The past, present and future of online biodiversity knowledge systems

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Abstract:

In recent decades, there has been an exponential increase in the availability and accessibility of biodiversity data and a profusion of portals, tools, and platforms through which to utilise it. This reflects the extensive variety of challenges biodiversity data is being used to address and the need to enhance decision-making by different stakeholder groups. Whilst this has provided unprecedented opportunities for those outside mainstream academia to contribute to and benefit from these resources, it can create confusion in navigating biodiversity data within a highly saturated landscape.

This paper reviews the current state of online tools for biodiversity capturing both global systems, alongside a non-comprehensive sample of regional and national systems. We aim to highlight areas of duplication and identify gaps and offer suggestions on paths forward to consolidate systems to provide greater impact. We present a new database of around 700 global, 250 regional and potentially over 3000 national web-based data systems and apply bot a newly developed online data systems typology as well as the DPSR+B (Drivers, Pressure, State, Response, Benefits) framework to categorise them. Finally, we consider whether target groups are well defined for these platforms.

Our analysis shows that gaps exist for natures benefits, agricultural and wildlife related supply chains, and specific pressures such as illegal and unsustainable use. Moreover, we discuss that users' inability to find the right tools, or interpret some accurately, may lead to poorer conservation outcomes. We make a series of recommendations in relation to a next-generation of online systems that reduce redundancy, lower costs, and improve delivery of information for decision-making.

Introduction:

Biodiversity has been declining globally for decades (1–3), and in some parts of the world for centuries (4). This is largely due to increased human activities resulting in a series of pressures on species, with the most damaging ones being land use change and loss of natural ecosystems, unsustainable harvesting of species, pollution, climate change, and invasive alien species displacing original flora and fauna (1, 3).

For most of the past century, information on biodiversity trends, pressures affecting biodiversity, and the actions taken to reverse negative biodiversity trends was only available in printed scientific papers, books, and reports (5–7). Information on the contributions that biodiversity makes to human livelihoods was even harder to access; the concept of ecosystem services was only developed in the 2000s (8)and the related concept of Natures Contributions to People later in the same decade (9). This largely inaccessible, paper-based, information system meant that knowledge - and hence the potential for informing decision-making related to the natural environment - was in the hands of a few tens of thousands of scientists, government officials and NGO staff - globally.

Early versions of web-based platforms that served data and knowledge for specific needs were built from long-established "paper based" data systems. Examples include Protected Planet (10), a platform for collating and sharing data on protected and conserved areas worldwide, the IUCN Red List of Threatened Species (11), which categorises species in terms of their risk of extinction, and fisheries and forestry and agriculture databases maintained by the Food and Agriculture Organization of the UN (12). These systems have now been digital for over 30 years, continuously improving their offering. For species data, electronic databases were started in the 1990s and were fed into the Global Biodiversity Information Facility (GBIF) which became operational in 2001, establishing a global online portal in 2008 (13).

Over the past two decades there have been increasingly rapid changes in information availability globally. Technology to collect, compile, and disseminate knowledge on the environment has become easier to access, cheaper and faster; and the skills to deploy the technology have become mainstream. The internet has provided ever increasing accessibility and opportunities for data sharing (14–16) and recently, the prevalence of citizen science initiatives has been steadily rising (17, 18) . This shift is a powerful one as historical geographic, financial and language barriers to contributing to and accessing data have been gradually mitigated. Novel data sources available through online biodiversity platforms are able to provide unique insights into species distribution (19) and behaviour (20) that typical surveys and monitoring projects would find it difficult to capture. Moreover, in the past couple of years Artificial Intelligence has also opened further possibilities for data capture and processing and outreach to different user-communities to facilitate decision making (21).

However, the rapid proliferation of web-based biodiversity data systems and tools has come with a series challenges key amongst these is a widening potential user base with a lower level of biodiversity expertise, leading to increasing confusion among the potential users. Additionally, keeping the existing online data systems available and up to date is a significant undertaking, requiring both funding and technical expertise, with systems at risk of becoming obsolete should availability of these things lapse. In other cases, the user-base for a new system can be ill-defined, resulting in a lack of users or a system failing to fulfil its intended niche. These challenges can equate to a sub-optimal user experience, difficulty accessing data suitable for purpose and unfulfilled potential in the biodiversity tools and platforms which have been created. Another potential downside is that developing online biodiversity systems might become a 'displacement activity' (22) i.e., building a new system is no longer seen as a tool to accomplish a specific goal, but a goal in itself.

In this review paper we build on published papers (23) and unpublished reviews by UNEP-WCMC (24, 25) to overview the current "ecosystem" of online data systems delivering biodiversity information to decision makers. We use our review to look for areas of overlap and identify gaps in what is available. We also take a user-needs perspective on available systems, looking to see whether the system addresses the kinds of decisions users want to be able to take. This builds on the work of Buschke et al. (26) where the usability of a data platform is only one equally important consideration among user-needs (are users aware, do they have the skills to use the platform, and do they have adequate IT infrastructure) and data characteristics (are the data trusted, scientifically valid, and fit-for-purpose. Finally, we explore how the current landscape of online knowledge systems might evolve and become more sustainable with long term core funding and the ability to reduce redundancies and costs through the deployment of latest technologies.

Conceptual framing:

To assist this review, we have developed a typology of online systems (Table 1) (further detail in Annex S1), which outlines six main types of systems with differing core functions. Use of these standardised terms within the field would assist communication between system developers and facilitate the rationalisation of the online offering that relates to biodiversity data.

Table 1: Typology of online knowledge systems for biodiversity

Type	Description	Core functions
Data Portal	Provides an 'official' home for and access to one (or a small number) of databases. Some visualisations or pre-packaged analysis may be available alongside search functionality, but the expectation is that analysis and use of the data will occur away from the site.	Point/official source for a database (where you go to access or otherwise interact with the database); Does not facilitate complicated analyses; May offer visualisation of associated information; May combine information from different sources to generate information;
Decision-support tool	Provides a dedicated tool to assist a well-defined user group carry out one of more	Meets the needs of well-defined user group(s); Generates tailored information for user(s) to answer

	specific tasks. The tool may combine datasets and methodologies in a transparent and configurable manner.	specific questions; Predefined methodology that guides users; May not be the original source of data
Flexible analysis platform	Provides access to multiple datasets or multi-purpose tools. Allows users to develop their own methodologies and custom processes.	Customizable and flexible analysis platform, supporting a wide variety of analyses; Offers more user control; User-generated methodology and analysis; May not be the original source of data
Libraries/catalogues	Often thematically curated libraries or catalogues of data or information	Limited interaction with the information on the website; Most systems directs users to the relevant information; Usually does not host the datasets and only directs to where they are hosted
Repositories	Repositories are ‘catch-all’ systems that hold multiple datasets of all types, often indiscriminately..	Intended as a place to keep data where others can locate and use; Includes systems like Zenodo, Dryad, or Figshare. But also catch all spatial data systems without a clear theme. May also include citizen science data repository systems like iNaturalist and eBird
Data capture/reporting systems	Data capture or reporting systems gather data from users against specified (policy) needs; Can also provide summary information back to users;	Mainly intended to gather data from governments for policy reporting, but can also capture inputs from other users in “commitment platforms”

Methodology:

This review centred on online data to decision support systems that are biodiversity- or nature- related.

<u>Database of existing online knowledge systems</u>.
Whilst there are many online systems that host biodiversity data at local, national and regional scales, the focus of this review was on systems that aim to provide global coverage. Our database comprises systems relating to all major realms (terrestrial, marine and freshwater) and builds upon considerable work done in recent years at UNEP-WCMC (24). We included tools and platforms produced by the authors over the past 4 years (27–31) and the expertise of the wider UNEP-WCMC staff and collaborators. This was augmented with comprehensive internet searches that employed both traditional search engines and AI tools to generate candidate lists of new online systems developed by NGOs, UN agencies and business support bodies. These lists were manually checked by the authorial team and further cross-checked by other UNEP-WCMC staff members of differing expertise with 10 systems assigned per person. This resulted in a final list of 698 global online systems for further analysis and lists of around 250 regional and over 1000 national systems. Despite the

international nature of the team compiling these lists, most of the global tools and platforms found were in the English language.

Analyses completed

We used our database of online systems to undertake a series of descriptive analyses.

First, we analysed each system against our typology (see Table 1), providing the scientific community with clarity on how we propose different systems should be described.

Second, we looked at the spread of online systems relating to the DPSR+B framework; drivers of biodiversity change, pressures on biodiversity, biodiversity state, responses being taken to address ongoing biodiversity declines in most parts of the world, and benefits accruing from the existence or use of biodiversity. We identified gaps in coverage of these different aspects of biodiversity decision making.

Third, we mapped the intended target user groups of the systems through manual review and AI assessment of expected users. We graded expected users as government, business (encompassing both financial institutions and real economy), civil society and NGOs, academics and researchers, or the public including journalists seeking information for the news or as an input to education programmes. Where the expected users were not obvious, we also noted this using a "generic" tag.

Fourth, we looked at the main kinds of data being served up within the systems, covering trade, sustainable business, finance, oceans, remote sensing, natural capital/ecosystem services, climate change / disaster risk reduction, ecosystems, various aspects of species data, genetics (including traits), and "generic".

As some of the systems we reviewed were also ones UNEP-WCMC created, we worked with external experts to ensure that the treatment of all platforms was fair and comparable.

Results

Overview of online data systems according to our typology

From our review, focusing on systems that operate at the global scale we have identified 204 online knowledge systems as data sources (portal), 172 decision-support tools,114 library / catalogues**,** 90 flexible analysis platforms, 51 other **–** initiative organization (mainly business facing systems), 44 repositories and18 data capture/reporting systems (Figure 1A).

When looked at through the lens of the DPSR-B framework (Figure 1B), the majority relate to biodiversity state (252 systems), pressures (191 systems), and multiples of these angles (132 for multiple and 111 for general), with data systems for drivers (91), responses (60) and benefits (52) having lower numbers of online systems available.

Examples of systems that fit within these categories (Table 3) highlight the breadth of what has already been created. Further examples of systems that address different aspects of biodiversity and different use-cases and user needs are provided in subsequent sections.

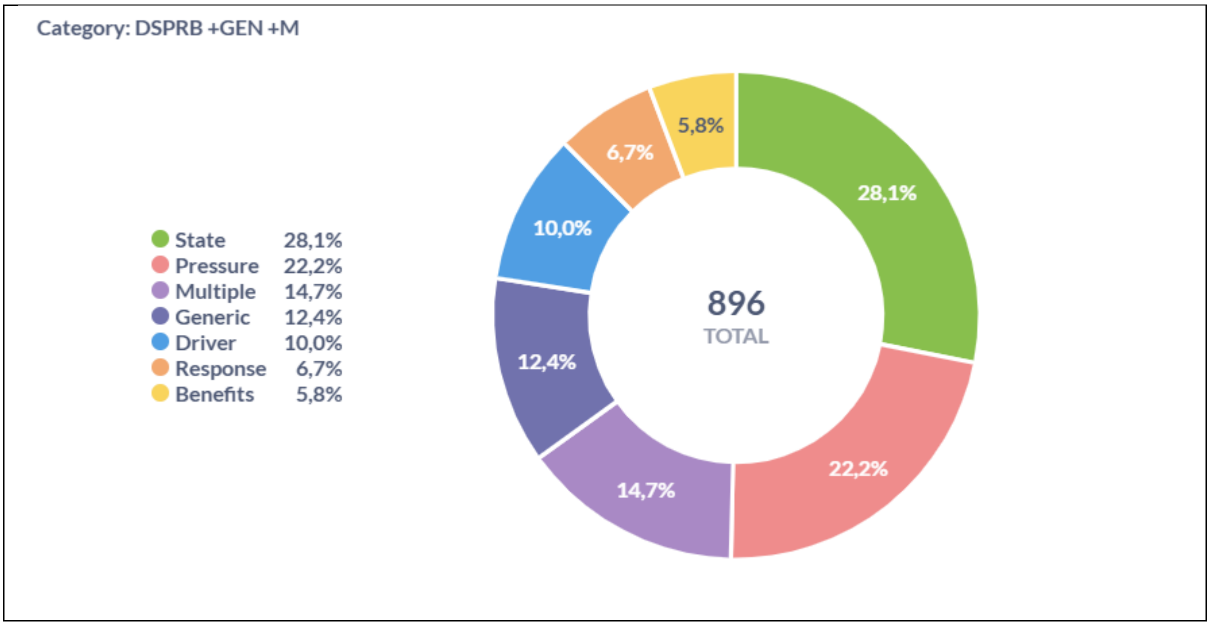


Figure 1: Kinds of online biodiversity data systems and basic data they contain; A) Numbers of different types of online system according to our typology; B) Breakdown of the proportion of systems falling into the categories of our DPSR+B (plus multiple or general) framework;

Table 2: Example systems according to our typology

Typology category	Example 1	Example 2
Data portal	World Database on Protected Areas (WDPA)	Global Biodiversity Information Facility (GBIF)
Decision-support tool	UN Biodiversity Lab	CITES Non-Detriment Findings tool
Flexible analysis platform	WePlan Forests	Marxan online
Library / catalogue,	UNEP World Environment Situation Room	WRI ResourceWatch
Repository	GenBank	iNaturalist
Data capture/reporting systems	Online Reporting System	Target Tracker

Key: WDPA = World Database of Protected Areas (32)
GBIF = Global Biodiversity Information Facility (13); UN Biodiversity Lab (33); CITES Non-Detriment Findings tool (34); WePlan Forests (35); Marxan online (36); World Environment Situation Room (37); ResourceWatch (38); GenBank (39); iNaturalist (40); Online Reporting System (41); Target Tracker (42).

