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Technical Note

Delivering Systematic and Repeatable Area-Based Conservation Assessments: From Global to Local Scales

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Abstract: Protected and conserved areas are a key area-based strategy to address the biodiversity and climate change crises. Indicators are fundamental to understanding performance over time. The Digital Observatory for Protected Areas (DOPA) was born in 2013 as a set of open-access web services and applications to be used to assess, monitor, and report on protected and conserved areas. For over a decade, it has delivered over 50 indicators to support policy processes, national and regional governments, and practitioners. DOPA has also developed a versatile and efficient back-end approach that is widely applicable in other area-based conservation contexts. Here, we describe the methods and workflows behind DOPA's back end and provide examples of policy relevant questions it can answer. We discuss the key advantages and limitations of this systematic and replicable approach and explore the use of this back-end architecture to inform progress in area-based conservation targets for the following decades. This approach, embedded in multiple services provided by the Knowledge Centre for Biodiversity of the European Commission (KCBD), can also support the implementation and monitoring of area-based targets of the Kunming Montreal Global Biodiversity Framework at international, regional, and national levels.

Keywords: protected areas indicators; biodiversity; spatial planning

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1. Introduction

The world faces a multifaceted environmental crisis, often referred to as the double (biodiversity loss and climate change) or triple (biodiversity loss, climate change, and pollution) crisis [1], which is pushing the capacity of the planet to its limits [2]. The drivers behind these pressures that are causing biodiversity loss are well known and include land and sea use change, over-exploitation, introduction of invasive alien species, climate change, and pollution [3]. Over the last decades, several policy responses to this crisis have shaped international, regional, and national policy. The 2030 United Nations agenda and its 17 Sustainable Development Goals (SDGs) [4], or more recently, in 2022, the new Kunming Montreal Global Biodiversity Framework (KM-GBF), agreed by the parties of the Convention on Biological Diversity (CBD) [5], are notable examples of such processes.

One of the recurring strategies to tackle biodiversity loss and climate change included in these multilateral agreements is area-based conservation [6,7]. Area-based conservation involves using spatial planning to identify places of importance for conservation and prioritize actions to advance the biodiversity conservation agenda. One example of this is international agreements on goals and targets focused on protected areas for over 50 years [8]. These agreements aim to increase the effectiveness, equity, and coverage of protected areas to halt biodiversity loss. IUCN defines protected areas as "*A clearly defined geographical space,*

recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" [9] (p. 8). The term "conserved areas" is also used to recognise other area-based measures that do not meet the IUCN definition of protected areas but still provide conservation benefits. In the context of the CBD, Other Effective Area-Based Conservation Measures (OECMs) are the best example of this [10]. Today, well-managed, governed, and appropriately resourced protected and conserved areas (hereafter "PACs") are critical strategies to halt biodiversity loss. However, although PACs are a fundamental building block of area-based conservation and one of the most widespread protection mechanisms on earth, they will not be able by themselves to stop biodiversity loss. Integrated spatial planning across the whole landscape is needed to, for example, address and manage pressures on PACs and biodiversity. Supporting this, Target 1 of the KM-GBF calls to ensure "all areas are under participatory, integrated, and biodiversity inclusive spatial planning. . ." [11].

Metrics and indicators are developed to determine whether PACs' goals and targets set in policy domains have been achieved. For example, the KM-GBF includes Target 3, which calls for increasing the quantity and quality of PACs to cover 30% of the globe, including sites important for biodiversity and ecosystem services [5]. Target 3 headline indicator is Coverage of Protected Areas and OECM [11]. Similarly, regional and national efforts are aligning with these Goals. The European Union (EU), for example, is committing through Target 1 of the EU Biodiversity Strategy to "Legally protect a minimum of 30% of the EU's land area and a minimum of 30% of the EU's sea area, and integrate ecological corridors, as part of a true Trans-European Nature Network". Examples of EU indicators to monitor progress for this target include Terrestrial and Marine Protected Area Coverage and Natura 2000 Terrestrial and Marine Protected Area Coverage [12].

To support the European Union's efforts and capacity to mobilize and use biodiversity data so that they are readily accessible to policymakers, managers, researchers, and other users, the Digital Observatory for Protected Areas (DOPA) was developed by the Joint Research Centre of the (JRC) European Commission [13]. Specifically, its original purpose was to periodically provide up-to-date metrics and indicators on protected areas from global to site scale. DOPA was built on web-based technologies, pulling together global datasets that were further processed before being integrated into key indicators, which could then be shared through web services and applications [14,15]. Its front end, the DOPA Explorer, was designed to provide protected area indicators efficiently, systematically, and periodically. Since then, the DOPA has been endorsed by the Convention on Biological Diversity as a reference tool that can help parties, as well as the CBD Secretariat, which assesses progress towards related targets [16]. The DOPA also became the technical backbone of a large conservation program, the Biodiversity and Protected Areas Management (BIOPAMA) program, which assists the African, Caribbean, and Pacific countries to address their priorities for improved management and governance of biodiversity and natural resources (www.biopama.org (accessed on 20 June 2024)). Most importantly, the DOPA architecture used by the European Commission's in-house science service, the Joint Research Centre, to provide the EC with the scientific and technical support on global biodiversity required to assess and prioritize conservation efforts.

DOPA's back end has evolved since 2016 beyond being a protected area-focused platform to an area-based conservation service developed and delivered by the EC. This has been mainly due to two factors. First, responding to user demands over the years, and second, in the face of the key role, spatial planning, in general, and area-based conservation, in particular, will take in biodiversity policy over the next decades [17]. Thus, an innovative and versatile back-end approach to answering area-based conservation questions in much less time than before has been developed, building on experience and user feedback over the past 10 years.

Here, we present the current workflows and methods of this new back-end architecture and show examples of its applications, uses, and policy relevance. We then discuss the innovation and versatility aspects, key advantages, and limitations of its systematic and

replicable approach. Finally, we explore the benefits of this design to ensure consistency and repeatability over time and discuss the future of this architecture to inform progress in area-based conservation targets in the following decades through a series of services and applications.

2. Methods: Developing a New Back-End Approach for Area-Based Planning

The need to regularly update figures and to provide up-to-date metrics on a wide range of indicators, using the latest releases of relevant datasets while maintaining previous versions, required finding solutions to a number of technical challenges and exploring ways of reducing long processing times that hindered timely updates [14].

