policy processes, most notably SDGs. Established in 2015 and set to conclude in 2030, SDGs rely on a global indicator framework developed by the Inter-agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDGs (IAEG-SDGs, 2026; SDG Fund, 2015; UN, 2023)). Previous research has demonstrated that ESs underpin nearly all 17 SDGs, providing the essential biological foundation for human health, poverty alleviation, and climate resilience (Wood et al., 2018). As NCPs represent the conceptual expansion of the ES approach, incorporating a broader range of cultural perspectives and negative contributions, the data resources identified in this study could be used to support tracking global development (Díaz et al., 2018).

Recent progress reports indicate that while some gains have been made, many SDGs have seen a stagnation or even a reversal of progress. These challenges are exacerbated by declining international development support and the fact that nature-based indicators are frequently treated as secondary to economic metrics (Dickens et al., 2020; Grunewald et al., 2024b; IAEG-SDGs, 2026; Shinwell & Cohen, 2020). However, leveraging advanced monitoring technologies and Earth Observation data is critical for bridging the gap between ecological health and the achievement of societal targets (Cochran et al., 2020). By providing a clear overview of available data, our work simplifies the process of developing robust measurement systems that link human well-being directly to the state of nature. As the international community begins to draft the post-2030

sustainable development agenda, the evidence base presented here ensures that the next generation of global goals can be built upon a measurable foundation of nature's benefits. By identifying current data gaps and providing a modular database of resources, this paper supports the integration of the complex, multifaceted value of biodiversity into global decision-making and finance.

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Data availability

All data used in the analysis are accessible through the supplemental material under stable doi: https://doi.org/10.6084/m9.figshare.31032079. We furthermore invite readers to explore the dataset further through the provided UI (NCP_resource_explorer.html; NCP_data.xlsx) following the tutorial in the supplemental material.

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Figure captions

Figure 1. Ecosystem Service (ES) to Nature's Contributions to People (NCP) flow and reasons for the conceptual switch in classification. Conceptual diagram illustrating the ecosystem services provided by the oceans and the ways humans depend on oceans. (Díaz et al., 2018; IPBES, 2026). Symbols and graphics edited and/ or created with

Inkscape. Base symbols freely available through uxwing.com. Image attribution: Caroline Donovan, Integration and Application Network (ian.umces.edu/media-library).

Figure 2. Flowchart outlining the main analytical steps and data outputs from synthesizing and reviewing resource pertaining to Nature's Contributions to People (NCP). More details can be found under Supplements_S1 and NCP_DMR. Base symbols freely available through uxwing.com. Image attribution: Tracey Saxby, Integration and Application Network (ian.umces.edu/media-library).

Figure 3. Coincidence network for Nature's contributions to people across online monitoring and data resources (n = 251). Linkages of co-occurrence between NCPs as well as potential cross-operability with the Kunming-Montreal Global Biodiversity Framework (KMGBF) goals and targets. Connections based on Haberman z, inclusion criteria $p(z)<0.05$. Node size reflects incidence frequency. Node color reflects degree (connections to other nodes). Symbols and graphics edited and/ or created with Inkscape and netCoin (Escobar & Martinez-Uribe, 2020). Base symbols freely available through uxwing.com.

Figure 4. Coverage and confidence gaps for Nature's contributions to people (NCPs) across online resources (n = 251). (a) *Coverage Gap*, which compares each NCP's observed coverage within the four functional resource categories (EAMP; FDI; PPFM; BIFT). This metric identifies NCP coverage within functional categories. (b) *Confidence Gap* measures whether observed coverage within functional resource categories is based on strong, direct evidence (confidence score = 3) or weaker, inferential links (score = 1), highlighting where monitoring data potentially relies on uncertain or indirect information.

Figure 5. Maturity and FAIR gaps for Nature's contributions to people (NCPs) across online resources (n = 251). (a) Maturity gaps were assessed across four pillars: Data Availability & Quality (DAQ), Monitoring Infrastructure (MI), Analytical Capacity (ACI), and Governance & Human Capacity (GHC), along with their subcategories (e.g., DAQ1, DAQ2). For each NCP, pillar scores were averaged across relevant resources and inverted to derive *Maturity Gaps*, pinpointing either resource characteristics or potential bottlenecks in resource quality and system readiness. (b) FAIR gaps were computed for the four FAIR pillars (Findable, Accessible, Interoperable, Reusable) and their subcomponents (e.g., F1, F2). Each gap represents the inverted percentage of covering resources that meet the pillar's criteria, indicating potential usability limitations.

Tables and table captions

Table 1. Overview of main criteria to assess and evaluate synthesized online resources on Nature's Contributions to People (NCPs) in a standardized manner. Criteria cover the official 18 NCP categories, with confidence scores from 0 to 3; Kunming-Montreal Global Biodiversity Framework (KMGBF) connections based on official goals and targets as well as resource maturity level and adherence to the FAIR principles (Supplements_S1; NCP_DMR).

Assessment framework part & objective	**Scoring system**	**Variables assessed & base definitions**
Nature's Contributions to People (NCP): Assess ecological relevance for monitoring ecosystem services.	4-point scale (0-3); confidence	**Natures' contribution to people (n = 18):** NCP 1: Habitat creation and maintenance NCP 2: Pollination and dispersal of seeds NCP 3: Regulation of air quality NCP 4: Regulation of climate NCP 5: Regulation of ocean acidification NCP 6: Regulation of freshwater quantity, location and timing NCP 7: Regulation of freshwater and coastal water quality NCP 8: Formation, protection and decontamination of soils and sediments NCP 9: Regulation of hazards and extreme events NCP 10: Regulation of detrimental organisms and biological processes NCP 11: Energy NCP 12: Food and feed

		NCP 13: Materials, companionship and labor NCP 14: Medicinal, biochemical, and genetic resources NCP 15: Learning and inspiration NCP 16: Physical and psychological experiences NCP 17: Supporting identities NCP 18: Maintenance of options
Kunming-Montreal Global Biodiversity Framework (KMGBF): Assess policy alignment and utility for global reporting.	Binary (0/1 or No/Yes)	**KMGBF headline indicators** assessed (n = 53): "Does the resource provide data or material to help monitor any of the KMGBF goals and/or targets?" **Goals** (n = 4): high level visions for 2050 Indicators: n = 12 "Answering the WHY" **Targets** (n = 23): action-oriented steps for 2030 Indictors: n = 41 "Answering the HOW"
Data System Maturity: Evaluate operational readiness, quality, and robustness.	4-point scale (0-3)	**Maturity (readiness) criteria (n = 12):** **Data Availability and Quality (DAQ):** Spatial coverage; Temporal coverage and frequency; Data quality and uncertainty **Monitoring Infrastructure (MI):** In-situ networks; Remote sensing application; Data management system **Analytical Capacity for Indicators (ACI):** Methodological sophistication; Scientific publication record; Institutional mandate and expertise **Governance and Human Capacity (GHC):** Policy integration; Public accessibility and reporting; Funding stability
FAIR Principles: Audit technical stewardship and data management best practices.	Binary (No/Yes)	**FAIR sub-principles assessed (n = 15):** Findable (F1-F4): Data should be easy to find for both humans and computers through clear identifiers and searchable metadata. Accessible (A1; A1.1; A1.2; A2): Once found, data should be retrievable via standardized protocols, possibly with authentication or authorization when necessary. Interoperable (I1-I3): Data should use standardized formats, languages, and vocabularies so it can be integrated with other data and tools. Reusable (R1; R1.1-R1.3): Data should be well-described and licensed so others can understand, replicate, and build upon it in future research.

Table 2. Nature's Contributions to People (NCPs) to Kunming-Montreal Global Biodiversity Framework (KMGBF) crosswalk assessment criteria based on whether NCP resources provide monitoring information for a linked KMGBF target or goal (based on network analysis; $p < 0.05$ for links) regarding Context, Data & Trends, Drivers or Options (future).

NCP in Isolation	Crosswalk interpretation (NCP to Target link)	Definitions

"Do we understand what 'Food & Feed' is?"	"Do we have a conceptual framework that explains how changes in 'Food & Feed' impacts progress towards e.g. Target 2 (Restoration)?"	**Context:** Do the resources simply describe the relationship? (e.g., "Resource X discusses how pollination theoretically supports Target 2").
"Do we have global statistics on crop yields?"	"Do we have indicators that track how e.g. ecosystem restoration (T2) is specifically changing food security outcomes?"	**Data & trends:** Do the resources contain time-series, indicators, or monitoring data? (e.g., "Resource X measures changes in pollination services over 10 years").
"Do we know what causes crop failure?"	"Do we have evidence linking the specific drivers of biodiversity loss (e.g., land use change) to the failure of this Target?"	**Drivers:** Do the resources analyze causality? (e.g., "Resource X uses regression to show how fertilizer use caused the decline").
"Do we know how farm practices shape NCP?"	"Do we have valid policy options where monitoring this NCP contributes directly to actions designed to meet the Target?"	**Options:** Do the monitoring resources exist to measure progress? (e.g., "Resource X evaluates a policy intervention").

Table 3. Crosswalk analysis of Nature's Contributions to People (NCP) and the Kunming-Montreal Global Biodiversity Framework (KMGBF) Goals and Targets. The table illustrates the connections between specific NCP resources and KMGBF targets and goals, categorized by four assessment dimensions: Context, Data & Trends, Drivers, and Options (future). Performance within these dimensions is indicated by color-coded markers representing High (green), Medium (yellow), and Weak (red) resource to KMGBF target or goal alignment. The linkage column quantifies the significance of the initial association within the network (Figure 3; Table S2).