Analysis of the global systems in our database shows that the largest proportion contain species data, followed by ones that contain general data, and those that contribute inputs to or capture outputs from assessments of business impacts and risks (Figure 2A). We also see that over time the number of new systems created to hold data relating to different realms has increased considerably (Figure 2B), and that the overall number of systems has also increased over time (Figure 2D), with the users of the systems being dominated by systems where the users are not too well defined (general in our categorisation), followed by systems that seem to be targeting scientists, business, government and then civil society user groups (Figures 2C, D)

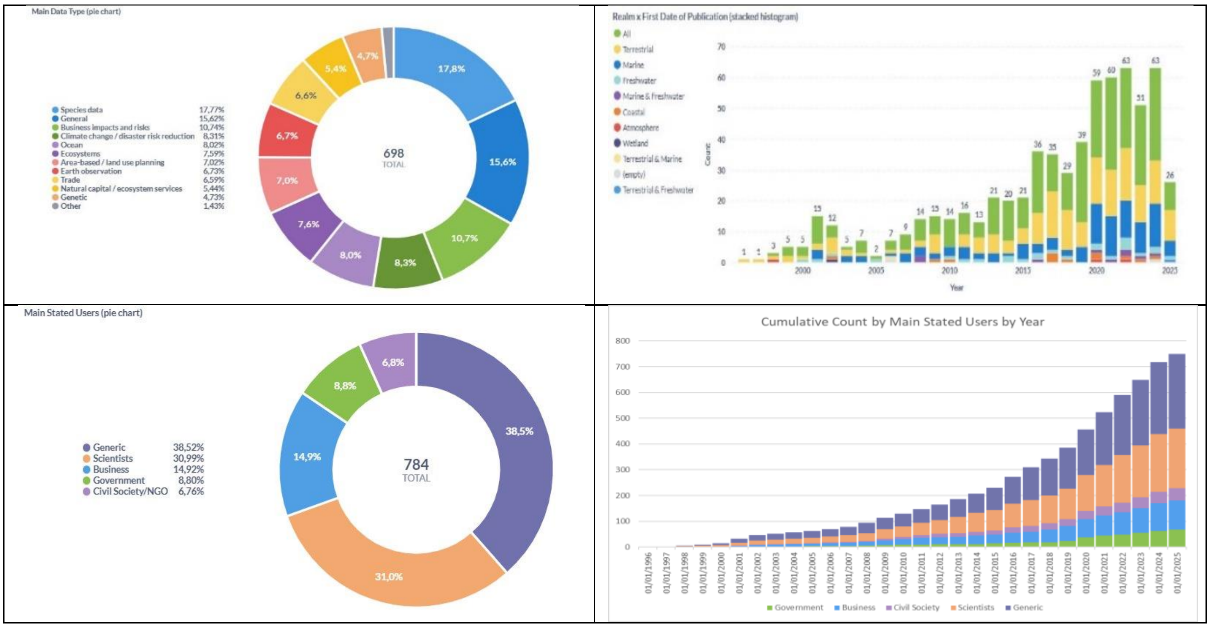


Figure 2: Overview of the online data systems collated for this review, using information gathered on "global" systems. A) numbers of systems that contain data relating to species, ecosystems, genes etc; B) Annual creation of new online data systems from 1996 to 2024 relating to different realms (terrestrial, marine, coastal, freshwater etc); C) Main stated user groups for global systems (scientists, governments, business etc); D) Cumulative growth of online data systems for different user groups over time;

Example platforms aligned against the framework of Drivers, Pressure, State, Response, Benefits

Global nature policy covering planning, implementation, monitoring and evaluation of benefits and impacts uses the DPSR framework, with the additional consideration of benefits (DPSR+B). Online systems often follow this framework of information needs, sometimes with a clear focus on one area, but not always. Systems also provide access to information straddling many areas - we term "generic". Approximately 16% of the global tools are classified as "generic," while around 19% span more than two categories within the framework, thus falling under the "multiple" classification. Further examples are presented din Tables S1 and S2. Full lists of systems reviewed available in Annexes 1,2,3. We initially focused on systems with global scope (Annex 1), but as the review progressed, we realised that there were also numerous regional, national and even sub-national online systems in existence. These are included in Annex 2 (over 250 regional systems located) and Annex 3 (Over 3000 national systems located). These annexes are likely not complete, but provide a snapshot of biodiversity online systems in September 2025.

Drivers: Drivers play a major role in creating the direct pressures on biodiversity that result in a change in state and benefits. The main (indirect) drivers of biodiversity loss, as defined in the IPBES Global Assessment (1) are: a) socio-economics; b) human demographics; c) issues of governance such as inequity, transparency, stability; and d) the increasing role of technological innovation. Data platforms exist to cover most of these drivers, often being maintained by UN agencies working on human development issues. Examples include data systems on the global economy (43), global material flows (44), sustainable production and consumption (45), sustainable development (46), human development (47), global infrastructure (48), agriculture, forests, timber (12, 49), legal and illegal trade flows between nations (43, 50, 51).

Also available is detailed gridded data on the global human population change and distribution (52). Some of these drivers of biodiversity loss have been included in decision support and flexible analyses modelling frameworks that assess the current and possible future status of biodiversity (1, 53–55).

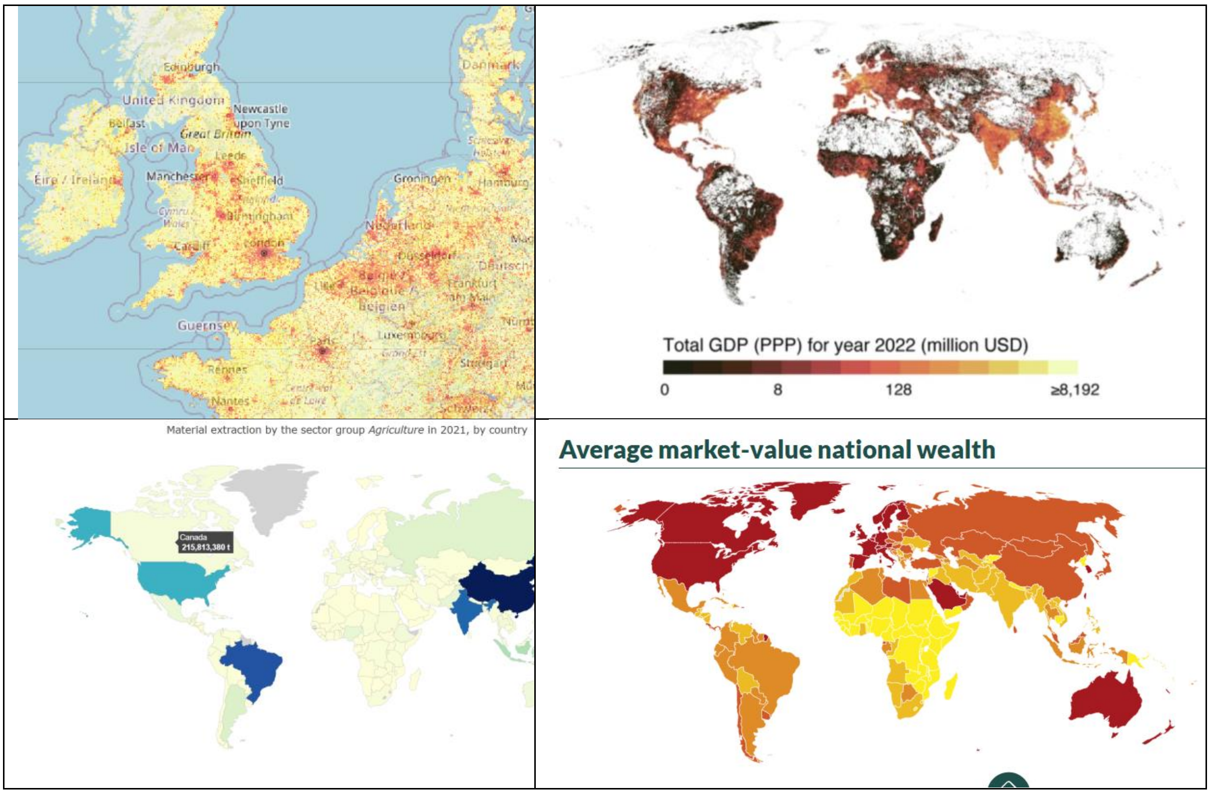


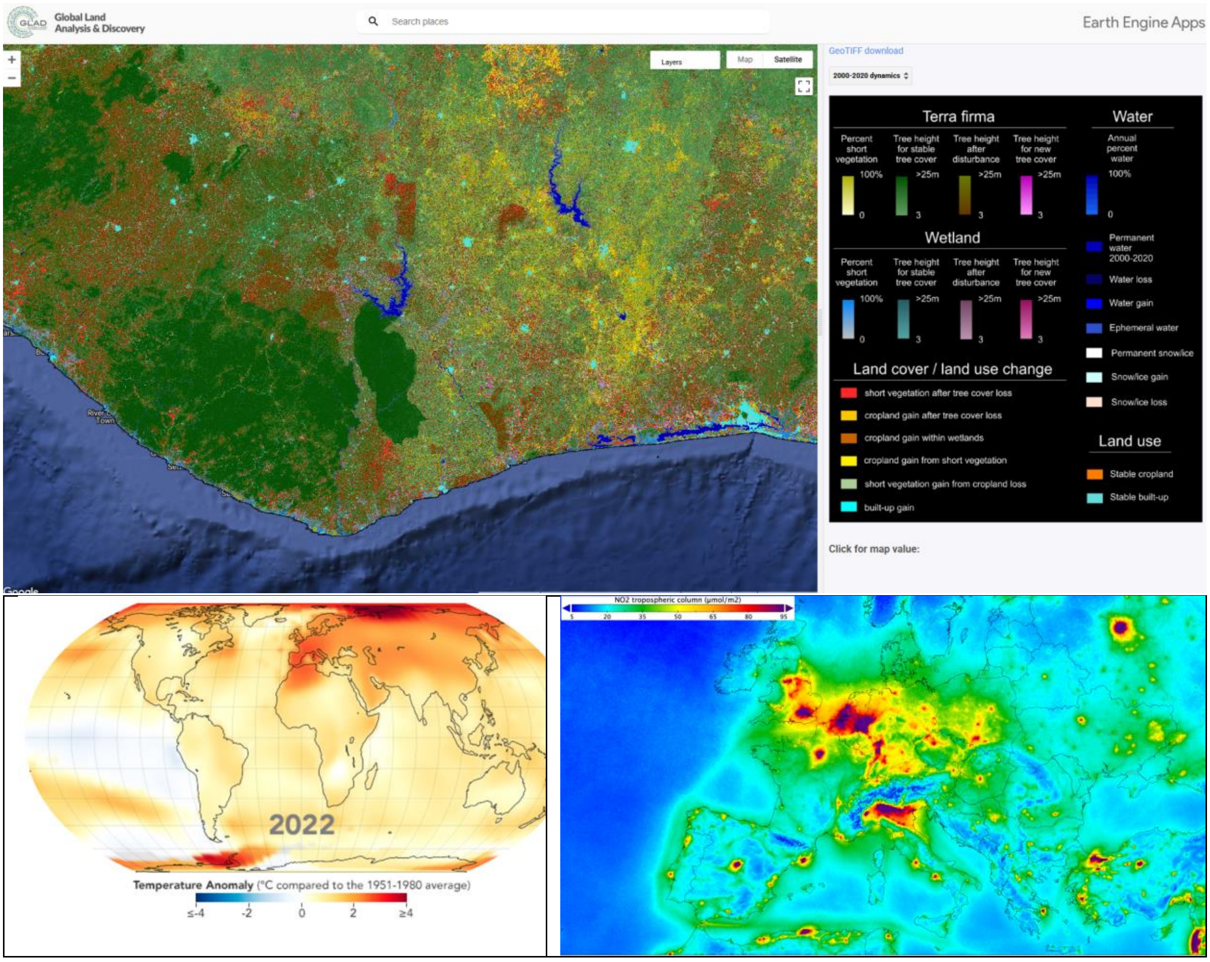
Figure 3: Example outputs related to “drivers” of biodiversity loss
A) Data portal on human population density showing part of northern Europe where the darker the red the higher the human population density and the greener the colour the lower density of people able to exert pressure on the land and its biodiversity (52), B) Data portal showing total GDP (PPP) for 2022 in million USD. Plotted from the 5 arc-min resolution product, overlaid with country (admin 0 level) boundaries from Natural Earth data. Note: log2 scale for the colour scale (56), C) Decision-support tool on global material extraction for agriculture in the year 2021, by country. The darker the colour the higher the amount (57): Sector profile for the sector 'Agriculture'. Visualisations based upon the UN IRP Global Material Flows Database. Vienna University of Economics and Business. Online available at: materialflows.net/visualisation-centre/sector-profiles) D) Decision support tool on global income inequality measured as average market value national wealth, with colour scale from dark red (high) through oranges (medium) to yellow (low). This plot shows the wide variation in wealth between countries, with major differences between countries in Africa and Europe and Northern America and hence a wide range of potential impacts on nature from high-wealth related consumption (data from World Inequality Database (58))