The lessons learned over a decade of the history of DOPA led to an approach whose main purpose was to reduce the computational effort needed to deliver quickly and efficiently values for any of over 50 indicators in any part of the world. Four steps were followed to improve the quality and speed of the process. First, create a structured and standardized workflow to avoid desktop analysis conducted by different operators with different tools, methods, speeds and outputs. Second, to reduce the number of steps needed by developing a base layer (which also provides the principal coverage indicators) and intersecting it with a series of thematic datasets (aggregated too, when possible) to calculate the rest of the metrics. Third, simplify the complexity of the numerous global datasets used by flattening the data (i.e., reducing overlaps) and harmonizing boundaries. Finally, optimize the process by parallelizing calculations (i.e., using different cores for computation) and reducing redundant processes.

The new back-end approach is underpinned by a global processing framework that delivers a pre-processed database used for storage, post-processing, and distribution for analytical and reporting tools. The distribution is conducted via REST services to feed a series of web services and applications aimed at informing conservation strategies and policies for a variety of users (Figure 1). A notable example of these applications is the DOPA front end called DOPA Explorer [15].

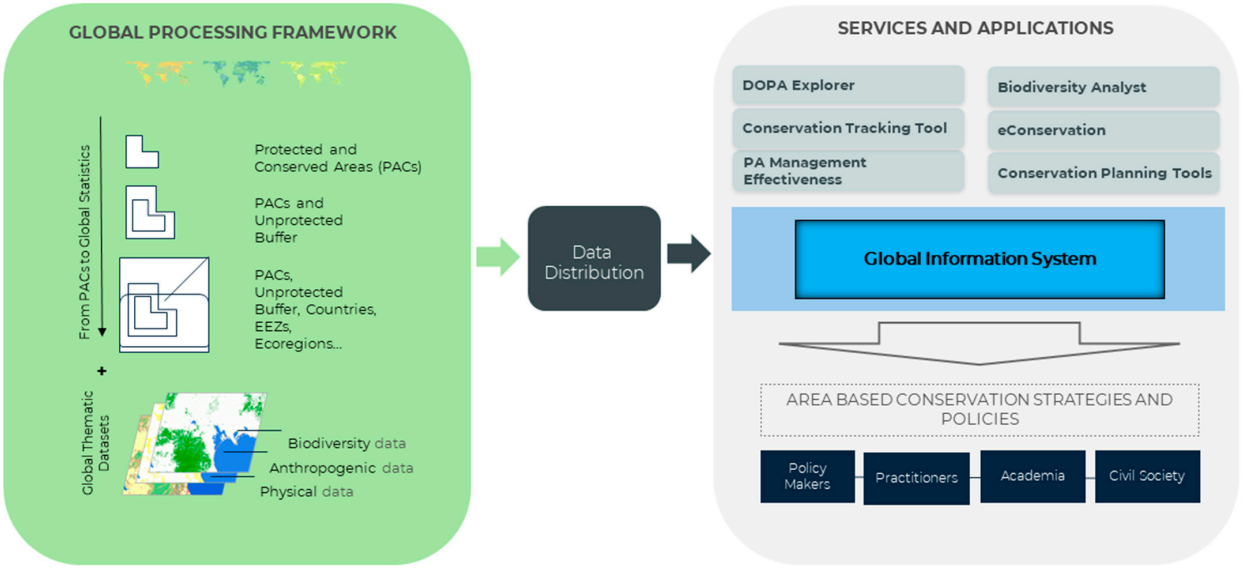


Figure 1. Schematic representation of the back-end approach, including high-level processes and workflows.

The new workflow consists of a sequence of bash scripts, which, in turn, launch in parallel a series of PostGIS functions, and is divided into three distinct phases (Table 1): (i) pre-processing, where key core and some of the thematic datasets are standardized and stored into a relational, spatial-enabled, database; (ii) processing, where the base and thematic dataset are intersected; (iii) post-processing, where raw results are aggregated,

according to both standards (e.g., DOPA Explorer) or on-demand (e.g., a specific reporting for a region, a subset of species assessment, etc.) aggregations. A detailed technical description of these workflows is available in Supplementary Data S1.

Table 1. Inputs, tools, and outputs in the DOPA workflow. For a detailed workflow description, see Supplementary Data S1.

Phase	Inputs	Tools	Outputs
Pre-processing	**Baseline datasets (=reporting levels)** Administrative layers • Global Administrative Units Layer (GAUL) [18] • Economic Exclusion Zones (EEZs) [19] Ecosystems • Terrestrial Ecoregions of the World (TEOW) [20] • Marine Ecoregions of the World (MEOW) [21] • Pelagic Provinces of the World (PPOW) [22] Conservation Sites • World Database on Protected Areas and Other Effective Area-Based Conservation Measures (WDPA/OECM) [23] **Thematic datasets** *Conservation sites* • World Database on Key Biodiversity Areas (WDKBA) [28] *Species* • IUCN species spatial data [29] • IUCN non-spatial data (assessments) [29] *Other* Global landcover and carbon datasets	**PostGIS** flattening scripts for multi-overlapping vectors. **GRASS-GIS**: Full workflow, organized as a series of scripts, for the estimation of Total Carbon Stocks as the sum of 5 different carbon 'pools'. The procedure is based on methodologies published in [24,25]	**Pre-processed relational database that includes** • Flat CEP (Countries, Ecoregions, Protection) vector spatial, polygon table; id = list of original components, in form of an array of ids) Flat species (vector spatial, polygon table; id = checklist, in form of an array of ids) species richness maps: cardinality of the array) Five global carbon datasets: • FAO Global Soil Organic Carbon, v. 1.6 [26] • ESA Biomass CCI Above Ground Carbon, v.4 (2020) [27] • Below Ground Carbon, Dead Wood Carbon, and Litter Carbon
Processing	Pre-processing outputs + global thematic datasets	**Postgres SQL-only scripts** for base protection coverages (country/land/marine/ecoregion/protection). ○ GRASS GIS scripts for base/thematic intersections (different for continuous or discrete raster datasets)	**GLOBAL output tables** Global raw intersections of base/thematic datasets (coverages cover the whole global surface)
Post-processing	processing outputs	○ Postgres SQL-only aggregation scripts (different for vector, raster continuous, or raster discrete inputs)	Country/ecoregion/protected area indicator tables (i.e., standard DOPA outputs) On-demand aggregations (e.g., specific reporting for a region or a site, a subset of species assessment, etc.)