NCP	KMGBF Link	Context	Data & trends	Drivers	Options	NCP to KMGBF linkage
NCP1	Goal A	🟡	🟢	🟡	🔴	6.52
	Target 2	🟡	🟢	🟡	🟡	2.23
	Target 3	🟡	🟢	🟡	🟡	3.89
	Target 21	🟡	🟡	🔴	🟡	2.08
NCP2	Goal B	🟡	🔴	🟡	🟡	3.41
	Target 6	🔴	🟡	🔴	🔴	2.51
NCP3	Target 2	🔴	🔴	🔴	🔴	2.05
	Target 7	🔴	🔴	🔴	🔴	4.61
	Target 12	🔴	🔴	🔴	🔴	4.48
NCP4	Goal B	🟢	🟢	🟡	🟡	1.71
	Goal D	🟡	🟡	🔴	🟡	1.82
	Target 2	🟢	🟡	🟡	🟡	3.53
	Target 7	🟡	🟢	🟡	🔴	2.46
	Target 8	🟡	🟢	🟡	🔴	3.19
	Target 12	🟢	🟡	🟡	🟡	1.81
	Target 18	🟢	🟢	🟡	🟡	2.12
NCP5	Target 7	🟡	🟢	🔴	🔴	4.26
	Target 8	🟡	🟢	🔴	🔴	2.44
NCP6	Goal B	🔴	🟡	🔴	🔴	3.19

	Target 2	🔴	🟡	🔴	🔴	3.08
	Target 7	🟡	🟢	🟡	🔴	2.51
	Target 8	🟡	🟢	🟢	🟡	2.08
	Target 12	🟢	🟢	🟡	🟡	2.30
NCP7	Goal B	🟡	🟡	🔴	🟡	3.55
	Target 7	🟡	🟡	🔴	🟡	5.00
NCP8	Target 2	🟡	🟡	🔴	🔴	3.77
	Target 7	🟡	🟡	🟡	🔴	2.89
NCP9	Target 2	🟢	🟢	🟡	🔴	3.10
	Target 8	🟡	🟡	🔴	🔴	4.35
	Target 12	🟡	🟡	🔴	🔴	1.82
NCP10	Target 6	🟡	🟢	🔴	🟡	3.69
NCP11	Goal D	🟡	🟢	🔴	🔴	2.86
NCP12	Target 5	🟡	🟡	🔴	🔴	2.19
	Target 10	🟢	🟡	🟡	🟡	4.86
NCP13	Goal D	🟢	🟢	🟡	🟢	2.16
	Target 5	🔴	🟢	🔴	🔴	1.85
	Target 10	🟡	🟢	🔴	🟡	1.74
	Target 15	🟢	🟢	🟢	🟢	1.68
	Target 18	🔴	🟢	🟡	🔴	3.32
NCP14	Goal A	🔴	🟡	🔴	🔴	5.91
	Goal C	🔴	🔴	🔴	🔴	3.25
	Target 6	🔴	🟡	🔴	🔴	4.81
NCP15	Goal A	🟡	🟡	🔴	🔴	1.98
NCP16	Goal B	🟡	🟡	🟡	🟡	3.48
	Target 9	🔴	🔴	🔴	🔴	3.34
NCP17	Goal B	🟡	🔴	🔴	🔴	1.78
	Target 3	🟡	🔴	🔴	🔴	1.93
	Target 22	🟡	🟡	🟡	🟡	2.81
NCP18	Goal A	🟡	🟢	🟡	🟡	5.94
	Target 2	🟡	🟢	🟡	🟡	1.83
	Target 3	🟢	🟢	🟡	🟢	2.25
	Target 6	🟡	🟢	🔴	🟡	2.92
	Target 10	🟡	🟢	🟡	🟡	1.82
	Target 21	🟢	🟡	🟡	🟡	2.34

Figure 1.

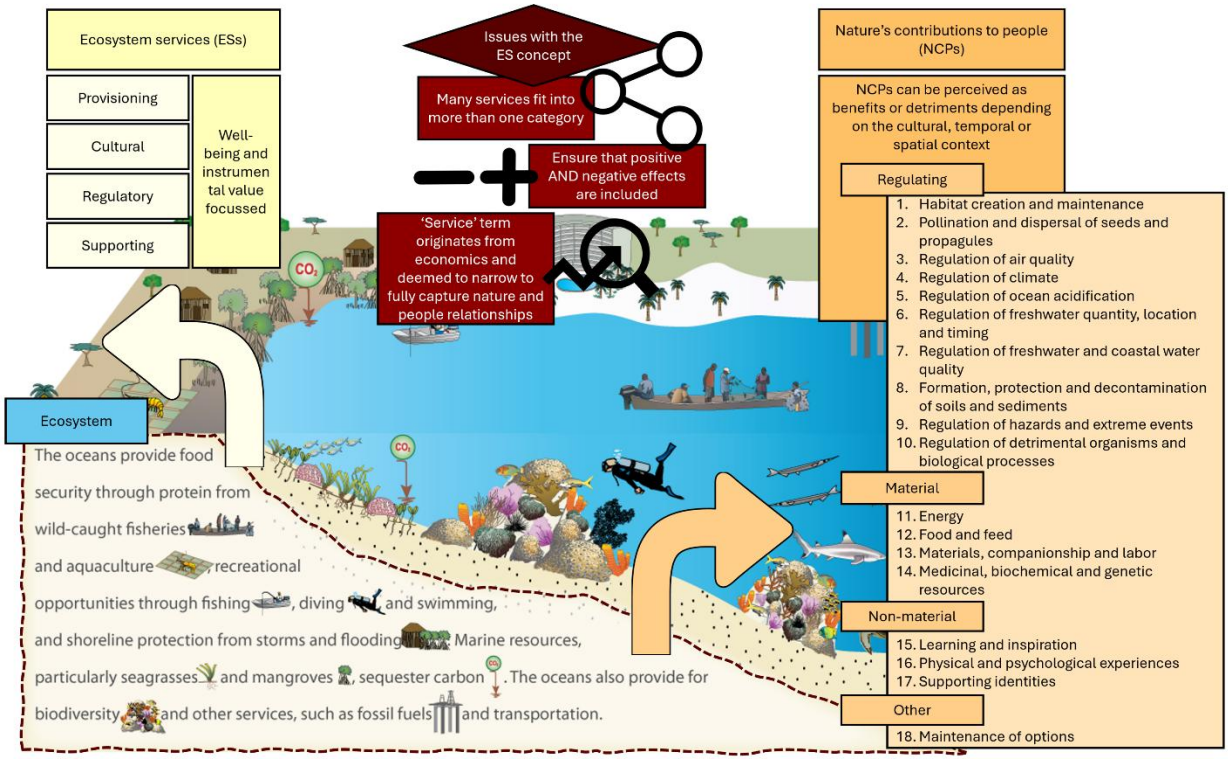

Ecosystem services (ESs)
Provisioning
Cultural
Regulatory
Supporting
Well-being and instrumental value focussed
Issues with the ES concept
Many services fit into more than one category
Ensure that positive AND negative effects are included
'Service' term originates from economics and deemed to narrow to fully capture nature and people relationships
Nature's contributions to people (NCPs)
NCPs can be perceived as benefits or detriments depending on the cultural, temporal or spatial context
Regulating
1. Habitat creation and maintenance
2. Pollination and dispersal of seeds and propagules
3. Regulation of air quality
4. Regulation of climate
5. Regulation of ocean acidification
6. Regulation of freshwater quantity, location and timing
7. Regulation of freshwater and coastal water quality
8. Formation, protection and decontamination of soils and sediments
9. Regulation of hazards and extreme events
10. Regulation of detrimental organisms and biological processes
Material
11. Energy
12. Food and feed
13. Materials, companionship and labor
14. Medicinal, biochemical and genetic resources
Non-material
15. Learning and inspiration
16. Physical and psychological experiences
17. Supporting identities
Other
18. Maintenance of options
Ecosystem
The oceans provide food security through protein from wild-caught fisheries and aquaculture, recreational opportunities through fishing, diving and swimming, and shoreline protection from storms and flooding. Marine resources, particularly seagrasses and mangroves, sequester carbon. The oceans also provide for biodiversity and other services, such as fossil fuels and transportation.

Figure 2.