Pressures:

What our DPSR framework terms “Pressures” are named in the IPBES global assessment (1) as “direct drivers”, which are further defined as natural and anthropogenic drivers that unequivocally influence biodiversity and ecosystem processes. The IPBES global assessment (1) defines the most important of these as follows: a) changing use of sea and land, b) direct exploitation of organisms, c) climate change, d) pollution and e) invasive non-native species. Online systems exist for each of these pressures.

Databases of land cover and land use change are now widely available (59, 60), with the quality of products increasing every year as new remote sensing products become available and computer processing power increases. For “direct exploitation of species” legal trade in species is quantified in CITES legal trade database (61), the TRAFFIC illegal trade database (62) and UNODC (63) and other forms of use in IIED SSC Species Use Database (64) and in databases on medicinal plants use (also a benefit) (65), for example in India (66) but there are no comprehensive data systems for the human use of nature.

For the pressure of “climate change” there are numerous systems online that relate to climate data and changes alone, without a link to nature. Systems also exist that relate climate changes to impacts on biodiversity (67), climate risks systems (68). For “pollution” as a pressure, systems are found for freshwater (69), air quality (70) and soil pollution (e.g., nitrogen and phosphorous, but also heavy metals and chemicals (71)). Invasive non-native species covered by the Global Invasive Species Database (72), and the CABI database (73). For more general changes to pressures on land and in the sea, there are online data systems serving up an Ocean Health Index (74), or human changes to the land (75), or general pressures on land (76, 77).



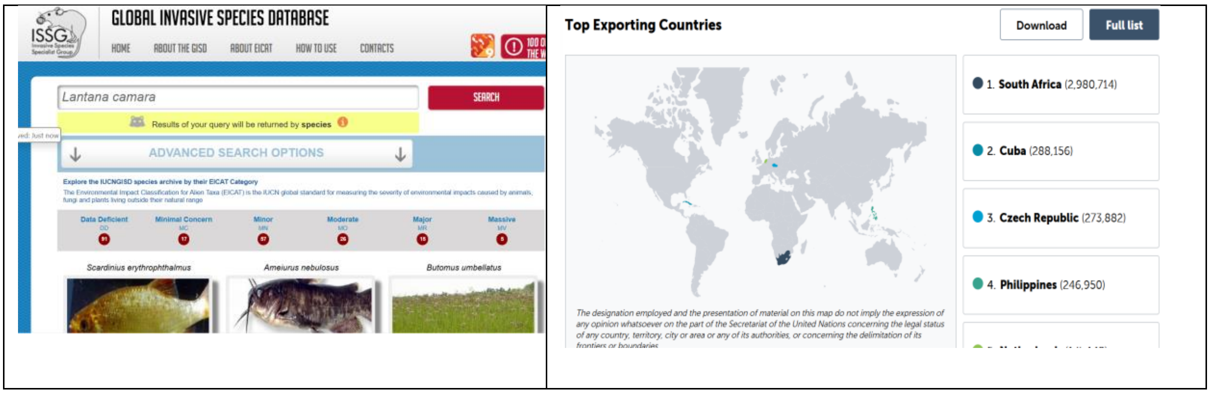


Figure 4. Examples of online systems delivering information on drivers of biodiversity loss *A) Data portal providing access to land cover and change data. Image from the Global Land Cover and Land Use Change (GLAD) database for West Africa, showing Ivory Coast where there has been significant forest loss within reserves (red areas within defined polygon), expansion of agriculture and built up areas, but also the maintenance of the Tai National park (dark green polygon) (59). The GLAD alert system quantifies changes in forest extent and height, cropland, built-up lands, surface water, and perennial snow and ice extent from the year 2000 to 2020 at 30-m spatial resolution. Products were derived using state-of-the-art, locally and regionally calibrated machine learning tools. And validated independently using a statistical sampling. Provided under Creative Commons Attribution License (CC BY). B) Data portal on global temperature anomalies in 2022, which tied for the fifth warmest year on record. The past nine years were the warmest since modern recordkeeping began in 1880 (59), C) Data portal on nitrogen dioxide air pollution across Europe, based on measurements gathered by the Copernicus Sentinel-5P mission between April 2018 and March 2019. (78) Nitrogen dioxide pollutes the air mainly because of traffic and the combustion of fossil fuel in industrial processes. D) Decision support tool on invasive alien species. Global Invasive Species Database interactive viewer (72) as a location to search for key information on invasive alien species that can be invasive. The Environmental Impact Classification for Alien Taxa (EICAT) is the IUCN global standard for measuring the severity of environmental impacts caused by animals, fungi and plants living outside their natural range. The Global Invasive Species Database was developed and is managed by the Invasive Species Specialist Group (ISSG) of the Species Survival Commission (SSC) (79) of the International Union for Conservation of Nature (IUCN). It was developed as part of the global initiative on invasive Decision support system on wildlife trade, showing direct exports of parrots (Psittacidae spp.) 2014-2023 based on records of legal trade managed under CITES. CITES Wildlife TradeView is an interactive online tool for exploring and visualising CITES trade data. The tool is directly linked to the CITES Trade Database (managed by UNEP-WCMC on behalf of the CITES Secretariat) and is automatically updated once CITES annual reports are entered into the trade database. It therefore provides a way to access the most up to date CITES trade data available (80).*

State (genes, species, ecosystems)

Biodiversity state refers to the current abundance, distribution or condition of biodiversity at the levels of genes, species or ecosystems. It is the most common way that conservation scientists have studied biodiversity, and there are also the largest number of online systems available to provide data and knowledge for this aspect of the DPSR+B framework.

Genes**:** A handful of online systems hold data on genetic sequences of species. The INSDC system of related databases and services (81) brings these together, incorporating GenBank, European Nucleotide Archive (EMBL) and the databank of Japan. These are well-funded and provide data freely to the user community. Well-developed data sharing protocols and standards ensure that most genetic scientists submit their data into these systems. For plant and animal genetic resources there are data systems relating to seed vaults (82), plants in botanical gardens (83, 84), animals in zoological gardens (84), plants traits databases (85), and animal traits database (86). Online systems also link species genetic data to species ranges and other aspects to provide overviews of where species are genetically ancient, or are recently evolved – for example the phylogenetic diversity maps on Map of Life (87). GEO BON also has a working group (88) that has largely been collecting population size data in line with the population 500 indicator.

Species: Web-based systems for species location and abundance data are largely managed within a handful of well-established online systems: GBIF (13) which contains species occurrence data, both as ad hoc observations and as part of structured surveys, as well as taxonomic data derived from shared checklists and literature-based treatments; the IUCN Red List (11) which contains data in species distributions, threats, extinction risk, etc, the Living Planet database (89) and BIOTIME (90), which both contains species population trend data, and the Map of Life (87) which contains various species-related datasets. Tree plots databases also provide a means to determine species composition and trends around the world (91).

In recent years citizen science systems have also emerged as important online platforms for gathering and disseminating knowledge; for example eBird (92), iNaturalist (40), eDNA (93), the international Barcode of Life (94), camera trap data (95). AI enabled tools within major technology firms are also starting to facilitate both gathering and dissemination of biodiversity information – for example Google Lens (96), also for plants (97, 98). Most systems make data and knowledge available for free for non-commercial use, and some have payment systems for commercial use (99).

Although not the focus of this review, emerging regional and national systems that compile and make available biodiversity-related information also exist, for example in South Africa (100), Colombia (101, 102), Mexico (103), the Pacific region (104), and the broader Asian Region (105). These regional (and numerous national) systems have an increasing ability of these to share information with global platforms, for example with GBIF for species data.

Ecosystems**:** Despite there being multiple online systems that present ecosystem-level geospatial information, to date no single platform delivers comprehensive information on the structure, function, and composition of ecosystem properties on land and sea.
Among the multitude of platforms are those linked to initiatives that collect satellite imagery through public space agencies (106–108) or – increasingly – private satellite companies (109). Satellite-based classifications are adept at identifying ecosystem structure based on features such as vegetation physiognomy, but they are less suited for identifying biogeographical patterns based on species composition, ecological functioning or evolutionary history.

Broad scale maps of ecoregions (110) or indicative distributions of ecosystem functional groups (111) provide a more ecologically detailed picture of the world's ecosystems, but the underlying datasets combine coarse distributions, often based on expert delineations. Although this level of detail is valuable for global scale analyses, it is less suited for local landscape planning and management.

Detailed information at a high resolution is available from dedicated platforms for individual ecosystem types. These include information on corals (112), mangroves (113), forests (114, 115), grasslands (116) or surface water (117, 118). The developers of these single-ecosystem platforms tailor their mapping efforts to the specific spectral characteristics of their ecosystems, allowing for a higher level of detail than general remote-sensing classifiers.

The latest evolution of platforms aims to provide highly accurate information on all ecosystem types classified using the IUCN Global Ecosystem Typology (119, 120). These include the Global Ecosystems Atlas (121) and the World Ecosystem Extent Dynamics (122). Still in progress, these initiatives combine the bottom-up synthesis of national level ecosystem information, with the top-down application of machine-learning ecosystem classifiers. The aim is to provide ecosystem information that is sufficiently detailed to feed into national ecosystem accounts or allow countries to complete Red List of Ecosystem Assessments (109, 120, 123).