2.1. Pre-Processing

In the pre-processing stage, baseline and thematic datasets are standardized and stored in a database (Table 1). Baseline Inputs include administrative layers such as Global Administrative Units (FAO, 2015) or the Economic Exclusions Zones (EEZ), Terrestrial and marine ecoregions (i.e., TEOW, MEOW, PPOW), and Protection (the World Database on Protected Areas and OECMs-WDPA/OECM); Thematic inputs include for example global species ranges from the IUCN Red List of Threatened Species, or Carbon stocks. All the datasets used are open access for their use in conservation.

The CEP (Country-Ecoregion-Protection) is considered a core output in this stage and is used here as a representative example of a pre-processing workflow. The grid and the

input datasets (in this case, the country, ecoregions, and protected areas data) intersect with each other and with a one-degree global grid using PostGIS scripts.

The intersection in each individual tile is performed in parallel on a different thread of a multi-core server, with ordering inversely proportional to the number of nodes (the higher the complexity, the sooner they are launched). The more complex tiles, which require more time, are all calculated at the beginning and the simpler ones at the end to optimize calculation times and not wait for the processing to conclude for a single, very complex tile.

The result is a spatial table in which each of the 64,800 tiles has a unique ID (*qid*) and contains multi polygons, named *cid*, according to the unique combination of the original, overlapping components (Country/Ecoregion/Protection = CEP). This table is a Pseudo-topology, a flat, simple feature layer that keeps, at the level of each single atomic (i.e., indivisible) geometry resulting from the intersection of the overlapping input layers, all the information from the original sources. Consequently, each individual polygon of CEP represents a unique combination of country, ecoregion, and protected area(s) and is identified by the unique numeric identifier *cid*. The same treatment is applied, for example, to the IUCN and Birdlife species dataset. The result is a vector spatial table and an equivalent raster partitioned in one-degree tiles, where ~26,000 species ranges are 'flattened' in six layers representing corals, sharks, amphibians, reptiles, birds, and mammals (for example, the ~11,000 bird species dataset from 2023 were flattened in a single spatial table of ~30 million records, where each *cid* object represents up to ~700 overlapping species).

The main output of this stage is the pre-processed relational database, which includes the CEP, pre-processed species data, and other pre-processed thematic datasets (see Table 1, Supplementary Data S1, for further details about the pre-processing stage).

During the pre-processing stage, there are also workflows aimed at generating standardized datasets that are subsequently used for the computation of specific indicators. The most significant example is the Carbon stocks workflow, where, starting from two publicly available datasets (FAO Soil Organic Carbon and ESA-CCI Above-Ground Biomass), three new global datasets are derived: Below-Ground Carbon (based on Above-Ground Biomass root-to-shoot ratios published by [25], and Dead Wood Carbon and Litter Carbon (following the procedure described in [24]. The final five Carbon stocks are then summed up to derive the Total Carbon stocks dataset (See Supplementary Data S1 for further details).

2.2. Processing

This stage involves the spatial intersection of the base dataset (CEP), created in the previous phase and stored in the pre-processing database, with a series of global thematic datasets. The aim is to calculate relevant raw statistics that, in the post-processing phase, will be aggregated to derive a series of biodiversity indicators. It is developed using bash/GRASS-GIS functions, which provide a set of simple and computationally efficient tools for raster data processing.

Based on the type of raster dataset to be intersected with CEP, two different GRASS functions are used: (i) *categorical rasters*: the surface in square meters of each category of the raster is computed for each object (*cid*) of the CEP (*r.stats* module); (ii) *continuous rasters*: basic univariate statistics (*n*. of non-null cells, min, max, range, mean, st.dev., variance, coeff. of variation, 1st, 2nd, 3rd quartile, 90th percentile) are computed for each object (*cid*) of the CEP (*r.univar* module). Regardless of the function used, the analysis is always performed at the resolution of the thematic dataset (the resolution of the raster datasets currently used in DOPA is in the range of 30 m–1 km).

The computational approach is based on parallelization, which can be summarized in three steps:

1. The global CEP dataset is created in one-degree tiles and then aggregated into a 10×10-degree grid for a total of 648 tiles covering the globe.
2. The relevant GRASS function is run in parallel on each single tile, where processing in a single tile is assigned to a different core of a multi-core server. With the aim of making the best use of available memory, the number of cores used for parallelization

is optimized for each thematic dataset and is inversely proportional to the resolution of the raster to be processed (the higher the resolution, the more memory is allocated for each process).

3. Output statistics for each tile are merged into a single CSV file, which is subsequently imported as a table in the Postgres SQL database.

For example, the intersection between CEP and IUCN species ranges for birds is completed in a single run, and the raw results are non-spatial tables, reporting surface in sqm by the intersecting *qids* (tiles) and *cids* (unique identifiers of the original combinations of objects) from both CEP and birds. The birds' raw_result table, for example, contains ~34 million records.

2.3. Post-Processing

This stage involves the aggregation of raw statistics computed on CEP during the previous step and the built-up of the metric for a relevant indicator and for the relevant reporting levels (i.e., country and/or ecoregion and/or PAC).

The aggregation of raw statistics is performed in two steps:

1. Two general SQL functions for the post-processing of raw statistics (one for categorical and one for continuous raster datasets, respectively) have been developed. The appropriate function is run using as input the raw statistics table of each dataset and producing in output an intermediate table, where statistics are rebuilt for each individual object through the aggregation of all relevant, unique elements using the *qid* and *cid* codes.
2. For each indicator, a specific script, tailored for the needs of the corresponding metric, processes the intermediate table and returns the final metric for each of the relevant reporting levels, ready for distribution via REST and web services.

Following our example, the original components of the previous CEP/birds intersections would be expanded in two steps (before by CEP *cid*, then by birds *cid*) using SQL scripts and reaggregated according to multiple criteria. The results are the standard checklists and spatial coverages by country, ecoregion, and protected areas, but also protected portion in the country, the land portion in the country, the protected land portion in the country, protected portion in the ecoregion, protected portion of the ecoregion in the country, and a series of indicators summarized in Supplementary Data S2 (SD2).