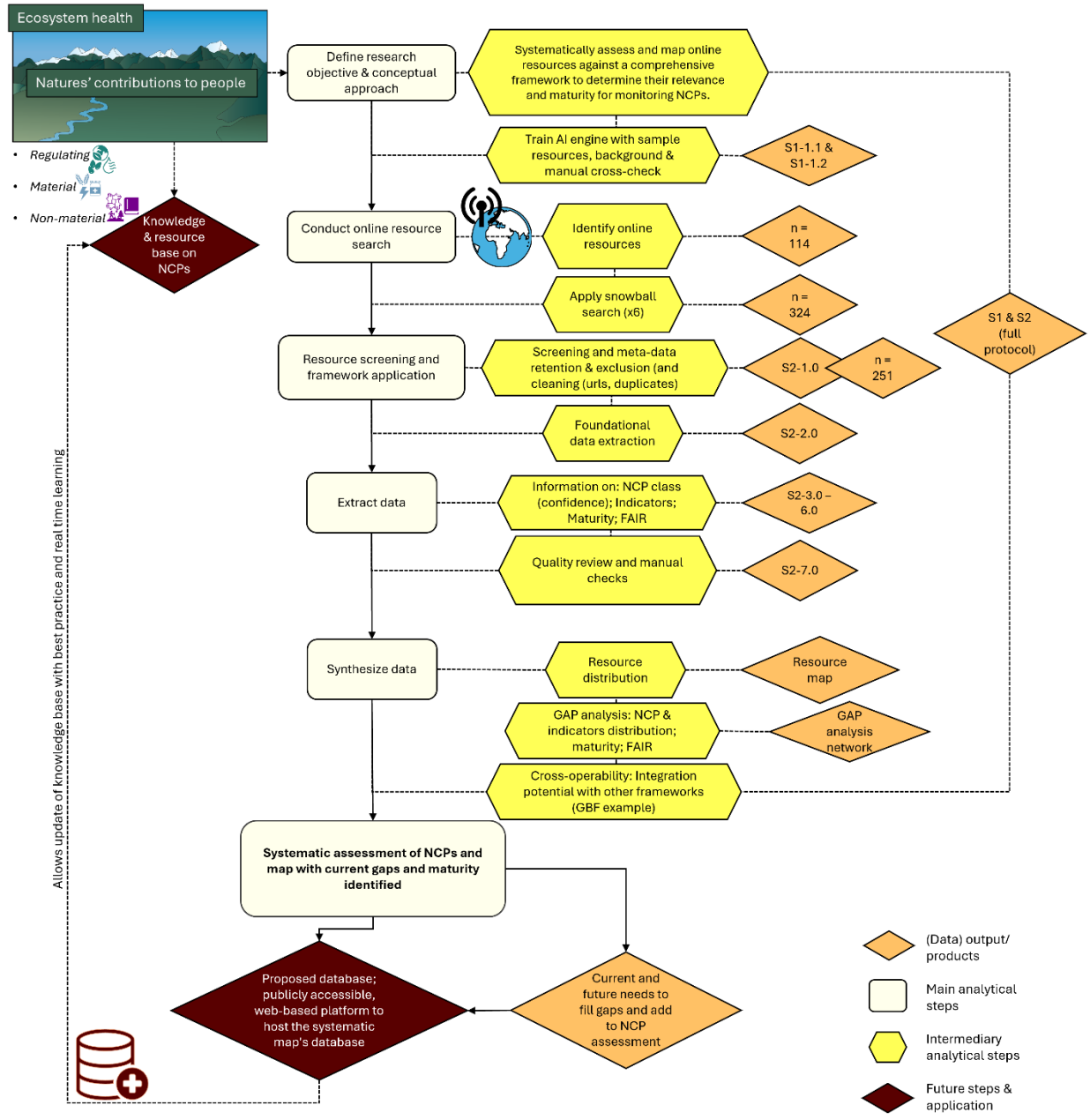

Ecosystem health
Natures' contributions to people
Regulating
Material
Non-material
Knowledge & resource base on NCPs
Define research objective & conceptual approach
Systematically assess and map online resources against a comprehensive framework to determine their relevance and maturity for monitoring NCPs.
Train AI engine with sample resources, background & manual cross-check
S1-1.1 & S1-1.2
Conduct online resource search
Identify online resources
n = 114
Apply snowball search (x6)
n = 324
S1 & S2 (full protocol)
Resource screening and framework application
Screening and meta-data retention & exclusion (and cleaning (urls, duplicates)
S2-1.0
n = 251
Foundational data extraction
S2-2.0
Extract data
Information on: NCP class (confidence); Indicators; Maturity; FAIR
S2-3.0 – 6.0
Quality review and manual checks
S2-7.0
Synthesize data
Resource distribution
Resource map
GAP analysis: NCP & indicators distribution; maturity; FAIR
GAP analysis network
Cross-operability: Integration potential with other frameworks (GBF example)
Systematic assessment of NCPs and map with current gaps and maturity identified
Proposed database; publicly accessible, web-based platform to host the systematic map's database
Current and future needs to fill gaps and add to NCP assessment
Allows update of knowledge base with best practice and real time learning
(Data) output/ products
Main analytical steps
Intermediary analytical steps
Future steps & application

Figure 3.

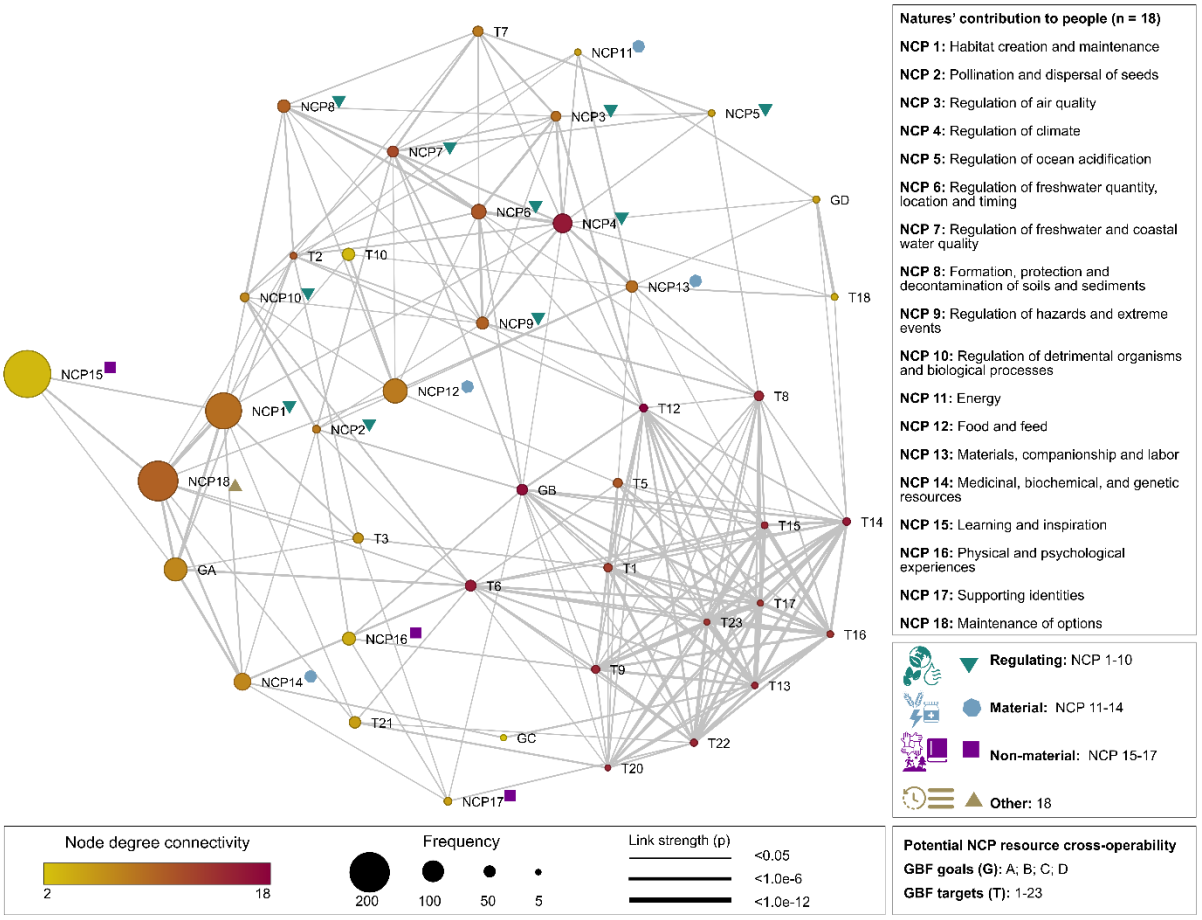
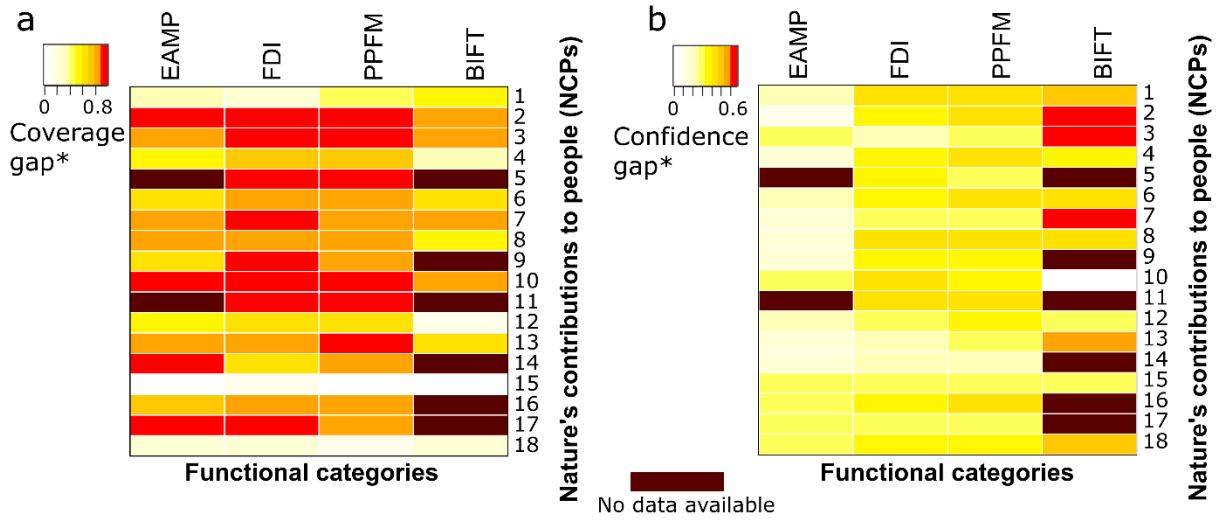