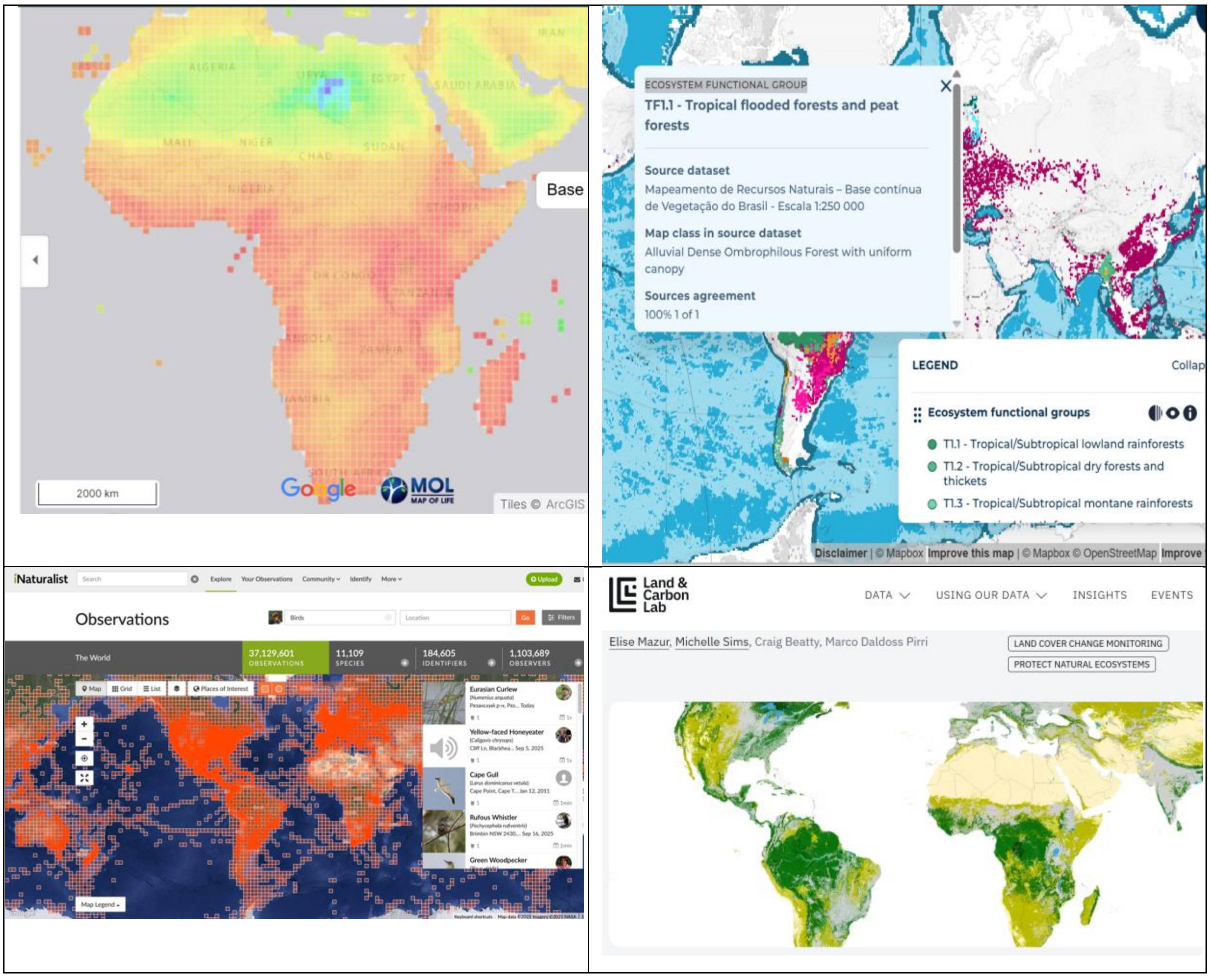


Figure 5: Example online data systems providing access to biodiversity state data and decision-support tools
A) Species Decision support tool: from Map of Life tool that contains species distribution, and various kinds of indicator data (87). The image shows summed scores for the geographical restriction of bird species per ~27km grid cell calculated from expert range maps. Red is high levels of rarity through to Green and Blue to lower levels of rarity of birds. B) Ecosystems data portal : Global Ecosystem Atlas (121) that aims to eventually provide access to ecosystem distribution data according to the IUCN Global Ecosystem Typology (119), and contains its own data catalogue to assist in this process. Map shows mapped ecosystem functional types with a focus on TF1.1 "tropical flooded forests and peat) in the Amazon Basin. C) Species data repository system: The iNaturalist citizen science portal (40) that gathers species identifications through smart phones used around the world. The data being collected is rapidly expanding and becoming a main source of data on the natural world. Every observation can contribute to biodiversity science, from the rarest butterfly to the most common backyard weed. D) Business relevant ecosystems decision support

portal : Land & Carbon Lab has collaborated with World Wildlife Fund and the company Systemiq to lead the development of an open source Natural Lands Map (124). This map uses the best available global and local geospatial data that establishes a common baseline companies can use to visualize the extent of natural land in 2020, and through target setting, to assess whether they may be responsible for conversion after 2020. The Natural Lands Map can also help companies make decisions around acquisitions and the impacts on natural land from future business activities.

Responses: Several online systems aim to provide information and insights on responses to addressing the drivers and emergent pressures on biodiversity. Some provide knowledge on the evidence for how conservation interventions work and best practices, for example Conservation Evidence (125), Panorama solutions (126), Protected Planet (32), and restoration planning (35); whilst others provide systematic conservation planning (36), ecosystem based adaptation (127), ecosystem based mitigation (128), trade system management (27), management of business risks (99), tools for understanding species risks, risks from proximity to ecologically sensitive areas, management of business dependencies (129) and safeguarding land rights (130). There are also a series of trackers of commitments to improve nature, for example for governments (131), restoration more specifically (132, 133), or for IUCN members that includes business and non-government organisations (134).

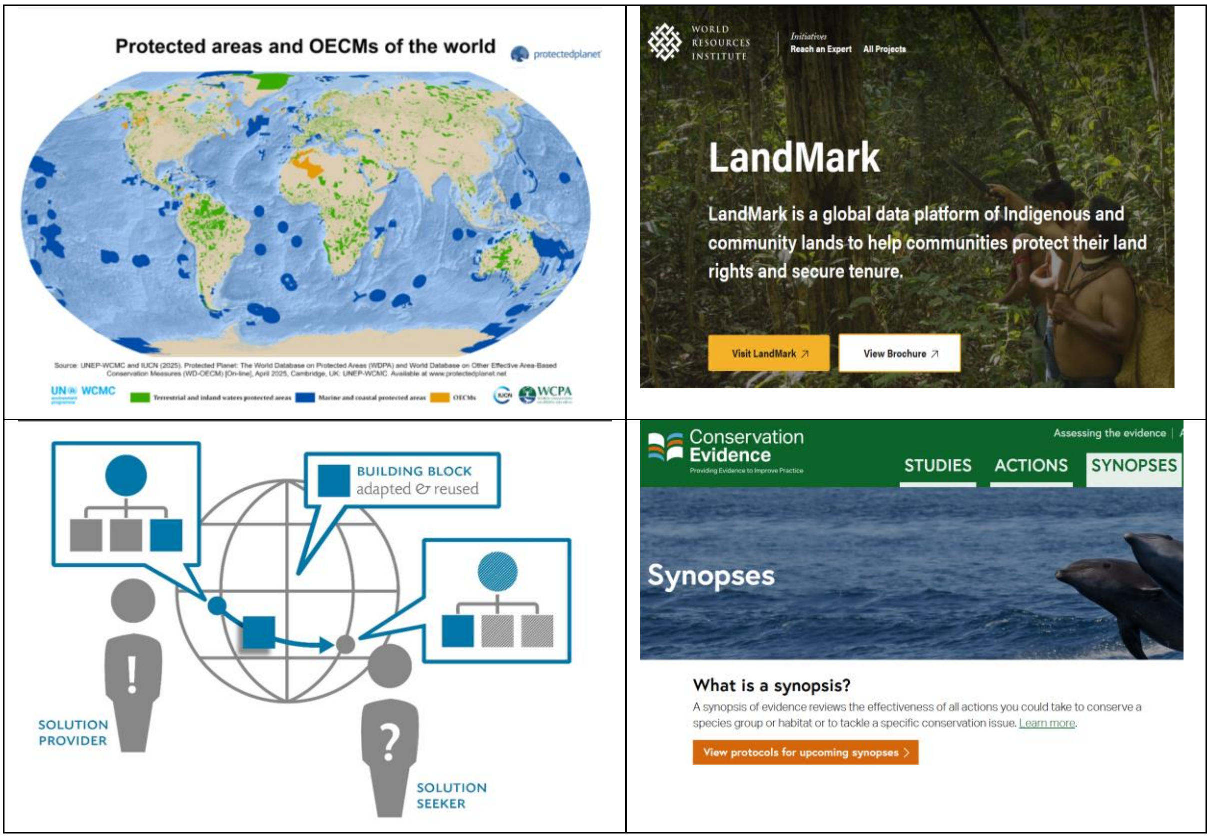
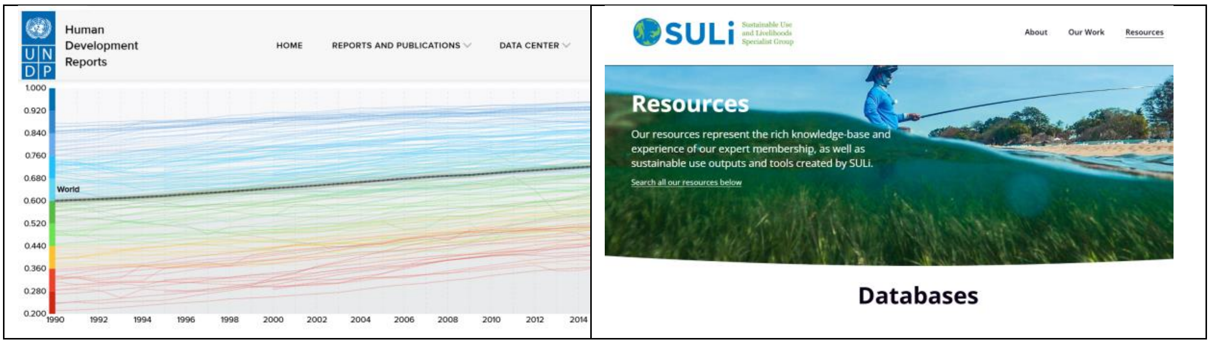


Figure 6: Examples of online data systems that cover human responses to the nature crisis
Decision support tool
***A)** Data portal and decision support tool: Protected Planet (32). Provides data on protected areas and "other effective areas based conservation measures". The latter is a new addition to the database and captures the kinds of reserves that are not primarily set up to conserve biodiversity but do achieve that goal as well. For example, forest reserves for timber harvest or hunting areas for large mammal hunting do have importance for biodiversity conservation and the OECM database is mapping their distribution globally (https://www.protectedplanet.net/en/thematic-areas/oecms?tab=OECMs); B) Data portal and decision support tool: LandMark (130) is a global data platform of Indigenous and*

community lands to help communities protect their land rights and secure tenure (https://landmarkmap.org/map). As of today, LandMark has mapped 34.7% of the world's land and natural resources as held or used by Indigenous Peoples and local communities, out of an estimated 50% or more that experts project is actually held or used. C) As an example of a decision support tool delivering information on conservation solutions, PANORAMA (126) – Solutions for a Healthy Planet is a global community where changemakers share, adopt, and scale-up inspiring Solutions for a healthy planet (https://panorama.solutions/en); Core to PANORAMA's methodology is that Solutions are broken down into replicable "building blocks" when being documented as case studies. This allows another practitioner to easily take up knowledge and replicate elements of the original Solution. For over a decade, PANORAMA has supported peer-to-peer knowledge transfer through online and offline tools and activities, supporting implementation of the Kunming-Montréal Global Biodiversity Framework (GBF) and other relevant policy frameworks. D) Decision support tool: Conservation Evidence (125) a freely available, authoritative information resource designed to support decisions about how to maintain and restore global biodiversity (https://www.conservationevidence.com/). We summarise evidence from the scientific literature (studies) about the effects of conservation actions such as methods of habitat or species management. We produce synopses of evidence that review the effectiveness of all actions you could implement to conserve a given species group or habitat or to tackle a particular conservation issue. Expert panels are then asked to assess the effectiveness (or not) of actions, based on the summarized evidence (for more details see What Works in Conservation).

Benefits: Human development relies on nature and there are various online systems set up to capture these benefits and provide data on them for further use by countries, NGOs, and businesses alike. Nature for development is captured through tools promoted by UNDP (135) and the associated Human Development Data (136) that feeds into the Human Development Report series (137). Similar benefits portals exist for the Sustainable Development Goals (46), and the UN System of Environmental Economic Accounting (138), but exist only in part for the UN Global Biodiversity Framework (139). Other tangible benefits of nature for people are addressed in platforms providing information on medicinal plants (65), wild foods (140), the more general use of wild species by people (64), timber (141), water (142) and carbon (143, 144). Databases that capture health (145) or household budget survey data (146, 147), can also be used to undertake analyses that relate biodiversity in its various forms to human development (142, 148).