This approach allows the production of the requested metrics for each reporting level (protected area, country, and ecoregion) quickly and efficiently. Despite the starting raw statistics tables usually having several hundreds of thousands (sometimes millions) of rows, data aggregation functions work only on numeric attributes (no operations are performed on geometries), which requires very little processing time compared to processing geometries.

3. Results: Implementing the Back End

The back-end architecture approach to calculate area-based conservation indicators described above significantly reduced the processing time for protected area indicators. For example, originally, the system took approximately 6 months to process one single indicator for 16,000 protected areas larger than 100 km^2 using traditional GIS tools. Today, this time has been reduced to approximately 40 days (considering only the processing time) to process over 50 indicators with global coverage, including over 270,000 protected areas, all countries, and terrestrial, marine, and pelagic ecoregions. A full list of metrics and indicators, including 16 themes, intersecting 28 sources, and distributing 1292 endpoints through 50 functions, is available in Supplementary Data S2.

More importantly, this new architecture can respond to several area-based conservation research and policy questions from global to local scales quickly and efficiently. For example, if the question is "What is the surface in km^2 of croplands within protected areas of Indonesia?" the processing sequence would be (see Section 2.1 for definitions of *cid* and CEP):

1. Compute flat CEP as described in Section 2.1.
2. Export flat CEP as raster tiles (10 × 10 degrees wide; 30 m spatial resolution) and import them into GRASS DB.
3. In GRASS, compute areas by categories using the latest available version of Copernicus Land Cover (100 m spatial resolution). The result is a non-spatial table with coverage values in km^2 of all categories of land cover for each *cid* of CEP.
4. Import the non-spatial table in Postgres.
5. Aggregate again the *cids* accordingly through
   - Selection of cids satisfying the criteria included in the original question (iso3 = 'IDN' AND is_protected IS true AND lc_class = 'cropland')
   - Sum up of coverages for selected *cids*
6. The final metric is the area in km^2 of croplands within protected areas of Indonesia.

Steps 1–4 are the more time-consuming steps and are run only once for each update of DOPA indicators. Once these raw statistics are available as a table in the PostgreSQL database, only step 5 (a simple, quick and inexpensive query) is required to answer the question.

The implementation of the workflow comes to life through two specific applications we use here as an example: computing of global indicators to support biodiversity policy reporting and spatial conservation planning for renewable energy in the EU.

3.1. Global Indicators to Support International Biodiversity Policy Reporting

Most countries in the world agreed to the KM-GBF to be achieved by 2050 with 2030 milestones. These include 23 targets, of which Target 3 calls for a global network of PACs that covers 30% of the globe and is well connected, ecologically representative, equitably governed, and effectively managed, among other important attributes. Similarly, the 17 SDGs of the UN's 2030 agenda [4] include Goal 14 and Goal 15, for which a protected area global and national coverage indicator calculation is needed. Fundamental to track progress towards these targets and goals and to facilitate country reporting is to offer easily accessible and up-to-date international and national relevant metrics and indicators. The latter is especially important for countries with low technical capacity. Through the workflows and techniques described above, the DOPA back end can provide this. For example, policy indicators at a national, regional, and global level that are recalculated regularly (Table 2) or more sophisticated analyses combining connectivity and protection metrics (Figure 2).

Table 2. Examples of outputs on global, regional, and national PAC indicators.

Indicator Relevant to KM-GBF and SDGs	**Global**	**Regional—Europe**	**National—Italy**
Terrestrial Protected Area Coverage	21,295,150 km^2 (14.45%)	1,086,134 km^2 (26.23%)	65,057 km^2 (21.57%)
Marine (EEZ) Protected Area Coverage	29,245,536 km^2 (8.06%)	654,856 km^2 (11.21%)	57,452 km^2 (10.71%)
Ecoregions representation	Number of ecoregions with these coverages: 0–17%: 644 17–30%: 180 30–50%: 137 More than 50%: 136	Number of ecoregions with these coverages: 0–17%: 16 17–30%: 16 30–50%: 20 More than 50%: 16	Number of ecoregions with these coverages: 0–17%: 4 17–30%: 4 30–50%: 5 More than 50%: 2
Protection of key biodiversity areas	KBA fully protected: 3278 KBA partially protected: 6780 KBA not protected: 5890	KBA fully protected: 1266 KBA partially protected: 1972 KBA not protected: 108	KBA fully protected: 41 KBA partially protected: 127 KBA not protected: 4