T7
NCP11
NCP8
NCP3
NCP5
NCP7
GD
NCP6
NCP4
T2
T10
NCP13
T18
NCP10
NCP9
NCP15
NCP12
T8
NCP1
T12
NCP2
NCP18
GB
T5
T14
T15
T3
GA
T1
T6
T17
T23
T16
NCP16
T9
NCP14
T13
T21
GC
T22
T20
NCP17
Node degree connectivity
2
18
Frequency
200
100
50
5
Link strength (p)
<0.05
<1.0e-6
<1.0e-12
Natures' contribution to people (n = 18)
NCP 1: Habitat creation and maintenance
NCP 2: Pollination and dispersal of seeds
NCP 3: Regulation of air quality
NCP 4: Regulation of climate
NCP 5: Regulation of ocean acidification
NCP 6: Regulation of freshwater quantity, location and timing
NCP 7: Regulation of freshwater and coastal water quality
NCP 8: Formation, protection and decontamination of soils and sediments
NCP 9: Regulation of hazards and extreme events
NCP 10: Regulation of detrimental organisms and biological processes
NCP 11: Energy
NCP 12: Food and feed
NCP 13: Materials, companionship and labor
NCP 14: Medicinal, biochemical, and genetic resources
NCP 15: Learning and inspiration
NCP 16: Physical and psychological experiences
NCP 17: Supporting identities
NCP 18: Maintenance of options
Regulating: NCP 1-10
Material: NCP 11-14
Non-material: NCP 15-17
Other: 18
Potential NCP resource cross-operability
GBF goals (G): A; B; C; D
GBF targets (T): 1-23

Figure 4.



FDI - Foundational Data Infrastructure: Primary function is the collection, curation, and provision of raw or aggregated data (e.g., species occurrence records, Earth observation imagery).

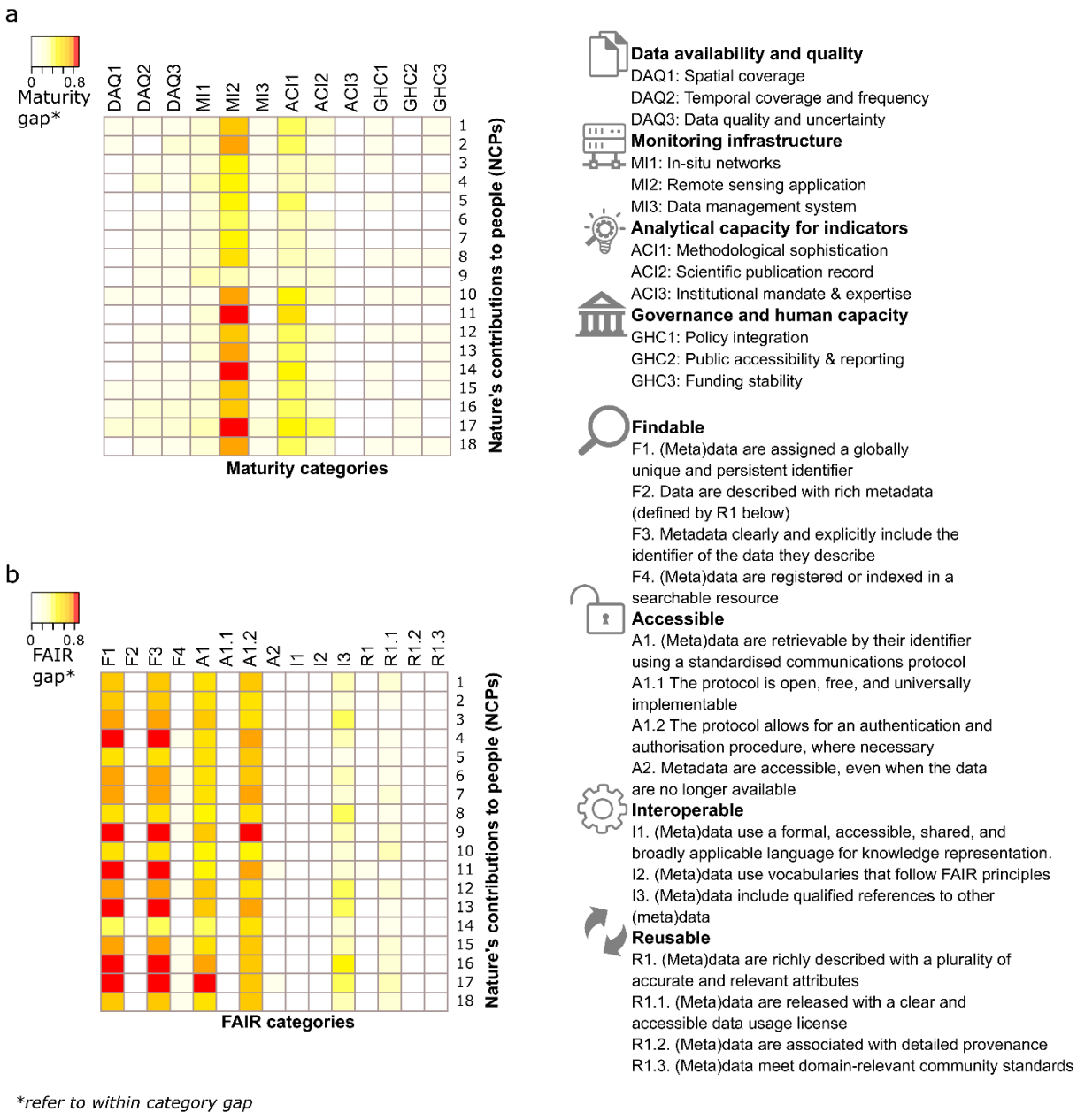
EAMP - Ecosystem Assessment and Modeling Platforms: Primary function is to use data to model ecological processes, analyze trends, or project scenarios.

PPFM - Policy, Planning, and Finance Mechanisms: Primary function is to support decision-making by translating scientific information into policy-relevant indicators or legal/management information.

BIFT - Business and Industry-Focused Tools: Primary function is to provide data or risk assessment tools tailored for the private sector (e.g., for Environmental, Social, and Governance reporting).

**refer to within functional category gap*

Figure 5.



**refer to within category gap*

Supplements_S1: Systematic protocol for the AI-assisted review and assessment of online resources for monitoring Nature's Contributions to People (NCPs) – summary

1.0 Protocol

This protocol is a summary version of the full review protocol which can be found under Supplements_S3.

1.1 A Systematic review for auditable evidence synthesis

This document outlines a standardized, sequential, and reproducible methodology for the evaluation of online data systems, tools, and platforms. The protocol is explicitly designed as an instrument for conducting a formal systematic review of these online assets. This methodological framing is deliberate, anchoring the protocol within the recognized scientific approach for evidence synthesis, that adheres to strict standards of planning, conducting, and reporting. The primary objective is to systematically collect, review, and assess a pre-defined list of online resources to determine their relevance and maturity the monitoring of Nature's Contributions to People (NCPs). By adopting the rigorous, explicit methods of a systematic review, the protocol is designed to minimize the bias inherent in traditional literature reviews, eliminate ambiguity in scoring, and reduce inter-evaluator variability while providing GeminiAI with clear sequential tasks. The goal of this methodology is to produce a final dataset that is auditable, transparent, reproducible, and defensible. The scientific rigor embedded in the protocol ensures the resulting data is of sufficient quality to support global-scale environmental assessments, such as those conducted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

1.2 The three guiding principles

The scientific defensibility of this protocol is derived not only from its structured workflow but from a foundational assessment philosophy that governs all data extraction, scoring, and analysis when using AI. This philosophy is operationalized as three mandatory Guiding Principles, which are summarized in Table 1. These principles are not arbitrary rules but are applications of established standards from professional auditing and environmental reviews. They are designed to support the reviewer, in this case GeminiAI, to prioritize verifiable facts over speculation and to withstand scientific scrutiny by pre-emptively addressing common pitfalls in resource evaluation, such as the overestimation of capabilities.

Principle I: The primacy of explicit evidence

This principle mandates that all scores, classifications, and justifications must be based on explicit, verifiable evidence found directly within the public-facing documentation of the data system under review. This reframes the assessment process as a formal audit and the evaluator's role as that of an auditor. As in professional auditing, all conclusions must be supported by objective, verifiable evidence. In practice, this principle requires the evaluator or AI to create a "clear and complete audit trail" for every decision. This is achieved by copying verbatim text snippets from the resource and recording their specific source URLs in the data extraction template. This practice ensures that every score can be traced back to its source, a fundamental requirement for verifiability. A critical implication is that aspirational statements about future functionality, goals, or missions are *not* considered evidence of current, implemented capabilities. Only documented, existing features are scored.

Principle II: The mandate for conservative inference

In any situation where the available information is ambiguous, incomplete, or subject to multiple interpretations, the evaluator or AI must assign the lower, more conservative score. This principle is a direct "operationalization of the Precautionary Principle". In the context of this assessment, it is meant to prevent the overestimation of a resource's capabilities or relevance. Such overestimation could lead to the inclusion of weak or indefensible data linkages in a global-scale assessment, thereby undermining its scientific credibility and leading to flawed policy decisions or reduced usability for a potential end user. This principle is operationalized by making '0' (None) the default score for all criteria, particularly the NCPs. A score greater than zero is permissible only if a direct, defensible, and non-speculative analytical pathway can be clearly articulated and documented with evidence.