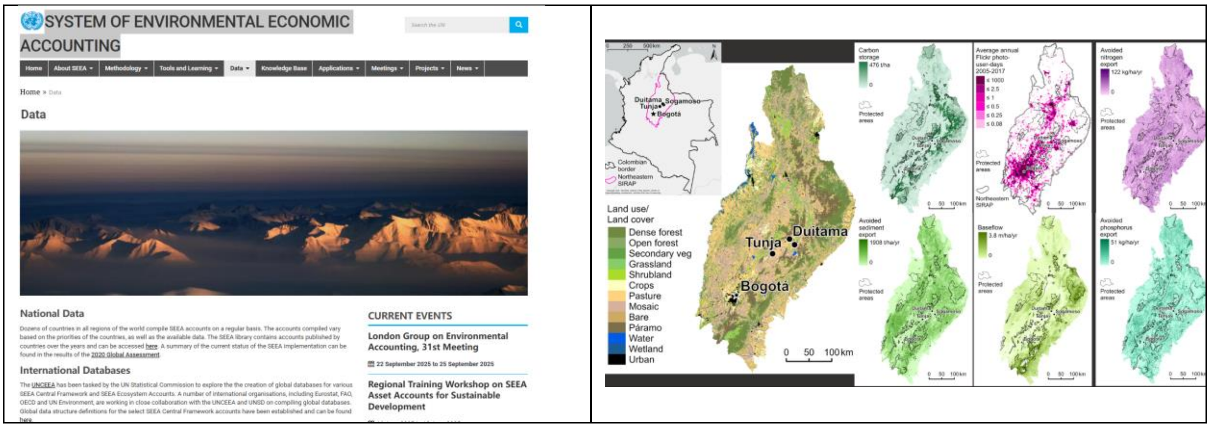


Figure 7. Examples of systems that provide online data sources or models related to the benefits people get from nature

A) Data portal: Human Development Index database (136) (https://hdr.undp.org/data-center/human-development-index#/indicies/HDI). The HDI was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone. The graphic shows the trends in HDI based off four indicators for most countries between 1990 and 2024. Country lines that are blue are above the global average (grey line), and country lines that are green, yellow or red are below the global average (grey line). (UNDP Human Development Report Office) B: Sustainable use evidence repository: The Species Use Database (SpUD) has been created by the IUCN Sustainable Use and Livelihoods Specialist Group (SULi) to help address this problem by collecting and synthesising information on the utilization of wild species globally, and specifically on the sustainability of that use (64) (https://www.iucnsuli.org/resources/species-use-database-spud). The purpose of the Species Use Database is to collect information from as wide a range of species and use regimes as possible, including published evidence about sustainability, but not to provide a formal assessment of whether use is sustainable (or of the quality of any evidence recorded). Any determination of sustainability presented in each record is based solely on the conclusion of the papers on which the record is based. each conclusion of the papers on which the record is based. C) System of Environmental Economic Accounting (138) (https://seea.un.org/content/data). The UNCEEA has been tasked by the UN Statistical Commission to explore the creation of global databases for various SEEA Central Framework and SEEA Ecosystem Accounts. Several international organisations, including Eurostat, FAO, OECD and UN Environment, are working in close collaboration with the UNCEEA and UNSD on compiling global databases. Global data structure definitions for the select SEEA Central Framework accounts have been established. D) InVEST® (149) (https://naturalcapitalproject.stanford.edu/software/invest) is a suite of free, open-source software models used to map and value the goods and services from nature that sustain and fulfil human life. If properly managed, ecosystems yield a flow of services that are vital to humanity, including the production of goods (e.g., food), life-support processes (e.g., water purification), and life-fulfilling conditions (e.g., beauty, opportunities for recreation), and the conservation of options (e.g., genetic diversity for future use). Despite its importance, this natural capital is poorly understood, scarcely monitored, and, in many cases, undergoing rapid degradation and depletion.

Alignment of platforms to user-community needs

We have assessed the stated users for the platforms in our inventory, where feasible. This was done from a combination of the expert knowledge of the authors, and review of the material online for each of 698 online global systems.

We were particularly interested in whether the platform has a theory of change that defines why it has been created, and whether there is a defined user community that can be proven to use the platform for decision making. This is important as where these things are unclear, then the impact of the system is likely to be much reduced.

Alignment to international policy uses cases. Seven international environmental conventions have been signed up to by most countries (150) with the addition of the Biodiversity Beyond National Jurisdictions agreement in 2023. For each convention there are defined things that countries need to do. Because the decisions needing to be made by countries are pre-defined in global and national policy, the scope and content of the online system is easy to determine. The same is true for regional agreements, such as the regulations agreed within the European Union.

A series of online data systems of various kinds have been created by UN and Intergovernmental (and NGOs) to facilitate countries meeting their commitments (Annex 1). We have focused on the CBD, UNFCCC, and SDGs, but we have also aligned where feasible with other MEAs (such as CMS and CITES) or intergovernmental assessment processes such as the IPCC guidelines or IPBES conceptual framework. Online reporting systems of various kinds have been developed for these, and other international agreements that seek to facilitate gathering of data for reporting and progress tracking purposes. Trade and environment issues are also of concern to countries and there are more than 10 online systems available to help countries identify and manage the production and consumption systems they are working with, which is also the essence of Target 16 of the GBF and goal 12 of the SDGs.

Alignment to the needs of businesses for impact, dependency and risk assessments. Business leaders across the world are taking on board the fact that their operations can pose a risk to the natural world and are in turn vulnerable to risks from the declining state of biodiversity and nature (151). The need to promote private sector monitoring and reporting of biodiversity impacts, dependencies and risks is also reflected in the KM-GBF Target 15. Business obligations to address biodiversity impacts and dependencies are increasingly supported by legal frameworks, for example, in the EU and UK, where mandatory reporting and disclosure requirements are being developed and implemented (152–155). Data products, such as the EU Joint Research Centre Global Forest Maps, has a direct link to the EU Deforestation Regulation (156) and is an example of how data systems can target business and policy needs.

While our review focuses on biodiversity data systems for academia and policymakers and on data systems that serve multiple target user groups, many tools purposefully designed for business have emerged in recent years. A mapping conducted by Conservation International and the Nature Tech Collective has identified over 600 such tools, many of which have or are being developed by tech startups (157).

Of the 698 biodiversity online data systems in our global inventory,113 mention “business” among their main stated user groups and aim to help companies understand and manage their biodiversity impacts, dependencies or risks. Some of the business-facing systems in our inventory are available for free, such as the ENCORE tool (129) or the SBTN Materiality Screening Tool (158). Others offer free access to basic functionalities but require users to pay for more advanced or analytical features, such as IBAT (99), WWF Risk Filter (159) or Global Forest Watch (114). There are however tools that restrict commercial use or make any commercial use possible only for a fee. For example, the Biodiversity Intactness Index (BII) developed by the UK Natural History Museum (160) is available for free but only for non-commercial uses or the Ecosystem Services Valuation Database (ESVD) enables commercial use only for organisations that become strategic partners.

Most of the data systems in our inventory that support business needs are flexible analysis platforms or decision-support tools (73% of business-focused systems, compared to 38% of all 700 data systems in the inventory). These tools often draw on academic and non-commercial use work. For example, Global Forest Watch visualizes spatially resolved data on tree cover from multiple academic studies (59, 161, 162). The IBAT tool enables businesses to visualize and analyse data from the WDPA, WD-OECM, WDKBA and the STAR metric derived from the IUCN Red List of Threatened Species data (163). This suggests that future improvements to data systems for academic and public sector audiences are likely to trickle down the "data value chain" and bring improvements to the flexible analysis platforms and decision-support tools designed to support business needs.

Alignment with the needs of trade and supply chains traceability. Legal trades operate according to rules set by global bodies such as the World Trade Organisation, regional deforestation free supply chains regulations (for example within the EU Deforestation-free Products regulation), sustainable trade requirements (for example as set out in Target 16 of the Kunming-Montreal Global Biodiversity Framework), and national rules (for example USA tariffs). Ongoing changes to the trade systems – such as the EU-DR regulation and proposed additional considerations of biodiversity in WTO rules - are starting to provide the political impetus for countries and businesses to understand and manage their impacts on nature, climate and people through their supply chains. As these requirements are new and emerging, fewer online systems are responding to these needs. In our inventory, 46 (6.6%) tools are related to trade systems, mainly at the nation-to-nation scale and for broader sectors of the economy that fall into the "Drivers" section of our review. Often these online systems lack links to the impact of trade on nature. Examples at national scale tools that include biodiversity impact measures include Commodity Footprints (164) or Trade Map (165). At the finer scale, online decision support tools provide help for businesses seeking to understand their supply chains and their impacts. For some agricultural commodities linked to deforestation there are tools like Trase (166), Global Forest Watch (114), EU Joint Research Centre Global Forest Maps (156) or the paid-for tool LandGriffon (167) and underlying data layers (https://source.coop/vizzuality/lg-land-carbon-data). Some systems are also available for fisheries (168) timber (141), but these lack a solid analytical link to biodiversity impacts. There are also major gaps in systems that link other kinds of trades (for example in cement, gravel, other bulk materials) to their biodiversity impacts. A compendium of existing online systems related to trade has also been created (27). Illegal trades are even harder to understand, and they can have both direct (wildlife trade) or indirect (e.g. illegal cattle trades in South America linked to deforestation (169)) impacts on nature.

General systems providing data and knowledge for broader civil society. Several systems deliver a set of data for general use by civil society, journalists, or for others with an interest in a particular issue. Examples of these kinds of systems include the WRI Resource Watch (38) tool, and the UNEP World Environment Situation Room (37), but also include more biodiversity focused systems such as the UN Biodiversity Lab (33) and Map of Life (87). These kinds of systems can face challenges in terms of targeting their uses.

In summary, building use-cases and validating them (and in some cases changing or dropping the system) can take significant time and effort. But not doing this leaves online systems struggling to understand their role, and potential users may also face similar problems.

Towards a new generation of platforms

In this paper we have reviewed the existing global offering of online systems that are providing data and knowledge on biodiversity to different user communities. We show that there are 1000s of systems in existence and that more are being created all the time. Our focus has been on 698 global systems, but through our review we have discovered that there are at least 250 regionally focused systems, and potentially over 3000 nationally specific ones. It is certain that there is also an even finer level of spatial resolution for these systems, such as regions of countries, single protected areas, or peoples' "local patches". This plethora of systems has emerged in the last 30 years, with the rate of expansion accelerating in line with general treads in online technology.

Our review has also shown that significant numbers of similar systems exist. These offerings may duplicate or compete with each other. For example, data on species captured through a variety of observation methods, or ecosystems data based on remote sensing. and the set of online systems that deliver similar datasets in slightly different ways. This tends to occur when organisations based in different parts of the world, or with a slightly different user base, are inspired to address a common need for information - but select to create a new solution that may not build upon or be compatible with other solutions already in existence. The reasons behind this are varied – it may be challenging to find similar solutions that already exist, and the availability of suitable technology may constraint the form of solution that is most practical for a given set of users. In some cases, a methodology may become established for a specific use case or metric, and tools are developed that incorporate that specific methodology. All these factors can result in a number of similar digital tools being built. In recent years we can see that 100s of online systems and initiatives that focus on the business use case have been established. Many are offering similar products and services, and we would assume that most will be discontinued in the next 5 years due to challenges in securing sustainable funding streams.

We have also shown that there are gaps in the current array of online data and knowledge systems. The largest gaps are in systems that address the multiple pressures (threats) to nature, including trade related threats that can occur well away from the point of consumption, and systems that aim to capture and present information on the benefits people derive from nature. Systems that present information on the direct use of biodiversity is also a major gap, as legally traded species traded in non-industrial quantities may not be monitored or may lack species data-and national systems are not digitised and shared. Thus we often have many similar systems to deliver similar products, and then some elements entirely missing. More broadly, we also lack systems that present benefits from nature, especially for local communities and indigenous peoples, and these are often not active in the world of online data systems.