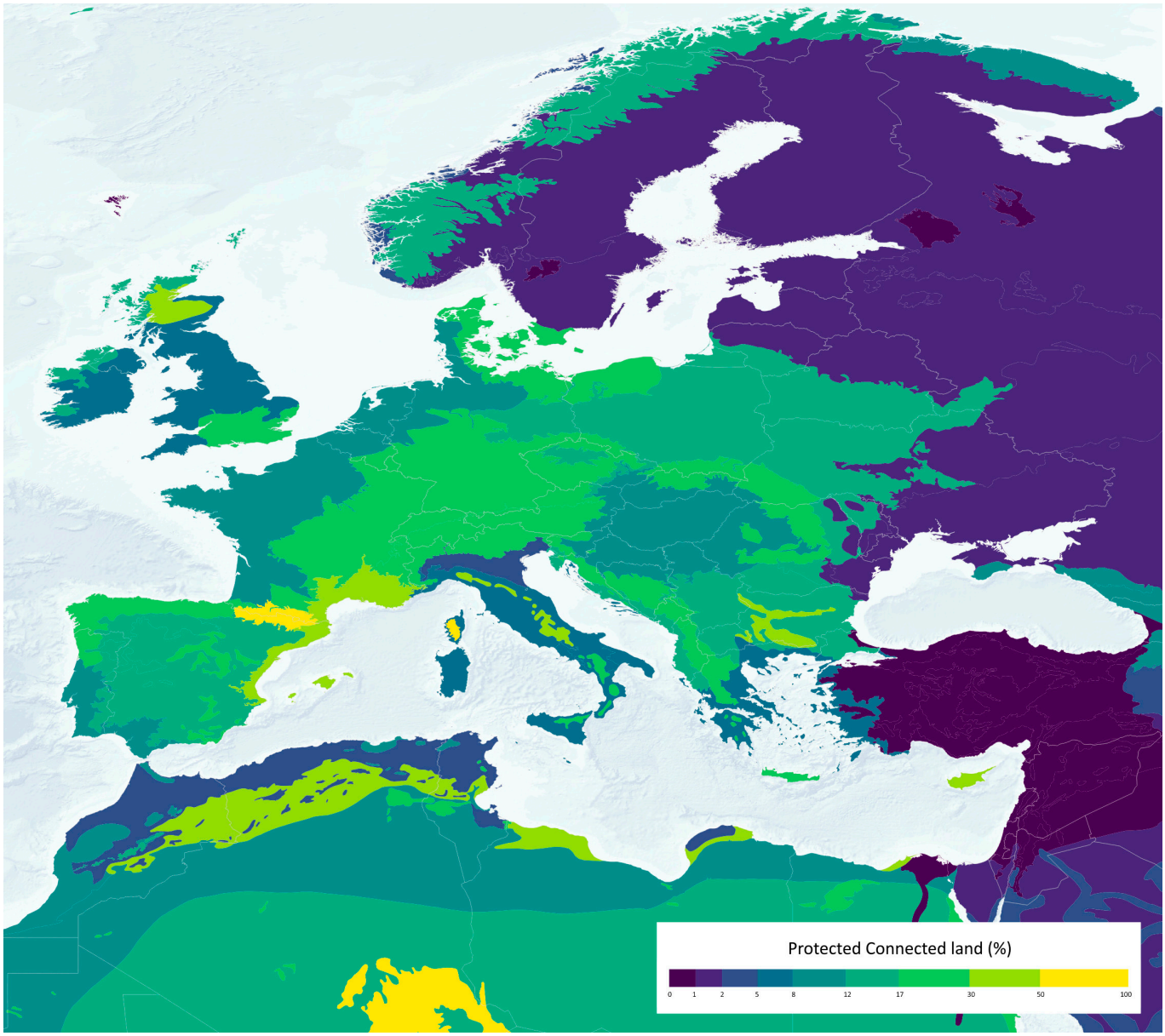


Figure 2. Percentage of area covered by protected and connected land in European and Northern Africa ecoregions, based on ProtConn indicator for a media dispersal distance of 10 km. Source: [30].

3.2. Spatial Conservation Planning for Renewable Energy in the EU

The EU needs to assess the risks and opportunities of approved policies and directives to ensure their effective implementation. In 2023, DOPA architecture was used to support the identification of go-to and no-go areas in EU 27 for the deployment of solar and wind farms. This consisted of developing checklists and maps of species richness outside and inside protected areas in the EU. The aim was to determine which endemic and threatened birds, mammals, amphibians, and reptiles could be potentially threatened by the development of solar and wind farm development. The final result was a map that showed the areas in the EU where more threatened and endemic species could be impacted by the development of renewable energy farms (Figure 3). This information is now publicly available at the EC Energy and Industry Geography Lab online platform (see https://energy-industry-geolab.jrc.ec.europa.eu/ (accessed on 20 June 2024)).

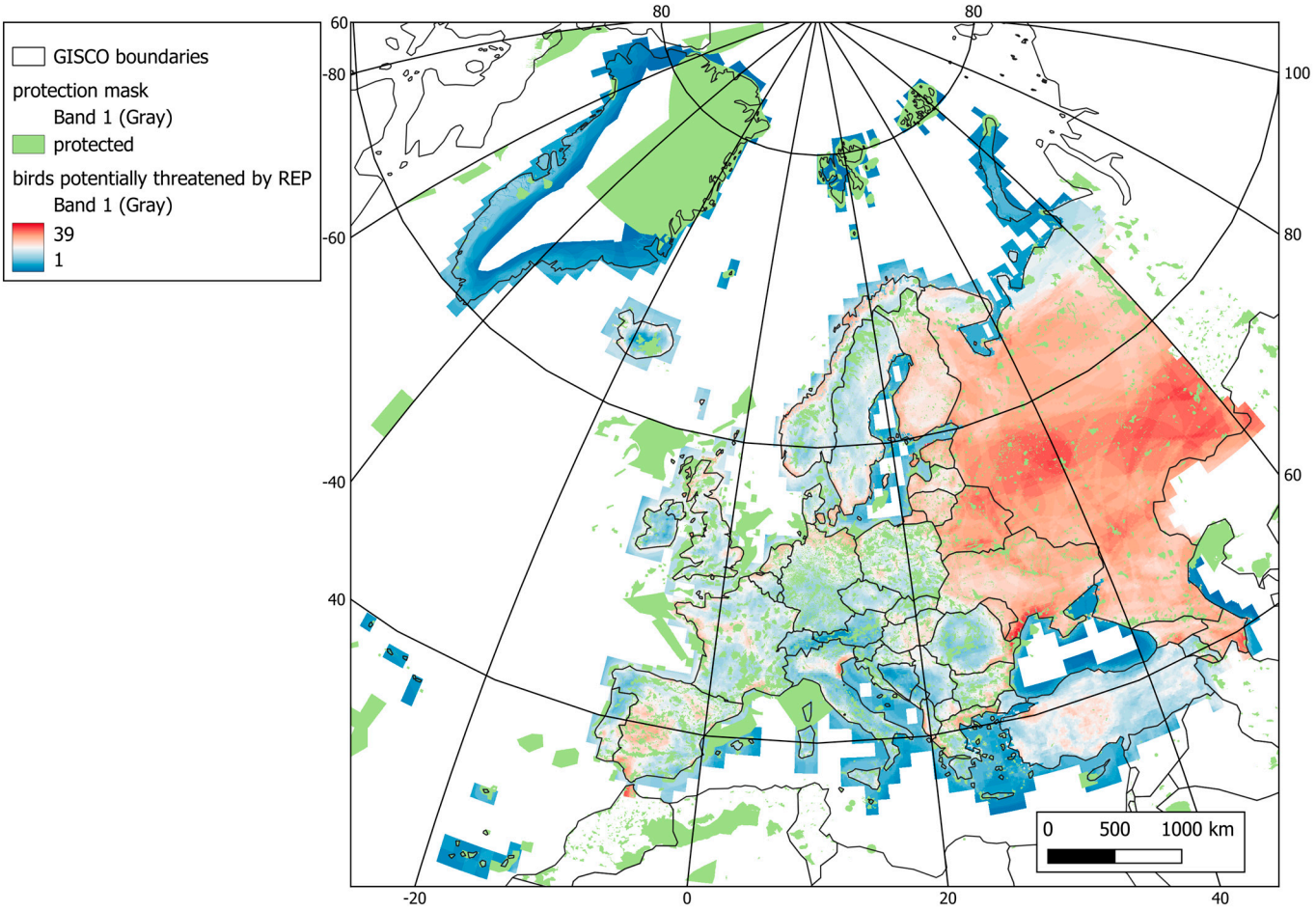


Figure 3. Number of birds potentially threatened by renewable energy production (REP) in the EU. Source: JRC (2024).