Principle III: Absence of evidence as a justified inference

For core data management and stewardship features, particularly those related to the FAIR Guiding Principles, a lack of explicit information must be interpreted as evidence of absence. The score 'No' shall be assigned. Consequently, the absence of any mention of, for example, Digital Object Identifiers (DOIs) in a platform's documentation is not a neutral observation; it is strong evidence that the platform has not implemented a persistent identifier system. This principle prevents the creation of an ambiguous record filled with "Not Found" entries and places the burden of proof on the resource provider to document their capabilities.

Table 1: The three guiding principles of the assessment protocol.

Principle	Summary	Practical application
I. Primacy of explicit evidence	All scores must be based on verifiable, public-facing documentation found *within* the resource.	Create a mandatory "audit trail" with verbatim text snippets and source URLs for every score/ meta-data retention.
II. Mandate for conservative inference	In cases of ambiguity, the lower, more conservative score must be assigned to avoid overestimation.	The default score for all criteria is '0' (None). A positive score requires a high standard of evidence.
III. Absence of evidence as evidence of absence	For core technical features, a lack of documentation is interpreted as evidence of absence.	Assign 'No' (not "Not Found") if documentation for a key technical feature (e.g., a data license) is missing.

2.0 The sequential assessment workflow

The protocol is executed as a sequential, seven-step workflow. Each individual resource assigned from the master list is processed through this workflow, and each step must be completed in order before proceeding to the next. This structured, step-by-step process ensures consistency and comparability across all evaluations and provides the procedural mechanism for enforcing the three Guiding Principles.

The seven steps of the evaluation process are:

1. **Step 1.0: Initial resource screening and functional categorization:** A rapid initial assessment to confirm the resource is active, in-scope, and to assign it to one of four pre-defined functional categories.
2. **Step 2.0: Foundational data extraction:** Recording of basic metadata (e.g., resource name, URL) and initiation of the formal, ongoing "audit trail" required by Principle I.

3. **Step 3.0: Nature's Contributions to People (NCP) scoring:** A systematic, criteria-based evaluation against the 18 distinct NCPs using a 0-3 scoring rubric to assess scientific relevance.
4. **Step 4.0: Global Biodiversity Framework (KMGBF) Indicator scoring:** A binary (Yes/No) assessment against all headline indicators (goals and targets) from the Kunming-Montreal Global Biodiversity Framework to determine direct policy relevance.
5. **Step 5.0: Data system maturity assessment:** A 12-criteria evaluation of the resource's operational readiness and robustness, organized into four pillars and scored from 0-3.
6. **Step 6.0: FAIR principles assessment:** A detailed, criteria-based audit of the resource's alignment with the FAIR (Findable, Accessible, Interoperable, Reusable) Guiding Principles using a binary (Yes/No) checklist.
7. **Step 7.0: Final quality review:** A mandatory evaluator-led self-audit to ensure all fields are complete, all justifications are provided, and the Guiding Principles were applied consistently before finalizing the record.

3.0 Core evaluation frameworks and scoring protocols

This section provides the detailed methodology for the core assessment steps (Steps 1, 3, 4, 5, and 6) and the data extraction protocols (Steps 2 and 7) that support them.

3.1 Step 1.0: Resource screening and categorization

The initial step determines whether a resource is active and within the project's scope.

Search and Discovery: The master list of resources was compiled by GeminiAi using a systematic process. This included searches conducted across all six official languages of IPBES (Arabic, Chinese, English, French, Russian, and Spanish) to mitigate language bias. This initial list was expanded using a structured "snowballing" or "chain referral" technique, a best practice in systematic reviews, which involves reviewing the partner lists and "related links" sections of known resources to discover others (backward snowballing) and identifying newer resources that link to the initial set (forward snowballing). This iterative process improves the yield of relevant, specialized resources. It is acknowledged that this method may still exclude valuable resources documented exclusively in languages other than the six official ones.

Screening: The evaluator navigates to the provided URL and records an access timestamp and the final URL status (e.g., "OK," "Redirected," "404 Not Found," "Error/Timeout"). If a URL is dead or inaccessible, the assessment for that resource terminates.

Functional Categorization: For active sites, the evaluator conducts a brief high-level review of "About," "Mission," "Data," and "Tools" sections to assign the resource to a single, best-fit functional category. This four-category framework, conceptually aligned with established classifications of decision support systems, is as follows:

1. **Foundational Data Infrastructure:** Primary function is the collection, curation, and provision of raw or aggregated data (e.g., species occurrence records, Earth observation imagery).
2. **Ecosystem Assessment and Modeling Platforms:** Primary function is to use data to model ecological processes, analyze trends, or project scenarios.
3. **Policy, Planning, and Finance Mechanisms:** Primary function is to support decision-making by translating scientific information into policy-relevant indicators or legal/management information.
4. **Business and Industry-Focused Tools:** Primary function is to provide data or risk assessment tools tailored for the private sector (e.g., for Environmental, Social, and Governance reporting).

Resources that do not plausibly fit any category (e.g., static PDF reports, news blogs, university department homepages) are formally excluded with a justification.

3.2 Step 2.0: Foundational data extraction

This step is mandatory for all resources that pass screening.

The evaluator records the basic identifying metadata: the resource's official name, the final resolved URL, and the managing organization(s). Most importantly, this step formalizes the audit trail mandated by Principle I. The evaluator must, for the remainder of the assessment, locate and record direct, verifiable evidence for every score assigned. This involves copying the relevant text snippet *verbatim* into the 'Justification/Evidence' field and immediately recording the full source URL of the specific page from which the evidence was copied. A justification without this direct, sourced evidence is considered an unsubstantiated claim.

3.3 Step 3.0: Nature's Contributions to People (NCP) Scoring

This step systematically evaluates the resource's direct relevance to each of the 18 distinct NCPs.

Scoring Rubric: The evaluator proceeds sequentially from NCP 1 to NCP 18, assigning a score from 0 to 3 based on the detailed definitions in the rubric, which is summarized in

Table 2. This rubric is strictly governed by Principle II (Conservative Inference), where '0' is the default score.

Justification Mandate: For *every* NCP assigned a score of 1, 2, or 3, a two-part justification is mandatory:

- **(a) Rationale:** A structured explanation that explicitly links the evidence to the formal NCP definition. The evaluator must state the NCP and score, cite the specific phrase from the NCP definition being applied, and explain the logical link.
- **(b) Evidence:** The verbatim text snippet and source URL that serve as the direct proof for the score, as per the protocol in Step 2.0.

A score greater than zero without this detailed justification is invalid.

Table 2: Nature's Contributions to People (NCP) scoring rubric (0-3).

Score	Level	Evidence Requirement (Definition)
3	**High**	**Explicit Evidence:** The resource explicitly states that it provides data for monitoring the NCP or a direct, unambiguous synonym. It offers a dedicated data product, indicator, or model for this purpose. The evidence is direct and requires no inference.
2	**Moderate**	**Direct Foundational Data:** The resource does not explicitly name the NCP but provides direct, foundational data that is a *primary and necessary input* for monitoring that NCP. The link must be immediate (e.g., data on forest biomass is a '2' for NCP 11 - Energy).
1	**Low**	**Plausible Inference from a Widely Accepted Proxy:** The resource provides data that is a commonly accepted proxy in the scientific literature for monitoring an NCP. This score must be used with extreme caution per Principle II (Conservative Inference).
0	**None**	**No Defensible Evidence:** No clear or defensible link can be made, or any potential link is purely speculative. This is

		the default score. (e.g., a species occurrence database is '0' for NCP 16 - Physical/psychological experiences).

3.4 Step 4.0: Global Biodiversity Framework (KMGBF) indicator scoring

This step assesses the resource's direct relevance for global policy reporting.

Rationale: This assessment was integrated to provide immediate policy application by linking the protocol's outputs to the Kunming-Montreal Global Biodiversity Framework (KMGBF) Adopted in 2022, the KMGBF is the "preeminent global policy instrument" guiding efforts to halt and reverse biodiversity loss. By systematically searching for platforms relevant to KMGBF headline indicators, the protocol identifies resources that can directly support national governments in their implementation and reporting obligations, thus dramatically increasing the utility of the assessment's findings.

Indicator Selection: A systematic, "transparent, reproducible, and defensible" mapping of all KMGBF headline indicators (goals and targets) to the 18 NCPs was conducted (documented in Table 4.2.1 of the full DMR). This expert analysis, guided by Principle II, identified direct, component, or proxy relationships.

Scoring Protocol: The evaluator assesses the resource against each *retained* KMGBF headline indicator using a binary (Yes/No) score:

- **Score 1 (Yes):** The resource explicitly provides data, models, or analytical tools that *directly* map to the definition of the KMGBF headline indicator. The evidence must be direct.
- **Score 0 (No):** The resource does not provide defensibly linked data. This is the default score, applied in accordance with Principle III (Absence of Evidence).

A mandatory 'Justification/Evidence' field (verbatim snippet and URL) is required for every score of '1' (Yes).

3.5 Step 5.0: Data system maturity assessment

This step assesses the operational readiness, robustness, and maturity of the data system.

Rationale: The 12-criteria maturity framework provides a benchmark against which a resource's level of performance can be evaluated. To ensure external credibility, this framework is "conceptually aligned with established models from leading scientific and

technical organizations," such as NASA's formal, multi-stage Data Maturity Level framework for Earth observation data. Concepts from the NASA model, such as quantifying uncertainties and requiring peer-reviewed publication, are directly reflected in this protocol's criteria.

