GLOBAL ECOSYSTEMS ATLAS

The Global Ecosystems Atlas: comprehensive and systematic mapping of Earth's ecosystems

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Summary

Halting and reversing biodiversity loss is central to the Kunming-Montreal Global Biodiversity Framework, yet a lack of consistent, spatially comprehensive data on ecosystem distributions has undermined our ability to monitor progress against its goals and targets. Here we introduce the Global Ecosystems Atlas initiative, convened by the intergovernmental Group on Earth Observations (GEO) in collaboration with the Secretariat of the Convention on Biological Diversity (CBD) and International Union for Conservation of Nature (IUCN), and developed through an international collaboration among intergovernmental organisations, non-government organisations, scientists, governments, and practitioners. The core elements of the Global Ecosystems Atlas (www.globalecosystemsatlas.org) are (i) an open-access geospatial dataset designed to represent the spatial distribution of 110 ecosystem functional groups, 25 biomes, and 10 realms as classified by the IUCN Global Ecosystem Typology, (ii) a data catalogue of pre-existing geospatial datasets that were developed to represent ecosystems, and (iii) a spatial dataset of ecosystem occurrence records (*EcoTrain*) annotated by a team of trained interpreters to provide training and validation data across the initiative. In addition to these three core data products, the Global Ecosystems Atlas initiative includes guidelines, mapping and analysis tools, an online application and API, and online training resources to enable individuals, governments, corporates and other stakeholders to access ecosystems data, develop their own maps of

ecosystem functional groups, and produce reports on the extent and distribution of ecosystems at a variety of spatial scales. Future phases of the Global Ecosystems Atlas initiative will focus on developing further essential data and resources required to advance our knowledge of the distribution, change dynamics and condition of all of the world's ecosystems. We anticipate that the Global Ecosystems Atlas will emerge as a central resource for distributing knowledge about the distribution and change of all of the world's ecosystems to support conservation and restoration efforts worldwide.

1. Introduction

Ecosystems provide essential benefits for people, biodiversity and the economy, yet their ongoing degradation and loss remain a primary driver of the global decline of biodiversity[1,2]. The *Kunming-Montreal Global Biodiversity Framework*, which was adopted by 196 nations under the *Convention on Biological Diversity* in 2022, set an agenda for action to address this decline, with parties required to report comprehensive estimates of change in extent for all of the world's ecosystems as a basis for monitoring, management, planning and policy[3]. A range of global and national scale initiatives and platforms have been developed over recent decades to promote monitoring of the world's biodiversity, including defining Essential Biodiversity Variables[4], Global Forest Watch[5], the Nature Positive Initiative, and the IUCN Red List of Ecosystems[6]. However, no existing initiative has been able to provide a global, spatially comprehensive geospatial dataset on ecosystems suitable for consistent monitoring of extent and change of the world's diverse ecosystems. As a result, only 18 of the 75 country parties (24%) to the CBD that recently reported progress towards the KMGBF targets used ecosystem-specific data on ecosystem extent; others used land cover maps (33%), forest cover or inventory data (26.7%)[7]. The lack of ecosystem maps was identified as a common barrier for supporting national reporting, monitoring progress or enforcing spatial plans[8]. The paucity of fundamental spatial data on the world's ecosystems highlights a clear imperative for new efforts to compile, synthesise, and serve open-access geospatial data on ecosystems.

The Global Ecosystems Atlas initiative was launched in 2023 to provide consistent and spatially comprehensive data on the extant distribution of all ecosystems to meet the needs of the GBF and a variety of other applications (Figure 1). Here, we describe the first phase of this initiative (Figure 2) by introducing the challenge of ecosystem mapping to explain why a comprehensive geospatial dataset of the world's ecosystems has yet to be developed with a unified ecosystem classification system. We outline the importance of an ecosystem map dataset that is co-created with, and suitable for country-level stakeholders. We then describe the formulation of the Global Ecosystems Atlas initiative to fill this crucial gap, and its core innovations, including (i) a global-scale geospatial dataset designed to represent the spatial distribution of 110 ecosystem functional groups, 25 biomes, and 10 realms classified according to the IUCN Global Ecosystem Typology, (ii) a data catalogue of pre-existing geospatial datasets that were developed to represent ecosystems, and (iii) a spatial dataset of ecosystem occurrence records (*EcoTrain*). Lastly, we detail the operational system developed to achieve these open-access outputs and outline a future phase to provide data on change in ecosystem extent, higher thematic resolution maps of ecosystems and spatial data representing the condition of ecosystems.