Key means for building effective online systems

<u>Ensure a strong user focus, leveraging user understanding to shape system design</u>

In our review it was difficult to identify the target users for many online systems we reviewed (see Figure 2). If there is a genuine lack of clear target audience for a product, this has several consequences. One can invest resources in creating something for 'someone' and end up crating something that may be for 'no one'. Products created with no target audience in mind may be directionless. Meanwhile products created for a specific target audience but based on assumptions about that audience may not adequately cater for users' needs, challenges, and context. If so, the target group may not use the product, and so not achieve the desired behaviour changes and impacts. Alternatively, the 'wrong' target audience might take up the tool, also meaning the target outcome is not reached. Systems set up to provide information for government or business decision-making may discover that their main users are students, academics and journalists.

We identify a general challenge in ensuring online systems are ‘fit for purpose’. This results in new tools being made, rather than refining a product, testing it, monitoring and iteratively improving existing ones, because no-one really knows what is working and what isn't, which also means products relying on this data may use multiple different versions, making comparison challenging. This gap can be solved by investing in understanding users early on. If it is understood changes need to be made to enhance impact, making development changes after the product has been built costs much more than taking time at the start to home in on how to enhance impact (by identifying and then understanding target users). The attributes that define the value of a system to the user are: a) Legitimacy (i.e. is the source of data trusted, respected, and authoritative); b) Saliency (i.e. is the data suitable to solve the problem it is meant to: fitness for purpose); c) Credibility (i.e. is the info scientifically robust) (26)

For the future it is critical to consider that all impacts on nature are driven by human behaviour. To facilitate changes in human behaviour, system creators must understand whose behaviours they are seeking to change, and what product content and formats would be most effective for changing behaviours by that specific group. This is best achieved by conducting user research with prospective target users, avoiding making assumptions about what would be most suitable for them. If behaviour-leveraging products meet a group’s existing needs (i.e. have utility) and are easy and convenient for them to use (i.e. have good usability), users from that group will be more likely to engage with those products, enhancing the likelihood that target outcomes will be achieved as a result. User research enables creators to increase their confidence and depth of understanding of users’ needs and context to facilitate this.

Defining and describing users and their behaviours, we enhance the ability to maximize the utility, usability, and thereby impact of systems. Conversely, not centring users in product design can be costly: target behaviours might not be achieved and attempts to retrofit existing online products to meet user needs can be far costlier than identifying, understanding, and centring user needs from the start, before technical constraints are implemented.

Identify the roles of different agencies in the development of systems

Digital systems within the biodiversity landscape may or may not be created and maintained by a single organisation. Working across organisations is key to reduce duplication of effort and fill gaps, whether a product for a user, or a dataset or a service that builds on one or many datasets. Some organisations may specialise in the collection and collation of data for specific datasets. It may serve that organisation well to invest in the continued maintenance of that dataset, whilst another organisation makes that dataset available for use by organisations that specialise in the creation of products. Another organisation may have the funding and expertise to maintain a dataset, services and product for a specific set of target users. Which would mean they have a good user-based, but this might remain as a small and specialised case, and unable to scale to deliver larger impact.

Build trust

In developing the next generation of platforms, early adoption and trust-building are paramount. A platform’s reputation is strengthened not only by the quality of its data, but also by a clear signal of who it is for and what it intends to help them achieve. Systems that address a particular need, for example ENCORE (129) that supports business decision making, can gather 10s of thousands of users when their value is well-articulated and relevant to diverse user groups. Success requires understanding both what makes a platform thrive and the needs, knowledge levels, and application contexts of its intended audience. As the ecosystem matures, we may see a small number of highly specialised platforms that excel in specific domains, rather than a scattergun approach of launching tools in the hope they resonate. Trust, credibility, and purposeful design will determine which platforms endure.

<u>Build one system per "area" and serve the data to many products and users</u>

A consistent and robust data foundation can support a diverse range of tools tailored to different user groups and use cases. It is reasonable to assume that varying audiences may require data in distinct formats, with differing levels of aggregation, generalisation, and embedded interpretation. Far from being a limitation, the use of shared, high-quality biodiversity data across multiple tools enhances comparability and strengthens the basis for informed decision-making.

Our vision is that a gradual consolidation of online data and knowledge systems can take place around different areas of knowledge and user groups, with multiple partners playing a role in accordance with their expertise. A useful framing of an overall mechanism by which scientific information on biodiversity can support political and business commitments on conservation is presented in the conceptual diagram below (Figure 8). This is perhaps slowly happening with the GBF monitoring framework's 'Data Custodians' that are supposed to house the key dataset needed to calculate global indicators

From the user perspective: merge / grow / add functionality to existing platforms rather than creating new ones could be beneficial. Users do not want to engage in continuous re-learning - thus adding functions to existing platform which users are familiar with is advantageous - consider minimizing changes to platform-enabled processes (when still good for purpose, working well and widely accepted)

<u>Use the latest technology</u>

A challenge for all systems, but especially for those that have existed for a long time, is to keep systems updated as technology changes. All long-term data systems have gone through several rounds of technology upgrades and can show signs of "technology fatigue" after some years. More generally, when systems when they are launched use the latest technology, but unless there is a source of funding the interface and data will gradually age and eventually go offline when the technology fails, or web-hosting costs for data sets or analytical capacity runs out. An example of a useful system which has come and gone is the portal of Southeast Asian biodiversity data (170). The ongoing emergence of standardised technology platforms are helping to simplify the technology landscape and are also serving as repositories of datasets that can then be used in many ways. Examples of these developments are the Google Earth Engine, Planetary Computer and ESRI data catalogues). As these systems are privately-owned there are concerns about all kinds of data ending up in the hands of a few, and also that systems for global benefit might be closed on the whim of an incoming CEO or financial controller.

The emergence of AI may also transform the way we deliver and consume data and knowledge. If an AI system can retrieve and organise things from across the internet against specific user questions, then this may provide an alternative solution to that provided by bespoke online systems. Careful design of Large Language Model pipelines enables expert-level retrieval of evidence-based information from syntheses and databases (171). Conversely, if the AI is pulling erroneous or manipulated information from the internet, having a source of "high quality" information can become even more valuable and important. We are not sure which way this technology will affect online knowledge, but we can perhaps draw some lessons from the evolution of social media platforms over the past decade.

<u>Ensure sustainable funding</u>

Maintaining an increasing number of online data systems is costly and is perhaps one of the greatest challenges facing the field at this time. For biodiversity only a handful of systems have managed to solve the challenge of long-term sustainable funding, primarily boiling down to GBIF (13), OBIS (172), and – thanks to the funding flows from the commercial-use tool IBAT - the IUCN Red List (11), the World Database on Protected Areas (32) and the World Database on Key Biodiversity Areas (173) Funding challenges seen for online biodiversity systems are less obvious in other areas of global societal need. For example, agricultural and forest related data has been covered by online systems run by the UN agency FAO – funded by governments - for decades. Other broadly stable funding situations exist for health (174), education (175), weather (176), genetic data (39), wildlife trade (61), etc. Most of these systems are run by UN agencies or organisations close to the UN system and attract government funding over the period of many years, which helps them deliver data and decision support over decades. Demonstrating the impact of an online system is linked to its ability to attract funding. For example, GBIF had a review of its impact commissioned (177) and papers outline some of the impact of the GFW platform (178, 179). Measure of impact help these online systems maintain funding flows. To reduce redundancy and ensure sustainable funding flows to core systems funders could also insist that applicants (a) identify existing platforms related to their efforts, (b) engage with the owners of those platforms to maximise synergies, and (c) avoid funding the development of new platforms unless the need to fill a gap is clearly identified

Bringing it together

We use the insights from the analyses and discussion above to develop a conceptual model that outlines our vision for the future of online biodiversity data systems (Figure 8).

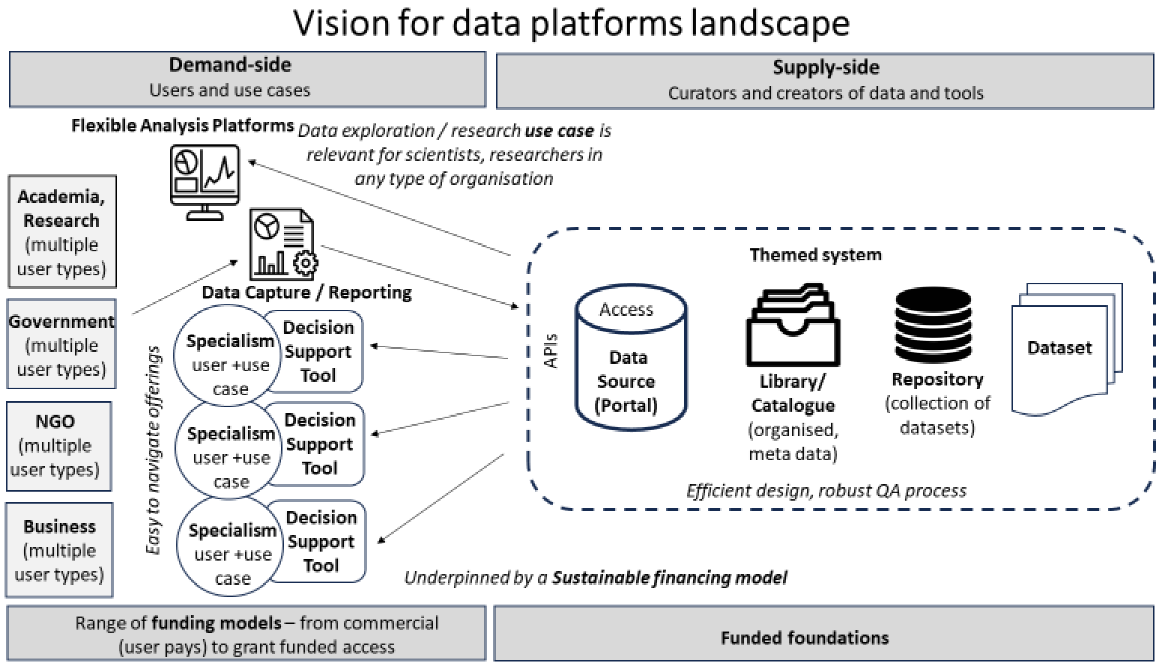


Figure 8. A conceptualised online data system for an area of biodiversity knowledge (which might be species distribution or protected area data for example).

On the **demand-side** of the diagram are the audiences who help define and then measure progress towards global, regional or national conservation targets or commercial targets. These organisations include academia and research institutes, and international agencies such as the UN, but this is not an exhaustive list. The target users of many of these digital products are policy experts, planners and decision makers in the public sector, NGOs and the private sector who have accountabilities that relate to nature and stewardship. There is a benefit to these data platforms being designed as ‘specialised’ tools, because they offer most utility when they are designed with specific users and use cases in mind. Therefore, they combine tailored functionality designed to be user-friendly and intuitive to use by their target audience, and incorporate curated data selected for robustness and relevance to the decisions and actions being taken through the use of the tool. In addition to the specialised ‘decision support tools’ just described, users may directly interact with other categories of data platform. One category is the ‘flexible analysis platform’ which is best suited to exploration of data – often through the use of data visualisation and mapping functionality – which can be used for testing hypotheses, modelling scenarios and developing metrics. The final category of user-facing tool included in Figure 8 is the ‘data capture and reporting platform’. This enables users to submit measures of biodiversity - for example those that they are required to report against the politically agreed targets. Therefore, new data is being added in to this ‘digital ecosystem’ by users through tools located on the demand-side.

The **supply-side** of Figure 8 describes a simplified representation of the categories of data platform involved in the complex data pipelines that store and supply nature knowledge for a wide variety of purposes. These data platforms hold information (data sets, data layers, derived metrics and indicators) including temporal and spatial data, about the state of nature, and of pressures, responses and benefits that impact biodiversity. Data from observing nature - from field work, satellite and sensor measurements for example - and from other direct measurements such as genetic analyses are collected, quality checked and compiled into biodiversity datasets (‘observational level’ data).