Framework: The evaluator assesses the resource against 12 criteria organized into four pillars (see Table 3). Each of the 12 criteria is assigned a score from 0 to 3 based on a detailed scoring rubric (provided in Appendix B.3 of the full protocol – Supplements_S3). The "Absence of Evidence" principle (Principle III) applies; if there is no information on a criterion, the lowest score ('0') is assigned. A brief, concise justification is required for each of the 12 scores. A critical caveat in applying this framework is "fitness-for-purpose." A lower score for a criterion like DAQ1 (Spatial coverage) does not necessarily imply lower quality or utility; it may simply reflect a focused operational scale. A local monitoring system designed for municipal planning is *fit-for-purpose* and may be of higher quality for that need than a global platform, even though it will receive a lower spatial coverage score.

Table 3: Data system maturity assessment framework (pillars and criteria).

Pillar	Criteria
I. Data Availability and Quality (DAQ)	DAQ1: Spatial coverage
	DAQ2: Temporal coverage and frequency
	DAQ3: Data quality and uncertainty
II. Monitoring Infrastructure (MI)	MI1: In-situ networks
	MI2: Remote sensing application
	MI3: Data management system
III. Analytical Capacity for Indicators (ACI)	ACI1: Methodological sophistication
	ACI2: Scientific publication record
	ACI3: Institutional mandate & expertise

IV. Governance and Human Capacity (GHC)	GHC1: Policy integration
	GHC2: Public accessibility & reporting
	GHC3: Funding stability

3.6 Step 6.0: FAIR principles assessment

This step conducts a criteria-based technical audit of the resource's alignment with the FAIR (Findable, Accessible, Interoperable, Reusable) Guiding Principles, the global standard for scientific data management and stewardship.

Scoring protocol: The evaluator assesses the resource against a detailed checklist of FAIR sub-principles (e.g., F1: Persistent Identifier, A1: Standardized protocol, R1.1: License) based on the foundational FAIR publication. Each sub-principle is assigned a binary score: 'Yes' or 'No'.

Link to Principle III: This assessment is the clearest application of Principle III (Absence of Evidence as Evidence of Absence). 'Yes' is assigned *only* if explicit, verifiable evidence of implementation is found (e.g., a "Terms of Use" page clearly states a Creative Commons license, justifying a 'Yes' for R1.1). 'No' is the default score and *must* be assigned if there is no evidence of implementation (e.g., a thorough search of data access pages yields no mention of DOIs, justifying a 'No' for F1). A mandatory justification is required for *every 'Yes' or 'No' score* to explain the basis for the decision, citing the presence or absence of specific information.

3.7 Step 7.0: Final quality review and completion

This final step is an internal quality control check to ensure the evaluator's own adherence to the protocol's rigorous standards before the assessment record for a resource is finalized.

Process: The evaluator (GeminiAI) must perform a self-audit using a formal checklist, confirming the following points:

- [ ] All required fields in the data extraction template are complete.
- [ ] The resource has been assigned a functional category or has been formally excluded with justification.
- [ ] Every NCP score of 1, 2, or 3 has corresponding 'Rationale' and 'Evidence' fields

completed.

- [ ] Every retained KMGBF Indicator has been assigned a score (0/1), and scores of 1 have a corresponding 'Justification/Evidence' field completed.
- [ ] All 12 data system maturity criteria have been assigned a score (0-3) and have a corresponding justification.
- [ ] All FAIR sub-principles have been assigned a binary score ('Yes' or 'No') and have a corresponding justification.
- [ ] The Guiding Principles (I, II, and III) have been consciously and consistently applied throughout the entire assessment process.

Once this self-audit is complete, the record for the resource is considered finalized, and the evaluator, AI, may proceed to the next resource.

Supplements_S2

Table S1. NCP resource network node scores ($p < 0.05$) of assessed online NCP resources. Scores cover node frequency and degree (connectivity/ position within the network) for NCPs as well as KMGBF targets and goals. Fully visualized network can be explored in a modular fashion through the NCP_resource_explorer html file in the supplements.

name	frequency	degree	name	frequency	degree
NCP1	167	9	GA	97	7
NCP2	15	8	GB	30	17
NCP3	26	9	GC	6	2
NCP4	74	16	GD	11	5
NCP5	9	5	T1	18	13
NCP6	52	11	T2	10	11
NCP7	32	12	T3	28	6
NCP8	41	10	T5	22	11
NCP9	38	10	T6	31	16
NCP10	21	7	T7	28	8
NCP11	8	5	T8	24	15
NCP12	103	8	T9	17	15
NCP13	35	9	T10	39	3
NCP14	64	7	T12	16	18
NCP15	226	3	T13	8	15
NCP16	43	4	T14	14	16
NCP17	15	5	T15	9	15
NCP18	187	10	T16	9	14
			T17	6	14
			T18	10	4
			T20	5	15
			T21	35	5
			T22	12	15

Table S2. NCP resource network link scores ($p < 0.05$) of assessed online NCP resources. Scores cover connection strength (Haberman) between NCPs as well as KMGBF targets and goals. Fully visualized network can be explored in a modular fashion through the NCP_resource_explorer html file in the supplements.

Source	Target	Haberman	p(Z)	Source	Target	Haberman	p(Z)	Source	Target	Haberman	p(Z)
NCP1	NCP4	2.66	4.14E-03	NCP12	T5	2.19	0.01	T6	T22	2.23	0.01
NCP1	NCP8	2.66	4.16E-03	NCP12	T10	4.86	1.04E-06	T6	T23	5.3	1.29E-07
NCP1	NCP14	3.33	5.01E-04	NCP13	GD	2.16	0.02	T7	T12	2.6	4.97E-03
NCP1	NCP15	3.51	2.67E-04	NCP13	T5	1.85	0.03	T8	T9	1.99	0.02
NCP1	NCP18	8.42	1.55E-15	NCP13	T10	1.74	0.04	T8	T12	2.13	0.02
NCP1	GA	6.52	1.97E-10	NCP13	T15	1.68	0.05	T8	T13	3.91	5.95E-05
NCP1	T2	2.23	0.01	NCP13	T18	3.32	5.24E-04	T8	T14	2.45	7.44E-03
NCP1	T3	3.89	6.46E-05	NCP14	NCP17	1.89	0.03	T8	T15	3.58	2.04E-04
NCP1	T21	2.08	0.02	NCP14	NCP18	4.59	3.57E-06	T8	T16	3.58	2.04E-04
NCP2	NCP7	3.22	7.31E-04	NCP14	GA	5.91	5.72E-09	T8	T17	4.77	1.59E-06
NCP2	NCP9	1.99	0.02	NCP14	GC	3.25	6.57E-04	T8	T20	2.31	0.01
NCP2	NCP10	5.47	5.56E-08	NCP14	T6	4.81	1.33E-06	T8	T22	2.83	2.50E-03
NCP2	NCP13	2.2	0.01	NCP15	NCP18	4.73	1.86E-06	T8	T23	4.77	1.59E-06
NCP2	NCP14	1.89	0.03	NCP15	GA	1.98	0.02	T9	T12	2.96	1.69E-03