4. Discussion: The Future of DOPA Back End and Its Applications

Integrated spatial planning, across scales and within all sectors of society, has become key to tackling the environmental challenges over the next decades. This includes needs ranging from assessing the performance of conservation actions to avoiding and minimizing impacts on biodiversity from human activity. Area-based conservation is a fundamental part of this as it focuses on the use of spatial planning tools to support decisions by governments, private and financial sectors, and conservation practitioners on the conservation and management of biodiversity in specific places [6,7]. Moreover, quick and efficient area-based analysis and tools are essential if we are to address the environmental challenges of the 21st century [17].

The DOPA was developed in its first decade to produce protected area indicators at global, regional, national, and site levels and inform area-based conservation decisions at different scales [15]. While the initial technological focus was on distributed services to ease data integration and address multidisciplinary challenges [31], including increased modelling capabilities, reporting needs, and fast support to policy requests, have been shifting efforts towards more reliable tools and faster updates of indicators [13–15]. Here, we describe how building from the development of the DOPA and responding to user and policy needs, the back-end architecture and analytical approach of DOPA has developed over the years, pursuing speed and efficiency. Timely and up-to-date biodiversity information, data, and metrics at global, national, and site level scales can now be provided at a speed that was not possible before. Moreover, it allows us to answer specific questions, such as the risk exposure of a specific point in the globe or the attributes of any of the over 250,000 protected and conserved areas globally. Below, we discuss further the novelty

of this approach, the infrastructure design and governance, and its potential to support policy processes at different scales and inform area-based conservation decisions over the next decades.

4.1. Achieving Technical Efficiency through Innovation

The novelty of this approach does not reside in the actual methods and techniques applied but in the design of the back end, and its implementation is driven by the need to meet user needs. Each step and tool has been carefully selected and tested to maximize efficiency and speed. Decoupling the tabular data to the geometry has greatly sped up the process, as well as the application flattening and parallelization, two very common GIS techniques that together significantly reduce the processing times.

Fundamental to this approach is the fact that DOPA is built and based on open code and open-access tools and that it uses global datasets that are also open-access for conservation purposes under specific terms of use. Limitations still exist in using some of these global datasets for commercial purposes. This is by for-profit organizations such as companies, independent consultants, or financial institutions. However, this is bound to change in a world where increasingly conservation practitioners, policymakers, impact assessors, businesses, and local communities need access to biodiversity data for informed decision-making on natural resource management [32].

4.2. Integrated System Design and Governance

DOPA's high-level back-end architecture emphasizes a co-design approach that integrates global monitoring with the flexibility for regional and national adaptation. This dual approach, involving both bottom-up and top-down processes, establishes a global baseline while allowing regional and national entities to adapt or complement this baseline with local inputs. This dynamic is moderated and further verified by regional and sub-regional hubs with potential local engagement.

The new back-end approach also offers a versioning scheme and licensing considerations to ensure traceability and uptake over time. The process plays a key role in data verification, ensuring the integrity and accuracy of datasets from different sources, particularly national and local. This is critical to incorporate diverse data and knowledge inputs, as well as indigenous and local knowledge. Moreover, the structured and openly-linked handling of datasets—including ontology, namespaces, topics, and controlled vocabularies—addresses current terminological confusion. An ontology for key variables and indicators, independent of thematic content, and the establishment of controlled vocabularies is fundamental to ensure clarity and consistency in data interpretation and use.

4.3. Developing Indicators for Area-Based Conservation 2030–2050

The back end developed through DOPA has the potential to become a reference model and resource for supporting third parties in their area-based conservation efforts toward implementing and achieving the 2030 and 2050 goals and targets. This architecture offers the means to further channel biodiversity data into policy and decision-making by providing an effective means to convert data into indicators and share these via REST Services. This includes serving key international, regional, and national policy processes supporting decisions for national governments and policy makers but also connecting to other global initiatives such as the Global Biodiversity Observing System (GBiOS). GBiOS is a proposal from the Group on Earth Observations Biodiversity Observation Network (GEO BON) and its partners, that would combine technology, data, and knowledge from around the world to foster collaboration and data sharing among countries [33].

For example, at the international level, the KM-GBF includes Target 3, for which most components need area-based planning global calculations. As explained here, DOPA has already been serving protected coverage, ecoregions [34], and connectivity metrics and indicators [35] to inform Aichi Target 11 of the previous GBF [36] and will continue to

provide this to monitor progress toward the achievement of the new targets under the KM-GBF. In addition, Target 1 calls for "...participatory, integrated, and biodiversity inclusive spatial planning" [5]. This includes the indicator "Percent of land and seas covered by biodiversity-inclusive spatial plans", which methodology is yet to be developed [11]. The new back-end infrastructure could serve directly as a resource for calculating and providing this indicator or as a model of work that can easily be replicated by anyone. Along the same lines, this architecture could also be adopted by the global knowledge support service for biodiversity (GKSSB, https://gkssb.chm-cbd.net/ (accessed on 20 June 2024)) that is currently under discussion at the CBD. This initiative, launched during CBD COP15 and led by UNEP-WCMC and its partners, aims to connect existing biodiversity knowledge hubs and other biodiversity-related data providers and tools to support national institutions in implementing and achieving the KM-GBF targets [37].

At the regional level, the EU biodiversity strategy commits to achieving 16 targets by 2030 [12]. To support the implementation of this strategy, the European Commission established the Knowledge Centre for Biodiversity (KCBD) in October 2020 to help monitor progress towards its actions and targets [38]. The indicators used and reported by the KCBD are derived from a variety of EU reporting schemes (e.g., Member States are reporting data on a number of indicators, including protected areas coverage) or obtained from independent sources (e.g., the grassland butterfly index, based on citizen science and sourced from the European Butterfly Monitoring Scheme partnership established by Butterfly Conservation Europe) [39]. From a policy point of view, the DOPA, by providing area-based conservation elements of the EU and the global biodiversity strategies independently from the data reported by countries, provides useful information that can be used to highlight potential discrepancies and help understand underlying causes. The DOPA also provides a well-documented open infrastructure that can help identify and structure complex information needed by researchers, policymakers, NGOs, industry, and citizens.