2. Challenges and opportunities for mapping the world's ecosystems

Geospatial datasets for ecosystems should be able to underpin fundamental activities for ecosystem conservation and reporting, including those ranging from landscape level planning and prioritisation for biodiversity at local, national and global scales to specific analyses designed to improve our understanding of ecosystem distributions and their spatial dynamics. These activities are often implemented at a range of spatial scales but ideally could be scaled up to comprehensive global analyses for all ecosystems. Geospatial data on the world's ecosystems should also be globally complete and spatially contiguous across environmental domains,

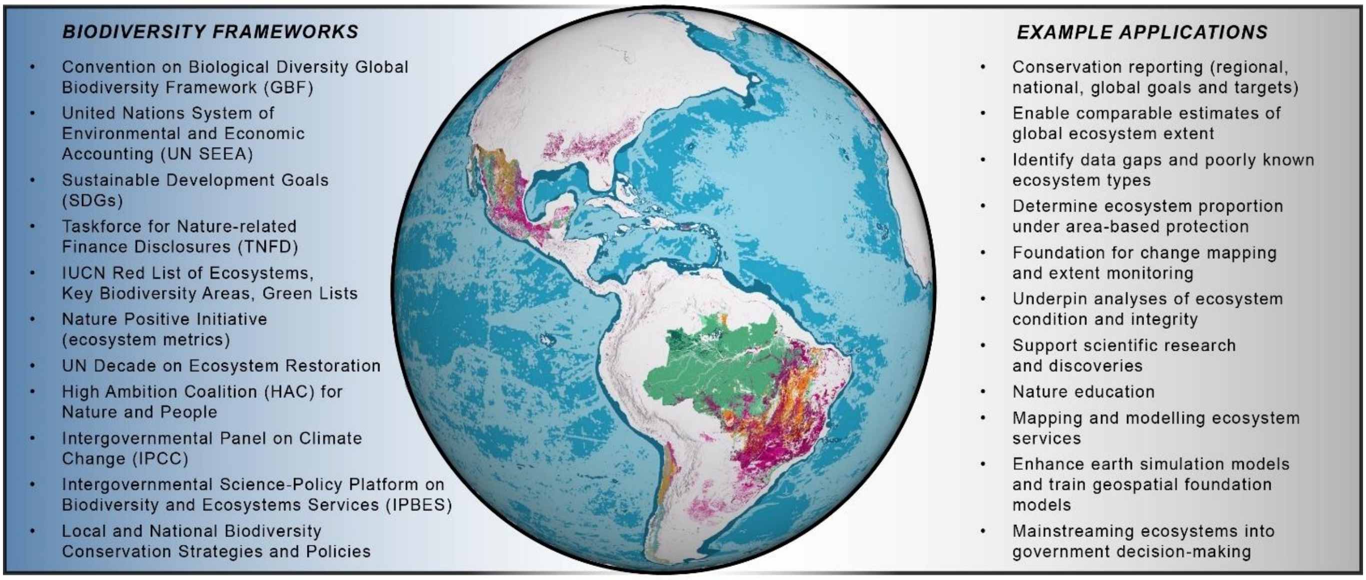

Fig. 1. Relevant environmental conservation frameworks and applications of the Global Ecosystems Atlas. Schematic detailing the range of conservation frameworks the Global Ecosystems Atlas expects to support. Example applications are those that typically require spatially explicit data on the distribution of ecosystems.

spanning the deepest ecosystems in the ocean to the highest altitude mountain ecosystems, while including rare natural ecosystems as well as anthropogenic ecosystems to enable cross-comparisons of all the world's ecosystem types. Finally, data and resources to support ecosystem conservation, management and restoration should be freely available, supported by open-access code repositories and accessible documentation to enable propagation of uncertainties and of knowledge, through to all possible end-use cases, while offering mechanisms for attribution that promote fair and equitable use of data[9,10].

Spatially comprehensive maps of ecosystem types that meet these requirements have been available sub-globally for decades[11]. Primarily developed at regional and national scales, these ecosystem maps are often underpinned by comprehensive field programs, extensive networks of contributors, and careful data curation and management[12], and have been instrumental in supporting policy implementation and governance at the spatial scales for which they were developed. Several studies have shown that maps developed at regional and national scales can generally achieve higher overall accuracy, because quality assurance of training data can better incorporate deep, localized expertise. Model predictors can also be better tuned to local conditions, and, for a given classification scheme, spatial variability in map classes is often reduced[13,14]. While regional and national mapping programs are often considered the optimal approach for developing ecosystem maps, owing to different data standards, program objectives, classification schemes, mapping methods, and the need to develop complex map synthesis routines, ecosystem maps developed at these sub-global scales have historically been difficult to bring together to support larger-scale analyses, though some domain-specific examples are available[15].