NCP2	NCP16	3.08	1.14E-03	NCP16	NCP17	2.38	9.02E-03	T9	T13	6.32	6.16E-10
NCP2	GB	3.41	3.82E-04	NCP16	GB	3.48	2.95E-04	T9	T14	4.39	8.50E-06
NCP2	T6	2.51	6.41E-03	NCP16	T9	3.34	4.82E-04	T9	T15	5.88	6.77E-09
NCP3	NCP4	5.07	3.83E-07	NCP17	GB	1.78	0.04	T9	T16	5.88	6.77E-09
NCP3	NCP5	2.27	0.01	NCP17	T3	1.93	0.03	T9	T17	7.49	6.15E-13
NCP3	NCP6	5.86	7.29E-09	NCP17	T22	2.81	2.64E-03	T9	T20	2.96	1.71E-03
NCP3	NCP7	3.48	3.00E-04	NCP18	GA	5.94	4.72E-09	T9	T22	6.05	2.69E-09
NCP3	NCP8	2.05	0.02	NCP18	T2	1.83	0.03	T9	T23	7.49	6.15E-13
NCP3	NCP9	2.3	0.01	NCP18	T3	2.25	0.01	T12	T13	5.08	3.65E-07
NCP3	T2	2.05	0.02	NCP18	T6	2.92	1.88E-03	T12	T14	3.46	3.20E-04
NCP3	T7	4.61	3.20E-06	NCP18	T10	1.82	0.03	T12	T15	4.71	2.03E-06
NCP3	T12	4.48	5.76E-06	NCP18	T21	2.34	0.01	T12	T16	4.71	2.03E-06
NCP4	NCP5	2.45	7.51E-03	GA	T2	3.35	4.62E-04	T12	T17	6.06	2.47E-09
NCP4	NCP6	7.98	2.75E-14	GA	T3	2.06	0.02	T12	T20	3.08	1.16E-03
NCP4	NCP7	3.89	6.36E-05	GA	T6	5.04	4.41E-07	T12	T22	5.08	3.77E-07
NCP4	NCP8	4.37	9.00E-06	GB	T1	2.86	2.31E-03	T12	T23	6.06	2.47E-09
NCP4	NCP9	5.24	1.71E-07	GB	T9	2.26	0.01	T13	T14	8.62	4.44E-16
NCP4	NCP11	2.83	2.54E-03	GB	T12	4.79	1.42E-06	T13	T15	9.03	0
NCP4	NCP13	5.38	8.53E-08	GB	T13	3.33	4.97E-04	T13	T16	9.03	0
NCP4	GB	1.71	0.04	GB	T14	5.31	1.24E-07	T13	T17	13.55	0
NCP4	GD	1.82	0.03	GB	T15	3.02	1.39E-03	T13	T20	4.69	2.25E-06
NCP4	T2	3.53	2.51E-04	GB	T16	3.02	1.39E-03	T13	T22	7.71	1.55E-13
NCP4	T7	2.46	7.32E-03	GB	T17	4.14	2.39E-05	T13	T23	13.55	0
NCP4	T8	3.19	7.94E-04	GB	T20	1.93	0.03	T14	T15	6.59	1.29E-10
NCP4	T12	1.81	0.04	GB	T22	2.3	0.01	T14	T16	6.59	1.29E-10
NCP4	T18	2.12	0.02	GB	T23	4.14	2.39E-05	T14	T17	10.12	0
NCP5	NCP7	2.87	2.26E-03	GC	T13	4.22	1.75E-05	T14	T18	2	0.02
NCP5	T7	4.26	1.44E-05	GD	T14	1.84	0.03	T14	T20	3.35	4.61E-04
NCP5	T8	2.44	7.76E-03	GD	T18	7.13	5.58E-12	T14	T22	6.81	3.71E-11
NCP6	NCP7	7.09	6.86E-12	T1	T3	3.06	1.24E-03	T14	T23	10.12	0
NCP6	NCP8	5.61	2.74E-08	T1	T8	3.51	2.63E-04	T15	T16	12.09	0
NCP6	NCP9	6.06	2.58E-09	T1	T9	2.67	4.05E-03	T15	T17	10.55	0
NCP6	NCP12	2	0.02	T1	T12	6.8	3.99E-11	T15	T20	4.38	8.65E-06
NCP6	GB	3.19	7.94E-04	T1	T13	4.72	1.93E-06	T15	T22	5.63	2.48E-08
NCP6	T2	3.08	1.14E-03	T1	T14	4.21	1.77E-05	T15	T23	10.55	0
NCP6	T7	2.51	6.30E-03	T1	T15	4.37	9.20E-06	T16	T17	10.55	0
NCP6	T8	2.08	0.02	T1	T16	4.37	9.20E-06	T16	T20	4.38	8.65E-06
NCP6	T12	2.3	0.01	T1	T17	5.67	2.04E-08	T16	T22	5.63	2.48E-08
NCP7	NCP8	3.92	5.84E-05	T1	T20	2.84	2.42E-03	T16	T23	10.55	0
NCP7	NCP9	4.24	1.57E-05	T1	T22	6.97	1.40E-11	T17	T20	5.51	4.43E-08
NCP7	NCP10	3.59	2.02E-04	T1	T23	5.67	2.04E-08	T17	T22	9.05	0
NCP7	NCP11	2.1	0.02	T2	T3	2.92	1.92E-03	T17	T23	15.72	0
NCP7	NCP12	1.79	0.04	T2	T7	1.9	0.03	T20	T21	4.26	1.43E-05
NCP7	GB	3.55	2.34E-04	T2	T12	3.08	1.13E-03	T20	T22	3.69	1.37E-04
NCP7	T7	5	5.34E-07	T5	T6	2.86	2.31E-03	T20	T23	5.51	4.43E-08
NCP8	NCP9	1.75	0.04	T5	T9	4.84	1.14E-06	T21	T22	1.95	0.03
NCP8	NCP10	2.15	0.02	T5	T13	2.89	2.12E-03	T22	T23	9.05	0
NCP8	NCP12	2.74	3.29E-03	T5	T14	1.69	0.05				
NCP8	T2	3.77	1.04E-04	T5	T15	2.62	4.66E-03				
NCP8	T7	2.89	2.12E-03	T5	T16	2.62	4.66E-03				
NCP9	NCP10	1.75	0.04	T5	T17	3.58	2.09E-04				
NCP9	T2	3.1	1.09E-03	T5	T20	2.47	7.17E-03				
NCP9	T8	4.35	9.92E-06	T5	T23	3.58	2.09E-04				
NCP9	T12	1.82	0.04	T6	T9	4.45	6.48E-06				
NCP10	NCP11	1.7	0.05	T6	T13	4.33	1.06E-05				
NCP10	NCP12	1.96	0.03	T6	T14	2.69	3.78E-03				
NCP10	T6	3.69	1.36E-04	T6	T15	3.97	4.77E-05				
NCP11	NCP13	3.98	4.45E-05	T6	T16	3.97	4.77E-05				
NCP11	GD	2.86	2.27E-03	T6	T17	5.3	1.29E-07				
NCP12	NCP13	3.48	2.96E-04	T6	T20	1.87	0.03				
NCP12	NCP18	2.41	8.27E-03	T6	T21	2.54	5.89E-03				

Table S3. NCP resource coverage (frequency) gap scores (0-1; with smaller scores indicating smaller gaps) for assessed NCP online resources based on overall proportionate frequency within the four fundamental resource categories (Ecosystem Assessment and Modeling Platforms; Foundational Data Infrastructure; Policy, Planning, and Finance Mechanisms; Business and Industry-Focused Tools), in accordance with Supplements_S1 protocol and NCP_DMR document. NCP resources can be further explored in a modular fashion through the NCP_resource_explorer html file in the supplements.

NCP	Ecosystem Assessment and Modeling Platforms	Foundational Data Infrastructure	Policy, Planning, and Finance Mechanisms	Business and Industry-Focused Tools
1	0.327	0.273	0.412	0.500
2	0.918	0.944	0.961	0.875
3	0.837	0.916	0.902	0.875
4	0.510	0.783	0.706	0.375
5	NA	0.944	0.980	NA
6	0.673	0.839	0.804	0.625
7	0.796	0.902	0.863	0.875
8	0.878	0.839	0.843	0.500
9	0.612	0.916	0.863	NA
10	0.939	0.909	0.922	0.875
11	NA	0.958	0.961	NA
12	0.551	0.608	0.627	0.125
13	0.857	0.839	0.902	0.625
14	0.898	0.615	0.863	NA
15	0.082	0.133	0.020	0.000
16	0.755	0.832	0.863	NA
17	0.959	0.965	0.843	NA
18	0.245	0.266	0.157	0.250

Table 4. NCP resource confidence gap scores (0-1; with smaller scores indicating smaller gaps) for assessed NCP online resources based on overall scoring from 0-3 within the four fundamental resource categories (Ecosystem Assessment and Modeling Platforms; Foundational Data Infrastructure; Policy, Planning, and Finance Mechanisms; Business and Industry-Focused Tools), in accordance with Supplements_S1 protocol and NCP_DMR document. NCP resource confidence scores can be further explored in a modular fashion through the NCP_resource_explorer html file in the supplements.

NCP	Ecosystem Assessment and Modeling Platforms	Foundational Data Infrastructure	Policy, Planning, and Finance Mechanisms	Business and Industry-Focused Tools
1	0.213	0.427	0.433	0.500

2	0.083	0.377	0.443	0.667
3	0.292	0.223	0.333	0.667
4	0.197	0.377	0.407	0.400
5	NA	0.377	0.333	NA
6	0.250	0.347	0.417	0.443
7	0.167	0.287	0.333	0.667
8	0.167	0.407	0.443	0.417
9	0.160	0.363	0.390	NA
10	0.333	0.410	0.383	0.000
11	NA	0.443	0.443	NA
12	0.243	0.333	0.390	0.333
13	0.143	0.260	0.333	0.557
14	0.200	0.260	0.257	NA
15	0.297	0.283	0.290	0.290
16	0.307	0.390	0.417	NA
17	0.333	0.333	0.333	NA
18	0.270	0.337	0.353	0.500

Table S5. Maturity gap scores (0-1; with smaller scores indicating smaller gaps) for assessed NCP online resources based on overall scoring from 0-3 in accordance with Supplements_S1 protocol and NCP_DMR document.

NPC	DAQ1_G	DAQ2_G	DAQ3_G	MI1_G	MI2_G	MI3_G	ACI1_G	ACI2_G	ACI3_G	GHC1_G	GHC2_G	GHC3_G
1	0.09	0.166667	0.15	0.226667	0.68	0.163333	0.4	0.213333	0.043333	0.116667	0.076667	0.116667
2	0.09	0.066667	0.223333	0.266667	0.733333	0.11	0.376667	0.133333	0.066667	0.176667	0.066667	0.133333
3	0.076667	0.13	0.166667	0.243333	0.463333	0.1	0.323333	0.23	0.063333	0.09	0.08	0.063333
4	0.063333	0.18	0.116667	0.293333	0.466667	0.143333	0.316667	0.2	0.063333	0.076667	0.073333	0.116667
5	0.036667	0	0	0.186667	0.483333	0.073333	0.406667	0.073333	0.036667	0.11	0	0.073333
6	0.073333	0.173333	0.133333	0.256667	0.423333	0.116667	0.313333	0.206667	0.033333	0.063333	0.07	0.07
7	0.063333	0.166667	0.106667	0.22	0.51	0.126667	0.356667	0.176667	0.023333	0.043333	0.043333	0.053333
8	0.066667	0.156667	0.13	0.236667	0.593333	0.14	0.34	0.19	0.04	0.146667	0.1	0.09
9	0.086667	0.133333	0.096667	0.28	0.29	0.09	0.246667	0.186667	0.02	0.036667	0.046667	0.043333
10	0.143333	0.126667	0.16	0.143333	0.793333	0.176667	0.476667	0.193333	0.08	0.11	0.11	0.11
11	0	0.083333	0.083333	0.21	0.833333	0.083333	0.626667	0.043333	0.083333	0.043333	0.043333	0.043333
12	0.07	0.166667	0.156667	0.25	0.706667	0.146667	0.373333	0.216667	0.063333	0.106667	0.1	0.126667
13	0.043333	0.176667	0.08	0.246667	0.736667	0.15	0.42	0.106667	0.063333	0.053333	0.07	0.123333
14	0.07	0.133333	0.12	0.15	0.896667	0.143333	0.483333	0.163333	0.033333	0.176667	0.08	0.11
15	0.093333	0.166667	0.146667	0.253333	0.71	0.163333	0.396667	0.246667	0.046667	0.096667	0.086667	0.103333
16	0.156667	0.2	0.186667	0.25	0.636667	0.156667	0.386667	0.263333	0.053333	0.076667	0.093333	0.086667
17	0.2	0.223333	0.243333	0.31	0.823333	0.223333	0.51	0.423333	0.043333	0.066667	0.09	0.066667
18	0.076667	0.163333	0.143333	0.223333	0.723333	0.153333	0.39	0.216667	0.043333	0.113333	0.09	0.11