Nationally, the switch from site-based conservation to considering the wider landscape requires more sophisticated analyses of the whole landscape matrix and its actors. However, the infrastructure can easily be customized to take more local datasets into account and support integrated spatial planning and coordination between government agencies, providing quick nationwide answers to key policy and conservation action questions. This also includes supporting biodiversity assessments and risk screening for private companies and financial institutions in two ways: first, to facilitate business corporate sustainability reporting in compliance with, for example, EU CSRD regulation [40]; second, to support private sector decisions to avoid and minimize impacts on biodiversity before they happen (see Section 3.2 for an example).

5. Conclusions

The tools, workflows, and processes developed through the evolution of DOPA have provided with metrics and indicators to a wide range of actors supporting biodiversity policy reporting for over a decade. Considering user feedback and aiming to address policy needs through technical innovation, the DOPA back end has developed into a faster and more efficient tool that can deliver on-demand analyses to respond to complex conservation questions.

Looking ahead, its architecture and back end have the potential to further support the implementation of international, regional, and national policies through timely and quick provision of answers to inform decisions to face the environmental challenges of the next two decades. More importantly, the transparency of the processes and workflows of the DOPA and the low-cost infrastructure that supports it allows for its reuse by third parties, and this is for local to global analyses. The technical capability of DOPA's back end to easily integrate new indicators that can be delivered quickly and efficiently to other platforms should motivate its further development and use in the fast-changing landscape of biodiversity knowledge management.

Supplementary Materials: Supplementary Data S1 (SD1): Links to detailed methodologies and workflows: DOPA workflows: https://github.com/andreamandrici/dopa_workflow, accessed on 10 September 2024; Carbon processing worklflows: https://github.com/giacomo-gcad/carbon, accessed on 10 September 2024. Supplementary Data S2 (SD2): The full list of parameters calculated by DOPA back ends is listed and updated in real time here: https://rest-services.jrc.ec.europa.eu/services/d6dopa/dopa_43/get_dopa_function_output_parameters?format=html, accessed on 10 September 2024.

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Data Availability Statement: All data used by the DOPA are in the public domain, as documented in the manuscript. Only a few datasets cannot be used for commercial purposes.

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References

1. UNFCCC. What Is the Triple Planetary Crisis? | UNFCCC. 2022. Available online: https://unfccc.int/news/what-is-the-triple-planetary-crisis (accessed on 6 May 2024).
2. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef] [PubMed]
3. IPBES. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services*; IPBES Secretariat: Bonn, Germany, 2019. [CrossRef]
4. United Nations General Assembly. *Transforming Our World: The 2030 Agenda for Sustainable Development*; outcome document of the United Nations summit for the adoption of the post-2015 agenda, RES/A/70/L.1.; United Nations General Assembly: New York, NY, USA, 2015.
5. CBD. Decision adopted by the conference of the parties to the convention on biological diversity 15/4. In *Kunming-Montreal Global Biodiversity Framework*; The Convention on Biological Diversity: Montreal, QC, Canada, 2022.
6. Bhola, N.; Klimmek, H.; Kingston, N.; Burgess, N.D.; van Soesbergen, A.; Corrigan, C.; Harrison, J.; Kok, M.T.J. Perspectives on area-based conservation and its meaning for future biodiversity policy. *Conserv. Biol.* **2021**, *35*, 168–178. [CrossRef] [PubMed]
7. Maxwell, S.L.; Cazalis, V.; Dudley, N.; Hoffmann, M.; Rodrigues, A.S.L.; Stolton, S.; Visconti, P.; Woodley, S.; Kingston, N.; Lewis, E.; et al. Area-based conservation in the twenty-first century. *Nature* **2020**, *586*, 217–227. [CrossRef] [PubMed]
8. Gurney, G.G.; Adams, V.M.; Álvarez-Romero, J.G.; Claudet, J. Area-based conservation: Taking stock and looking ahead. *One Earth* **2023**, *6*, 98–104. [CrossRef]
9. Dudley, N. *Guidelines for Applying Protected Area Management Categories*; IUCN: Gland, Switzerland, 2008. [CrossRef]
10. Alves-Pinto, H.; Geldmann, J.; Jonas, H.; Maioli, V.; Balmford, A.; Latawiec, A.E.; Crouzeilles, R.; Strassburg, B. Opportunities and challenges of other effective area-based conservation measures (OECMs) for biodiversity conservation. *Perspect. Ecol. Conserv.* **2021**, *19*, 115–120. [CrossRef]
11. CBD. Indicators for the Kunming-Montreal Global Biodiversity Framework. *Indicator Repository*. 2024. Available online: https://gbf-indicators.org/ (accessed on 21 May 2024).
12. EC. EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380 (accessed on 20 June 2024).