At the global scale, advanced mapping programs have developed high-resolution maps of specific ecosystem types that are now widely used to support management and conservation. For example, spatial data with acceptable accuracies are now available that depict the distribution of several ecosystem types, including mangroves[16], tidal flats[17], coral reefs[18], tidal marshes[19], sea ice[20], rivers and wetlands[21-24], seagrass[25], tropical moist forests[26], and glaciers [27] (see Supplemental Table S1). Many other large-scale mapping programs have focused on land cover types[28-32] as well as other environmental characteristics, such as surface water[33], tree distributions[34], biomass[35], multifactorial combinations of climate regions, land cover and topographic variables[36], and generic classes such as 'forest'[37]. Although these products have been essential for advancing the purposes for which they were developed, their utility for directly enabling national and global reporting on ecosystem-related targets and indicators is often limited by issues such the representation of map classes that are conceptually different to ecosystems (e.g., 'tree cover', 'bare earth' or 'water')[38-40], focus on one or a few map classes, or lack consistency with other spatial datasets.

Two additional issues have slowed the progress on the development of a global map of the distribution of ecosystems. First, the historical lack of a single, standardised ecosystem classification system has led to significant variation and inconsistency of ecosystem maps. This can be attributed to differing definitions of map classes, vague class descriptions[38], and large variation in the thematic scales at which map units are represented[41], even when they are intended to represent superficially similar ecosystem types. A major advance in resolving these inconsistencies was the development and adoption of the *IUCN Global Ecosystem Typology*[42], a unifying classification framework that integrates ecosystem functions and ecological processes, and their characteristic biota, into a conceptually robust and scalable classification system that can support spatially explicit representation of all ecosystems. The typology is structured as six hierarchical levels of classification to acknowledge varying levels of biotic organisation (from realms to biomes to ecosystem functional groups to ecosystem types), which supports application across different thematic and spatial scales and enables synthesis across a plethora of existing classification schemes[42]. The typology has now been broadly adopted as the international classification standard for ecosystems and is recommended for ecosystem-specific reporting on indicators agreed under the Convention of Biological Diversity, the UN System of Environmental Economic Accounts, and the International Union for Conservation of Nature (IUCN) Red List of Ecosystems [40,43,44]. The widespread adoption of the Global Ecosystem Typology has delivered the robust framework required to support coordinated global-scale mapping activities, with the 110 Ecosystem Functional Groups (Level 3 of the typology) identified as an appropriate thematic scale for developing the first global high-resolution map of ecosystems, noting that existing global ecosystem typology maps are for indicative purposes only and finer thematic resolution maps may be needed to support some of the diverse uses of ecosystem maps[42]. The typology provides a critical pathway for integrating a wide variety of ecosystem maps, developed for diverse purposes and at a range of administrative, thematic and spatial scales, into a common language for ecosystems. Crucially, this enables the use of cross-referencing, map harmonisation and synthesis approaches to bring together, for the first time, existing ecosystem maps into a single data product representing ecosystems[38].

The second issue that has slowed progress towards a global map of ecosystems is that Earth observation-based mapping approaches, which are well-proven in producing high-quality maps of specific ecosystem types at the global scale. These have been limited in their ability to achieve acceptable performance when predicting distributions of the large number of map classes required to represent Earth's full ecosystem diversity. Furthermore, many of the elements required to discriminate ecosystem types cannot be retrieved from earth observation data alone, such as soils, geology, topography, bathymetry and land use and management[45]. While access to Earth observation data archives and cloud-computing have advanced considerably over the last two decades, overcoming the challenge of distinguishing large numbers of diverse and, in some cases, highly similar ecosystems over large spatial scales has not yet been achieved[46]. Developing a global map of ecosystem functional groups (Level 3 of the Global Ecosystem Typology) requires distinguishing dozens of ecosystem functional groups in an analytical framework, which is many times greater than most traditional land-cover mapping programs have previously achieved. This limitation is compounded by issues related to the challenge of classifying continuous phenomena into discrete ecosystem classes, where ecosystem types can vary enormously in their physical expression across their distribution, such as occurring in a natural state or under varying amounts of human influence, or displaying seasonal, annual or multi-year dynamics[42,47,48].