These supply-side data repositories, catalogues and libraries and data source (portals) make up 52% of the global data platforms in the database of online knowledge platforms presented in this review paper. There appears to be scope for consolidation and reduction in the risk of duplication if these data platforms were to be managed under thematic groupings. Figure 8 illustrates this deliberate organisation into a ‘themed’ collection of related datasets and data platforms that underpin a thematic area of work, critical to biodiversity. This themed system allows datasets to be organised – in simple repositories, in referenced catalogues or libraries, and also in data portals. Confidence is built in the data these tools contain through adherence to best practices in data management – such as the use of common data standards, transparent methodologies for derived metrics, and scientific validation. When this themed system is equipped with functionality that enables data discovery and access - including documented APIs with which to build efficient, automated data pipelines – it becomes a coherent and interoperable foundation. More specialised data platforms and analysis ‘front end’ tools can pull data with confidence and serve them to the users via the demand-side tools. The supply-side of the biodiversity data ecosystem is supported by information curation and quality assurance activities which are predominantly undertaken by scientists, researchers and data experts in academia and technical institutes.

Two examples of biodiversity data platforms that exist in a themed data system. Are the Protected Planet tools and GBIF’s species information facility which is based upon the Darwin Core data standard. In the case of Protected Planet, national data about protected area is aggregated, standardized and shared via a data portal, and made available to other analytical platforms and tools via APIs (these include the IBAT tool. which supports business decision makers and enables them to take impact upon protected areas into account). The second example is the themed species data that forms part of the information system governed through GBIF. In this instance an extensive network of countries and organisations follow a defined set of data standards and processes, through which they contribute species information held in a wide variety of data formats (from museum specimens, and DNA barcodes, to field observations). This data is standardized then serviced to other platforms via APIs, where is it used in further analysis or presented to users in decision support tools.

The benefits of adopting this model

The future vision presented in Figure 8 has several potential benefits.

Firstly, it helps confirm the uniqueness of a proposed new data platform: by classifying a new platform at the concept stage as sitting on the demand-side or supply-side, and mapping it to a thematic area of biodiversity it should make it easier to check whether other data platforms already exist that perform the same function and in the same space, thus preventing duplication of tools in future.

Secondly, it enables new data platforms to plug into an existing themed eco system of tools and data pipelines (effectively adding a new piece to an existing jigsaw puzzle): which potentially reduces the effort and cost to create the new platform because other complementary data pipelines and sources, or user-facing tools, are immediately visible. It also increases the impact of the new tool, once it has gone live, as it can then be linked, rapidly, to other existing users and suppliers in that themed ecosystem.

Thirdly, by thinking in terms of a themed system it may be easier to introduce common data standards and ways of working: these should result in data platforms and their supporting pipelines becoming less problematic to maintain over time.

The fourth benefit is that user-facing platforms can be specifically targeted at gaps in the current landscape: with the added benefit that if they are they are targeted at a specific type of user who wishes to perform a specific task it will make it easier to involve those users in its design – resulting in a tool that is much more likely to be used and found useful once delivered.

The fifth and final benefit is that reviews based upon thematic classifications of all existing data platforms may enable a fragmented landscape to converge towards a more coherent and efficient ecosystem: an enabler for existing data platforms to be consolidated over time.

Recommended actions for stakeholders

In order to adopt the model described in this section, a number of actions need to be taken by the stakeholders involved in the creation, management, funding and use of biodiversity data platforms. These are the recommended actions

Data platform creators and curators: plan how to tackle the demand-side and the supply-side of the problem you are attempting to solve, building upon the knowledge, pipelines and tools that already exist wherever possible. For the demand side: when embarking on the design and delivery of a new tool, identify the target audience and the need that is being addressed. Review the user-facing tools already in existence in the thematic area that this data platform would sit in – are there some other tools that already address this need and this audience? If so, look to collaborate rather than duplicate. If this new data platform is filling a genuine gap, then proceed to design a solution involving the target users as much as possible in its creation. And finally, ensure that your target users can find your data platform and understand what it can do for them by clearly stating on the landing page who it is aimed at and its purpose (i.e. the primary use case). Make it easy for users to find your tool, and to use it. For the supply side: identify the thematic space, and its existing ecosystem of datasets, tools and providers. Build upon what already exists rather than starting afresh. Collaborate with established experts to accelerate delivery and learn from past work in the space,

Users of nature data platforms: have a clear understanding of the activities and outcomes you wish to achieve. Review and evaluate what is already available in terms of data and platforms, to support you in the nature-related actions you wish to undertake (for example, in planning or reporting). If you are involved in the development of a new tool or in adding new functionality to an existing tool, plan to invest time in shaping, testing and giving feedback to the tool creators. Keep engaged with the creators and curators of the data platform once it is fully operational – it is easier to influence the future functionality if you provide regular feedback on what works well and what is missing and share case studies of its usefulness.

Funders of data platforms: undertake a thorough review of the thematic space that you are funding or intending to fund work in. When assessing new proposals, request that all applicants identify all existing data platforms that are relevant to their proposed work (demand-side and supply-side). Ask the applicants to engage with the owners of existing tools so that synergies can be identified and ways of collaboration agreed. Examine the uniqueness of what the applicant is offering – avoid funding new data platforms unless the need to fill a genuine gap has been demonstrated. Once funding has been assigned, work with the recipients to agree the how the impact of the investment and the added value offered by this data platform can be measured and monitored (177). Finally, work with the applicant to identify sustainable funding solutions to ensure that any new data platforms that are created can be maintained and scaled once they have been launched and therefore can deliver maximum impact.

Summary Points

There are many online systems. The number of online data systems we located in this review amazed even us, working for decades on these subject areas. Across the world we estimate there are thousands of systems from global to local scales, with the numbers expanding every year. However, this expansion has not been equal across all data system types. We are seeing a lot more new tools and platforms that reuse existing data, than new original data sources. This makes the original data sources even more important.

Even with many systems, gaps remain. Some kinds of data – particularly species and protected area data - are repeated in many online systems. But there remain gaps in systems providing pressure related data, or that relating to the sustainable use of biodiversity, or ecosystem services / nature contributions to people.

There is considerable duplication of effort. Many online systems provide access to similar, or the same, datasets. Maintaining this unstructured ecosystem is costly and inefficient but is driven by institutional mandates and competition for resources. On the user-facing demand-side, an example is the competitive world of business platforms in which many platforms are competing to offer the same service - for example, business biodiversity risk assessment. Many of these platforms presumably use the same data sources. This leads to duplication of effort (and potentially to incompatible results if the same data is interpreted in different ways across the various tools). On the demand side, many different (national) authorities may require reporting on the same thing, such as MPAs. This can cause confusion and lead to decisions made on inaccurate information if different actors source the required data from different sources.

A gradual standardisation of technology (and better technology) is helping make these systems easier, cheaper and more reliable. But ongoing costs of maintenance and online hosting, and technology change over time, means that that there is considerable loss and gain of systems every year. Also, AI and other technological advances will help some types of data systems more than others. For example, AI has made remote sensing a lot more powerful. On the other hand, bottom-up data like the IUCN Red List still relies on a lot of human inputs.

For some areas of biodiversity knowledge one system has emerged to bring together data from many other systems and provide it to users in standardised ways. Examples are the systems collating and delivering genetic data (e.g. GenBank), species distribution data (GBIF, OBIS) and protected area data (Protected Planet). This process of consolidation is likely to take place in other areas, eventually leading to a simplified system with a handful of larger players working with networks around the world.

All online data systems need to support the needs of a specific user group to justify their existence. User needs research is an important first step in understanding the problem that is to be solved, or the perceived gap that is to be filled. This research establishes what actions and outcomes the solution needs to satisfy - in particular, what needs to be achieved and by whom. It should also capture how people use the tools that are currently available, and how they would want them changed to make them more useful. If this is not done, then poorly targeted tools will be created that may even duplicate other platforms already available – and the online biodiversity ecosystem will become ever more crowded with unused products.

Funding is a challenge. Funding an expanding portfolio of online data systems is an increasing challenge. Even long-standing systems struggle to attract reliable funding to maintain the core datasets, many of which are then used in a multitude of other systems. Solutions that blend commercial use and non-commercial use, and creation of systems with core UN / government funding seem the most promising to maintain core online systems into the future. However, there is a role for other types of funding, especially as 'seed funding' for innovative new tools or approaches where there is a different profile of risk to the work.

Future directions

Key future directions include:

Interoperability between systems. One cause of fragmentation and duplication in the current landscape is lack of interoperability. This covers two types of interoperability: technological interoperability (e.g. data systems providing APIs) and interoperability of terminology and categorisations (e.g. ontologies of threats or pressures, standardised taxonomic lists, or standardisation around ecosystem classifications, or common agreement on the terminologies for natures contributions to people, ecosystem services, or natures gifts or benefits). Tackling both these forms of interoperability will facilitate the exchange of information and create efficiencies for the target users.

Further deployment of AI. AI has started to show its potential in the last few years, and it seems likely that it will transform the knowledge and data landscape. The ability of AI tools to locate and organise data in ways that are fit for purpose by different users may prompt a radical realignment of the biodiversity knowledge sector. However, authoritative datasets with robust quality assurance will remain necessary, and not all aspects of quality assurance will be possible to replace with AI. Specialist providers of these datasets will face the challenge of having to compete with less robust tools that do not invest in quality checking and offer less robust but faster-to-generate alternatives to the use of bottom-up data which is more expensive to collect, process and maintain. The fitness-for-purpose of these competing solutions will need to be carefully assessed by users of the datasets and data platforms.

Moving to near real time or real time data. Computing power and data analysis are no longer constraints to delivering updated data and knowledge products. Many systems and seeking to move their offering to as close to real time as possible. Where data lags exist "nowcasting" approaches are being deployed to extrapolate to the present data from recent trends. However, this drive for data to be as close to real-time as possible might be impossible or very costly to achieve and may not be required for adequate decision making in every situation. A pragmatic approach is likely to be taken for some years to come, during which time the use cases for which real-time data has genuine benefit will emerge,

Developing sustainable funding models for online knowledge platforms. One of the current challenges is the availability of continued funding for online systems. UN agencies have traditionally had more stable funding, but even for these there are ongoing funding declines in 2025. Large NGOs and similar think tanks also maintain systems using a blended mix of funding, including commercial use models where possible. Some of commercial data platforms, including those offered by technology firms use a mixture of advertising income, commercial use contracts, and consultancy work as sources of income. Finding sustainable funding for some of the less attractive elements of work, such as gathering information from volunteers and making it freely available for all, requires further effort to solve.

Consolidation of data systems for specific use cases and thematic areas. There is some consolidation of data systems within fields such as genetics, species distribution data and protected areas, but this is not the case for other aspects of biodiversity. Over time a movement towards federated systems using common standards that allow interoperability, and consolidation would greatly assist in making progress and reduce duplication and fragmentation.

Increased effort to integrate non-traditional knowledge. The KM-GBF contains a target (Target 22) and a dedicated section (Section C) relating to indigenous peoples and local communities and their data and knowledge needs. The online systems available for these user communities are less well developed than for governments, NGOs and business, but they are likely to expand greatly in coming years.

Improved clarity on business user needs. Business facing networks such as TNFD and SBTN have introduced many nature-related concepts to business audiences. Biodiversity metrics and nature impacts are now becoming better understood by the private sector. Greater consensus is also emerging on data needs for business. For example, there is recognition that data used by business for initial screening and prioritization of locations at risk, needs to meet different specifications than data used to measure actual changes in state of nature. Better understanding of terminology and data use cases will allow data systems developers to communicate more clearly what their data is and is not suitable for.

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Author contributions
N.D.B., H.K conceived and designed the project; contributed to the acquisition, analysis, and interpretation of data; wrote and revised the article; and reviewed the article critically for important intellectual content. HS, FT, LM, O Mc-L, VB, ZT, CT, YS, ED, LW, AA, ND contributed to the acquisition, analysis, and interpretation of data and reviewed the article critically for important intellectual content. AH played key roles in data compilation and the development of the figures. AS, CT, NB, A van S, FB, PJS and AH provided critical comments on the text of the paper and helped make it much better. Many hundreds, or even many thousands, of people around the world have created the systems we have reviewed in this paper. We apologize to all those hard working and dedicated people for any mistakes we have made in relation to their systems when doing this work.