13. Dubois, G.; Schulz, M.; Skoien, J.; Cottam, A.; Temperley, W.; Clerici, M.; Drakou, E.; Klooster, J.V.; Verbeeeck, B.; Palumbo, I.; et al. *An Introduction to the Digital Observatory for Protected Areas (DOPA) and the DOPA Explorer (Beta)*; European Union: Luxembourg, 2013.
14. Bastin, L.; Mandrici, A.; Battistella, L.; Dubois, G. Processing Conservation Indicators with Open Source Tools: Lessons Learned from the Digital Observatory for Protected Areas. *Free. Open Source Softw. Geospat. (FOSS4G) Conf. Proc.* **2017**, *17*, 101–111. [CrossRef]
15. Dubois, G.; Bastin, L.; Bertzky, B.; Mandrici, A.; Conti, M.; Saura, S.; Cottam, A.; Battistella, L.; Martínez-López, J.; Boni, M.; et al. Integrating Multiple Spatial Datasets to Assess Protected Areas: Lessons Learnt from the Digital Observatory for Protected Areas (DOPA). *ISPRS Int. J. Geo-Inf.* **2016**, *5*, 242. [CrossRef]
16. UNEP. Actions Towards Achieving Aichi Biodiversity Target 11: Including Areas of Particular Importance for Biodiversity and Improving Ecological Representation. *UNEP/CBD/COP/22/INF/30*. 2018. Available online: https://www.cbd.int/doc/notifications/2015/ntf-2015-027-pa-en.pdf (accessed on 10 June 2024).
17. Hoffmann, S. Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. *Biodivers. Conserv.* **2022**, *31*, 325–352. [CrossRef]
18. FAO. The Global Administrative Unit Layers (GAUL). 2015. Available online: https://data.apps.fao.org/catalog/dataset/global-administrative-unit-layers-gaul-2015 (accessed on 19 April 2024).
19. Flanders Marine Institute. Maritime Boundaries Geodatabase, Version 12. 2023. Available online: https://www.marineregions.org/ (accessed on 20 June 2024).
20. Olson, D.M.; Dinerstein, E.; Wikramanayake, E.D.; Burgess, N.D.; Powell, G.V.N.; Underwood, E.C.; D'amico, J.A.; Itoua, I.; Strand, H.E.; Morrison, J.C.; et al. Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience* **2001**, *51*, 933–938. [CrossRef]
21. Spalding, M.D.; Fox, H.E.; Allen, G.R.; Davidson, N.; Ferdaña, Z.A.; Finlayson, M.; Halpern, B.S.; Jorge, M.A.; Lombana, A.; Lourie, S.A.; et al. Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. *BioScience* **2007**, *57*, 573–583. [CrossRef]
22. Spalding, M.D.; Agostini, V.N.; Rice, J.; Grant, S.M. Pelagic provinces of the world: A biogeographic classification of the world's surface pelagic waters. *Ocean. Coast. Manag.* **2012**, *60*, 19–30. [CrossRef]
23. UNEP-WCMC and IUCN. Protected Planet: The World Database on Protected Areas (WDPA)/The World Database on Other Effective Area-based Conservation Measures (WD-OECM) [On-line]. 2024. Available online: www.protectedplanet.net (accessed on 20 June 2024).
24. Harris, N.L.; Gibbs, D.A.; Baccini, A.; Birdsey, R.A.; de Bruin, S.; Farina, M.; Fatoyinbo, L.; Hansen, M.C.; Herold, M.; Houghton, R.A.; et al. Global maps of twenty-first century forest carbon fluxes. *Nat. Clim. Chang.* **2021**, *11*, 234–240. [CrossRef]
25. IPPC. Chapter 4: Forest Land. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPPC: Geneva, Switzerland, 2019.
26. FAO. *Global Soil Organic Carbon Map—GSOCmap v.1.6 Technical Report*; FAO: Rome, Italy, 2022. [CrossRef]
27. Santoro, M.; Cartus, O. ESA Biomass Climate Change Initiative (Biomass_cci): Global Datasets of Forest Above-Ground Biomass for the Years 2010, 2017, 2018, 2019 and 2020, v4. (2023) 5183 Files, 302039459020 B. Available online: https://catalogue.ceda.ac.uk/uuid/af60720c1e404a9e9d2c145d2b2ead4e/ (accessed on 24 July 2024). [CrossRef]
28. BirdLife International. The World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Re:wild, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. 2024. Available online: https://wdkba.keybiodiversityareas.org (accessed on 24 July 2024).
29. IUCN. *The IUCN Red List of Threatened Species*; IUCN: Gland, Switzerland, 2024.
30. Saura, S.; Bastin, L.; Battistella, L.; Mandrici, A.; Dubois, G. Protected areas in the world's ecoregions: How well connected are they? *Ecol. Indic.* **2017**, *76*, 144–158. [CrossRef] [PubMed]
31. Pearlman, J.; Craglia, M.; Bertrand, F.; Nativi, S.; Gaigalas, G.; Dubois, G.; Niemeyer, S.; Fritz, S. EuroGEOSS: An interdisciplinary approach to research and applications for forestry, biodiversity and drought. In Proceedings of the 34th International Symposium on Remote Sensing of Environment—The GEOSS Era: Towards Operational Environmental Monitoring, Sydney, NSW, Australia, 10–15 April 2011.
32. Stephenson, P.J.; Stengel, C. An inventory of biodiversity data sources for conservation monitoring. *PLoS ONE* **2020**, *15*, e0242923. [CrossRef] [PubMed]
33. Gonzalez, A.; Vihervaara, P.; Balvanera, P.; Bates, A.E.; Bayraktarov, E.; Bellingham, P.J.; Bruder, A.; Campbell, J.; Catchen, M.D.; Cavender-Bares, J.; et al. A global biodiversity observing system to unite monitoring and guide action. *Nat. Ecol. Evol.* **2023**, *7*, 1947–1952. [CrossRef] [PubMed]
34. UNEP-WCMC. Protected Planet Report 2020. 2020. Available online: https://livereport.protectedplanet.net (accessed on 21 May 2024).
35. Saura, S.; Bertzky, B.; Bastin, L.; Battistella, L.; Mandrici, A.; Dubois, G. Global trends in protected area connectivity from 2010 to 2018. *Biol. Conserv.* **2019**, *238*, 108183. [CrossRef] [PubMed]
36. CBD. Strategic Plan for Biodiversity 2011–2020. 2010. Available online: https://www.cbd.int/sp (accessed on 21 May 2024).

37. UNEP-WCMC. A Global Knowledge Support Service for Biodiversity: Perspectives, Options, and Next Steps. 2022. Available online: https://gkssb.chm-cbd.net/sites/gkssb/files/2023-02/GKSSB%20Discussion%20Paper%2013.12.22%20FINAL.pdf (accessed on 21 May 2024).
38. EC. Knowledge Centre for Biodiversity. 2024. Available online: https://knowledge4policy.ec.europa.eu/biodiversity_en (accessed on 21 May 2024).
39. Viti, M.M.; Gkimtsas, G.; Liquete, C.; Dubois, G.; Borg, J.; Costa, S.D.; Teller, A.; Hauser, R.; Robuchon, M. Introducing the progress monitoring tools of the EU Biodiversity Strategy for 2030. *Ecol. Indic.* **2024**, *164*, 112147. [CrossRef]
40. EU. Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as Regards Corporate Sustainability Reporting. 2022. Available online: https://eur-lex.europa.eu/eli/dir/2022/2464/oj (accessed on 21 May 2024).

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