Table S6. FAIR criteria gap scores (0-1; with smaller scores indicating smaller gaps) for assessed NCP online resources based on FAIR criteria proportions met (0/1; presence-absence). in accordance with Supplements_S1 protocol and NCP_DMR document.

NPC	n	F1_G	F2_G	F3_G	F4_G	A1_G	A1.1_G	A1.2_G	A2_G	I1_G	I2_G	I3_G	R1_G	R1.1_G	R1.2_G	R1.3_G
1	171	0.667	0.000	0.661	0.082	0.567	0.006	0.661	0.012	0.000	0.058	0.292	0.000	0.211	0.000	0.012
2	15	0.667	0.000	0.667	0.067	0.600	0.000	0.600	0.000	0.000	0.000	0.200	0.000	0.133	0.000	0.000
3	26	0.769	0.000	0.769	0.077	0.654	0.000	0.538	0.000	0.000	0.000	0.385	0.000	0.077	0.000	0.000
4	75	0.800	0.000	0.800	0.107	0.587	0.000	0.720	0.013	0.000	0.013	0.333	0.000	0.107	0.000	0.013
5	9	0.556	0.000	0.556	0.000	0.556	0.000	0.667	0.000	0.000	0.000	0.111	0.000	0.111	0.000	0.000
6	52	0.769	0.000	0.769	0.173	0.577	0.000	0.673	0.019	0.000	0.019	0.288	0.000	0.115	0.000	0.000
7	32	0.750	0.000	0.750	0.125	0.563	0.000	0.719	0.031	0.000	0.000	0.188	0.000	0.250	0.000	0.000
8	41	0.585	0.000	0.585	0.122	0.463	0.000	0.610	0.024	0.000	0.049	0.415	0.000	0.098	0.000	0.000
9	38	0.816	0.000	0.816	0.105	0.632	0.000	0.789	0.026	0.000	0.000	0.316	0.000	0.211	0.000	0.000
10	21	0.571	0.000	0.571	0.048	0.476	0.000	0.524	0.048	0.000	0.000	0.238	0.000	0.333	0.000	0.000
11	8	0.875	0.000	0.875	0.000	0.500	0.000	0.750	0.125	0.000	0.000	0.250	0.125	0.000	0.000	0.000
12	104	0.740	0.000	0.731	0.106	0.625	0.010	0.606	0.010	0.000	0.029	0.404	0.000	0.183	0.000	0.019
13	38	0.842	0.000	0.842	0.053	0.658	0.000	0.711	0.000	0.000	0.053	0.421	0.000	0.132	0.000	0.000
14	67	0.403	0.000	0.388	0.015	0.388	0.015	0.582	0.030	0.000	0.045	0.224	0.000	0.134	0.000	0.000
15	227	0.709	0.000	0.700	0.093	0.595	0.009	0.670	0.013	0.000	0.035	0.348	0.000	0.211	0.000	0.013
16	43	0.860	0.000	0.860	0.116	0.744	0.000	0.674	0.000	0.000	0.000	0.465	0.000	0.209	0.000	0.023
17	15	0.867	0.000	0.867	0.133	0.800	0.067	0.667	0.133	0.000	0.000	0.400	0.000	0.333	0.000	0.000
18	191	0.660	0.000	0.649	0.094	0.581	0.010	0.634	0.016	0.000	0.052	0.272	0.000	0.199	0.000	0.010

Table S7. NCP and KMGBF crosswalk results. Results cover resources that contain information on monitoring KMGBF targets or goals under four aspects (Context; Data & trends; Drives; Options) and scored from 1-3 in accordance with Table 2. NCP to GBF link strength is provided through Haberman h scores. Wg_prop covers the proportionate presence of a KMGBF target or goals within an NCP category. NCP to GBF linkage can be further explored in a modular fashion through the NCP_resource_explorer html file in the supplements.

NCP	KMGBF_link	KMGBF_ind	Context	Data & trends	Drivers	Options	Link_h	Wg_prop
NCP1	Goal A	A1; A2	1.81	2.39	1.73	1.52	6.52	0.54
	Target 2		2.22	2.67	1.89	1.78	2.23	0.06
	Target 3		2.19	2.50	1.78	2.03	3.89	0.17
	Target 21		2.23	2.06	1.48	1.74	2.08	0.19
NCP2	Goal B	B1	1.83	1.50	1.83	1.67	3.41	0.40
	Target 6		1.60	2.00	1.40	1.20	2.51	0.33
NCP3	Target 2		1.00	1.67	1.00	1.00	2.05	0.12
	Target 7		1.10	1.20	1.00	1.00	4.61	0.38
	Target 12	12.1	1.00	1.14	1.14	1.14	4.48	0.27
NCP4	Goal B		2.67	2.50	2.16	2.00	1.71	0.18
	Goal D		2.00	2.25	1.63	2.00	1.82	0.09
	Target 2		2.41	2.25	1.75	1.83	3.53	0.11
	Target 7		2.27	2.55	1.72	1.36	2.46	0.16
	Target 8		2.33	2.41	1.67	1.58	3.19	0.19
	Target 12		2.50	1.83	2.16	2.00	1.81	0.11
	Target 18		2.57	2.71	2.28	2.28	2.12	0.08
NCP5	Target 7	7.1	1.80	2.60	1.00	1.00	4.26	0.56
	Target 8		2.33	2.67	1.33	1.33	2.44	0.33
NCP6	Goal B		1.58	2.05	1.37	1.47	3.19	0.25
	Target 2		1.63	1.95	1.26	1.37	3.08	0.13
	Target 7		2.33	2.56	1.78	1.33	2.51	0.21
	Target 8		2.33	2.56	2.89	1.67	2.08	0.17
	Target 12	12.1	2.50	2.50	2.00	1.75	2.30	0.13

NCP7	Goal B		2.00	2.28	1.62	1.90	3.55	0.31
	Target 7	7.1	2.00	2.33	1.52	1.95	5.00	0.38
NCP8	Target 2		2.33	2.16	1.33	1.33	3.77	0.15
	Target 7		1.90	1.90	1.80	1.50	2.89	0.24
NCP9	Target 2		2.40	2.80	2.20	1.40	3.10	0.13
	Target 8		1.67	2.25	1.58	1.58	4.35	0.29
	Target 12	12.1	2.00	2.20	1.60	1.60	1.82	0.13
NCP10	Target 6		2.12	2.50	1.62	2.00	3.69	0.38
NCP11	Goal D		2.00	3.00	1.00	1.00	2.86	0.25
NCP12	Target 5		2.33	2.00	1.53	1.53	2.19	0.15
	Target 10		2.46	2.26	2.00	1.80	4.86	0.29
NCP13	Goal D		2.50	2.90	1.90	2.45	2.16	0.11
	Target 5	5.1	1.55	3.00	1.45	1.55	1.85	0.20
	Target 10		1.67	2.78	1.56	1.67	1.74	0.26
	Target 15		3.00	2.67	3.00	3.00	1.68	0.09
	Target 18		1.40	3.00	1.80	1.60	3.32	0.14
NCP14	Goal A		1.33	2.20	1.07	1.33	5.91	0.73
	Goal C		1.02	1.09	1.00	1.00	3.25	0.11
	Target 6	6b	1.45	2.15	1.05	1.40	4.81	0.31
NCP15	Goal A		1.95	2.17	1.61	1.61	1.98	0.41
NCP16	Goal B		2.12	1.76	1.82	2.00	3.48	0.28
	Target 9		1.47	1.23	1.53	1.59	3.34	0.16
NCP17	Goal B		1.75	1.50	1.00	1.00	1.78	0.27
	Target 3		2.00	1.25	1.50	1.25	1.93	0.27
	Target 22		2.00	1.67	1.67	2.00	2.81	0.20
NCP18	Goal A	A2	2.20	2.77	1.80	1.67	5.94	0.51
	Target 2		1.83	2.91	1.83	1.83	1.83	0.05
	Target 3	3.1	2.70	2.39	2.30	2.56	2.25	0.14
	Target 6		1.93	2.59	1.59	1.69	2.92	0.17
	Target 10		1.97	2.62	2.02	1.88	1.82	0.18
	Target 21		2.39	2.18	2.12	2.15	2.34	0.18

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