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Annexes

Annex 1: Alphabetical list of globally applicable online biodiversity data systems
Annex 2: Alphabetical list of regionally applicable online biodiversity data systems
Annex 3: National lists within major global regions of nationally applicable online biodiversity data systems (incomplete at this stage)

Online tables

Table S1. Example online systems relating to helping countries to deliver international agreements

	Name (with link)	**Commitment Tracked**	**Managed by**	**Users**
Convention on Biological Diversity				
https://unbiodiversitylab.org/en/	UNBL	Spatial data relating to the targets and indicators of the GBF and the SDGs, and also to the UN Decade for Restoration	UNEP-WCMC and UNDP	Governments, UN Agencies, NGOs and others working with governments
multiple – unique url for each instance https://ascobans-ort.ort-production.linode.unep-wcmc.org/	Online Reporting System	Streamlined online reporting system for many MEAs and other agreements including CMS family (CMS, AEWA, ASCOBANS, EuroBats), Ramsar, Bern Convention, The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC), Protocol on Water & Health	UNEP-WCMC on behalf of MEA secretariats	Governments
https://target-tracker.org/en/about	Target Tracker	Target Tracker", an online tool based on the headline indicators of the monitoring framework for the Kunming – Montreal Global Biodiversity Framework (Global Biodiversity Framework), to visualise progress towards each of the goals and targets of the Global Biodiversity Framework	UNEP-WCMC and the CBD Secretariat	Governments, UN Agencies, NGOs and others working with governments
https://www.cbd.int/article/launch-Nature-Commitments-Platform-25May2022	Nature Commitment Platform	Tracks area-based actions by non-government organizations, local communities and businesses to protect, sustainably manage and restore areas of land and water.	CBD Secretariat, UNEP-WCMC, Government of The Netherlands	non-government organizations, local communities and businesses
https://www.cbd.int/action-	GBF Action Agenda	Commitments with action(s) with targets, timeframes, target audience(s), location(s) and/or	CBD Secretariat	Government, business, IPLC, other

agenda/contribute	Commitments	partners against the GBF Targets.		organizations, individuals
https://www.iucncontributionsfornature.org/get-started	Contributions for Nature Platform	Platform documents where IUCN Members and other constituents are implementing conservation and restoration actions, and assesses the potential impact of these projects on biodiversity (via species extinction risk reduction) and climate change (via carbon storage and sequestration).	IUCN	IUCN member organisations
https://iucn.org/resources/conservation-tool/restoration-barometer	Restoration Barometer Report	The Restoration Barometer (launched in 2016 as the Bonn Challenge Barometer) is used by governments to track the progress of restoration targets across all terrestrial ecosystems including coastal and inland waters. It was designed for countries that have committed to restore landscapes under international goals or agreements.	IUCN	Governments
United National Framework Convention on Climate Change				
https://climateactiontracker.org/	Climate Action Tracker	The Climate Action Tracker is an independent scientific project that tracks government climate action and measures it against the globally agreed Paris Agreement aim of "holding warming well below 2°C, and pursuing efforts to limit warming to 1.5°C."	Climate Action Tracker	Governments
Sustainable Development Goals				
https://dashboards.sdgindex.org/rankings	Sustainable Development Report	Assesses where each country stands with regard to achieving the 17 Sustainable Development Goals.	Sustainable Development Solutions Network	Governments
https://sdgs.un.org/partnerships	SDG Actions Platform	Global registry of voluntary policies, commitments, multi-stakeholder partnerships and other initiatives made by governments, the UN system and a broad range of stakeholders to support	UN Department of Economic and Social Affairs	Whole of society and governments

		acceleration of the UN Sustainable Development Goals		
https://feldactiontracker.org/food-and-land-in-the-sdgs	Food and Land Use in the SDGs	Assesses where each country stands with regard to achieving the Sustainable Development Goals and the interactive map shows countries' level of deforestation as a percentage of total forest area.	Sustainable Development Solutions Network	Whole of society and governments

Table S2. Commitment gap trackers (response trackers)

	Name (with link)	Gap Tracked	Tracked by	Users
Convention on Biological Diversity				
https://www.mangrovealliance.org/news/new-the-mangrove-restoration-tracker-tool/	Mangrove Restoration Tracker	The tool invites mangrove practitioners to record and track their restoration projects across its lifetime while ensuring best practice towards sustainable long-living mangroves globally.	University of Cambridge, Conservation International, The Nature Conservancy, Wetlands International, and WWF	Governments and restoration scientists and practitioners
United National Framework Convention on Climate Change				
https://www.unep.org/resources/emissions-gap-report-2024	Emissions Gap Report	The UNEP Emissions Gap Report (EGR) is an annual assessment by the UN Environment Programme (UNEP) that tracks the gap between projected greenhouse gas emissions and the levels needed to meet the Paris Agreement's goals of limiting global warming to well below 2°C and pursuing 1.5°C.	UNEP	Governments
https://www.unep.org/resources/adaptation-gap-report-2022	Adaptation Gap Report	The UNEP Adaptation Gap Report (AGR) is an annual assessment that tracks global progress on climate adaptation, focusing on planning, financing, and implementation. It also	UNEP	Governments

		analyzes the gaps between what is needed and what is actually being done to address climate change impacts.		
SDGs				
https://unstats.un.org/sdgs/dataportal	The Sustainable Development Goals Report	The SDG Sustainable Goals Gap report, formally known as the Sustainable Development Goals Report, is the official United Nations report that tracks global progress towards the 2030 Agenda for Sustainable Development and the 17 SDGs.	UN Stats Division	Governments

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Side bars for the "online data systems" paper

Global systems

Typology of data systems. We provide detailed descriptions of each of the categories we have used in the data Annexes 1,2,3. In summary these are as follows: 1) Data portal=primarily a source of data; 2) Decision-support tool=facilitates decision making either by providing relevant data or knowledge, or allowing simple analyses; 3) Flexible analysis platform=allow more complicated analyses of data contained in the system, often also allowing external data to be brought in as well. Sometimes provides targeted analysis relevant to particular use cases (e.g. focused on the GBF spatial planning need etc); 4) Libraries/Catalogues=contain curated sources of data, or lists of species, or other forms of useful materials. Differ from a portal in terms of having a broader remit and containing broader kinds of data; 5) Data capture/reporting systems=contains systems that facilitate scientists or citizens to gather data (e.g. ebird or inaturalist), but also systems that facilitate reporting to particular needs (online reporting tools to conventions for example); 6) Repositories=broad systems where a lot of different datasets or kinds of data are located, often without a clearly stated use group; 7) Other -- initiative/organisation= a place to locate the many institution level systems, especially seeking to support the private sector, but where the system is integral to the organisation developing and promoting (and making money from) the system. Tend to be very targeted at business user needs for compliance and voluntary standards and reporting needs.

Side bar on use of Driver, Pressure, State, Response, Benefits (D, P, S, R,B), multiple (M), generic (GEN) coding. For the purposes of this paper, we use the well-established framework of DPSR+ benefits for assessing the main emphasis of the data within the various online data systems. For those systems with three or more focus areas we use the code M= multiple. And for those systems that cover many different things or it is hard to categorise we use the code G=general. Examples of the kinds of data within each category is as follows: D="indirect" driver such as human population or trade on land, or sea surface temperature in the oceans; P=direct driver or pressure like human land uses leading to land cover change, pollution, hunting, etc; S=State of species population or ecosystems extent or condition; R=Responses by humans to improve the state of nature, like protected areas creation, environmental policies, business sustainability commitments, or Ecosystem-based Adaptation schemes; B= Benefits like ecosystem services from nature, including fishes caught, hunted wild animals, carbon storage, water quality related to natural ecosystems, non-timber forest products, etc.

Side bar for main stated users (G, B, C, S, GEN). In this column we have tried to define the main stated user group for the online data system. This is not always easy, and in some cases we would not necessarily agree with the user group defined by the system (on their website) when compared with the actual uses (and users) of the system. Our categories for the main user group are as follows: G=governments ; B= Business (including financial institutions and consultancies) ; C=Civil Society/Non-Governmental Organisations or the general public (including community members); S= Scientists ; GEN=there are either many kinds of potential users, or the target users are unclear.

Side bar for access status (Free Access Y,N). We have looked at each of the various systems and sought to determine the following: Y= the data are fully open for download and use; N= if there is a pay-wall or pay-for-use function (generally for commercial users), even if the site offers some free data and functions. We have also used N for those systems connected to consultant and start up firms where the status of the system is unclear, but we assume the system works on a paid basis.

Side bar on date of system establishment. Here we have used both AI (Google Gemini) and human assessments to determine when the system was established. This works for online systems that are only established since the internet was created, but there are some older systems that started off as paper-based tools. In these cases we have tried to ensure that the start date reflects this older history.

Side bar on Update frequency. We have sought to understand the frequency of updating the data within the online system. This was not always easy and by default we tended to code systems as being "regularly" updated. Our options were as follows: Regular= updating often, perhaps more than once a year, or we assume so and its hard to tell; Annual=where the update can be seen to be annual (although some the tools assessed as regular might also be annual); Infrequent=the system does not seem to be updated that often; Static=It seems the system is not being updated, but it is still online in 2025. For systems that are obviously moribund, we deleted them from the list.

Side bar on "Realm". We have used the major global systems, and some combinations of these. Other ways of dividing the world will exist, but we regarded these as a simple way to group systems. 1) Terrestrial=systems that provide data for the land. 2) Marine=systems that provide data for the oceans; 3) Freshwater=systems that provide data for the worlds freshwaters (lakes, rivers, streams etc); 4) Coastal=systems that focus on coastal systems only; 5) Marine & Freshwater= systems that focus on marine and freshwater data together; 6) Terrestrial & Marine = systems that contain data on both marine and land; 7) All=systems that cover all realms but the scope is not always clear for this

Side bar for the spatial scope as presented the three annexes. We use the following definitions to split the online systems into three online annexes. 1) global systems where the online system either contains global data, or the system can apparently be used anywhere in the world, even if its analytical tools might be used more locally than the world. For the global systems we have undertaken a detailed review of the systems, a random cross check of 10 systems each by UNEP-WCMC experts, and we have sought input from thematic and realm experts to ensure we have covered a broad range of systems; 2) regional systems that are either covering a geographical or political region, for example North America or Africa for geographical, or the EU for political region. Some of these systems also cover sub-regions, such as Eastern Africa, or the Mediterranean sea region. 3) National systems that cover a country, or in some cases part of a country. For the regional and national systems we have not undertaken detailed reviews of each of the online systems. But we have sought to determine that the system exists, and can be used in simple lists of the number of systems online. We have not tried to gather or review all the local (small parts of countries) systems that are online. There are many more of them. There is a separate column for details of spatial scale, such as, if the system is limited to a certain country.

Side bar on the main type of data included. In this section we have tried to determine the **main type** of data included in the online system, which also potentially provides additional advice on the user grouped targeted by these online systems. Many systems includes several types of data. The categories we have used are as follows: 1) Trade=covers both online systems that relate to wildlife trade, but also systems that encompass agriculture and other trades that impact on biodiversity; 2) Business impacts and risks=covers the many systems that are now established that aim to provide data or otherwise help business reduce the impacts of their operations on biodiversity; 3) Finance=covers systems that address the biodiversity needs for data by the finance sector, or sometimes systems that contain finance data that can be regarded as an indicator of a driver of biodiversity loss; 4) Ocean= online systems that relate to the marine realm; 5) Area-based / land use planning= online systems that contain data on area based responses to the loss of biodiversity (e.g. protected areas), or which facilitate land or sea based planning efforts; 6) Earth observation=Systems that primarily contain earth observation data or products, there may be some overlap here with ecosystems classification; 7) Natural capital / ecosystem services=systems that contain data on the stock of natural capital or its flows to people in terms of ecosystem services / or natures contributions to people; 8) Climate change / disaster risk reduction=systems that contain information on climate changes and disasters that are also relevant to biodiversity (meaning that all weather, climate data, climate modelling systems etc that are not obviously linked to biodiversity are excluded); 9) Species data =All systems that contain information on species distributions, species trends, species taxonomy etc are included in this category; 10) Ecosystems= all online systems that have a focus on one or many ecosystems and their extent or condition; 11) Genetic=all systems that contain genetic data or traits data that can be used for biodiversity related purposes. This means that genetic databases relating to humans, health, crop breeding, protein structure or related issues are excluded; 12) General=there are many kinds of data included in the system and it is not possible to determine the main type.