Recent progress in the field of artificial intelligence offers considerable potential to assist in addressing these mapping challenges. Newly developed geospatial foundation models are trained on vast archives of earth observation data, often in concert with environmental layers, contextual data or other ecological datasets, to learn and encode spatio-temporal environmental patterns[49]. For select models, these embedded patterns are disseminated as static data products (often called 'embeddings') that are highly

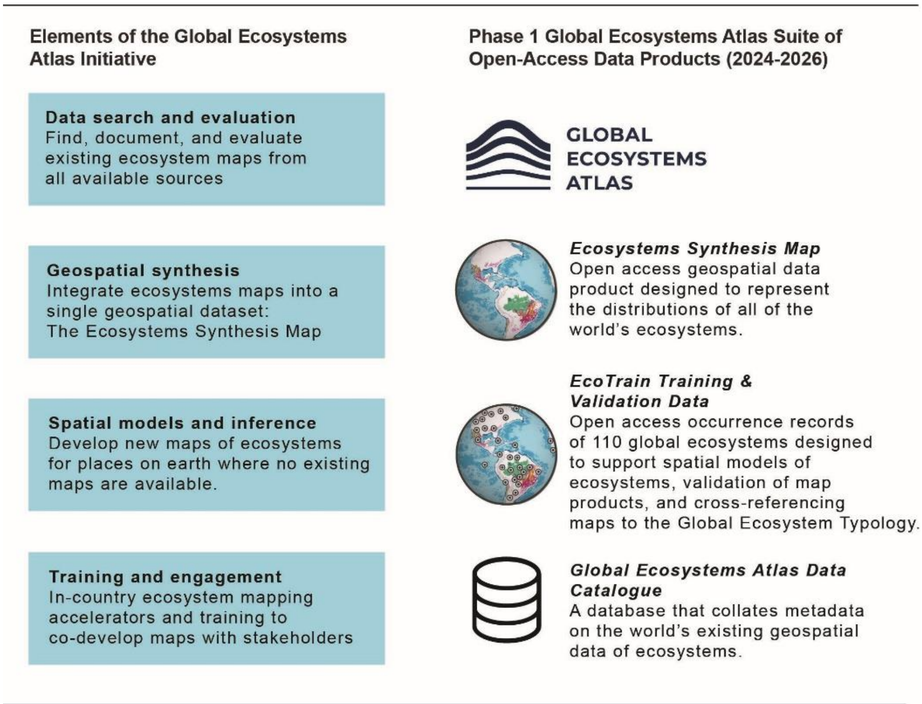

Fig. 2. Major elements and data outputs of the Phase 1 Global Ecosystems Atlas Initiative (2023-2026). The structure of the Global Ecosystems Atlas focuses on mobilising existing spatial datasets (Sections 4.1 and 4.2 and supplementing them with new maps developed through the application of spatial models (Section 4.3). Future expansion of the scope of the Global Ecosystems Atlas focuses on bringing data on ecosystem extent change, the spatial distribution of ecosystem condition and increasing the thematic scale of the Global Ecosystems Atlas synthesis map to National Ecosystem Types (See Section 5).

suitable for use in spatial models tasked with predicting the distribution of high numbers of map classes Geospatial foundation models and the embeddings derived from them show great promise for ecosystem mapping, outperforming classical remote sensing approaches across a range of different classification tasks, including in ecosystem mapping[49-52]. Although there are known limitations of the use of embeddings in spatial models, including limits to their interpretation for support modelling decisions, their principal benefits have been to (1) represent complex spatio-temporal land dynamics in analysis-ready data formats that can be rapidly utilised in the types of supervised spatial classification models widely used for mapping and monitoring, and (2) reduce the initial set-up costs (e.g. time and effort) and amount of baseline remote-sensing expertise needed to develop classified maps of ecosystems. Although the adoption of these new approaches still require traditional post-processing refinements, we expect these benefits will lead to their rapid adoption and deployment for the purpose of mapping ecosystems, with relevance to both bottom-up local and regional mapping programs as well as top-down global ecosystem mapping initiatives.

Even with these advances in geospatial analysis and the adoption of the Global Ecosystem Typology, achieving a global map of ecosystems remains extremely challenging. Unlike some global mapping programs where training data is developed through large investments in highly curated and globally coordinated training datasets[29,53] or where training data can be sourced by sampling existing map datasets[16], training datasets with high fidelity to the Global Ecosystem Typology classes have not yet become widely available. The paucity of high-resolution map datasets and training data representing Global Ecosystem Typology classification units may partly be due to the lag associated with the relatively recent publication and adoption of the typology, and we expect that additional time and targeted effort will alleviate this issue. Indeed, in some areas of the world this type of activity is already well underway[54].

3. The Global Ecosystems Atlas: design principles

The Global Ecosystems Atlas aims to become a comprehensive resource to support national and global-scale reporting on ecosystem-related targets, while broadly supporting manifold initiatives or investigations where high-quality spatial data about ecosystems is required. Formally established in 2023, the atlas initiative focuses on the delivery of carefully designed open-access data products for *all* ecosystems. A key design feature is the adoption of the Global Ecosystem Typology [42] as a framework for defining global mapping units and supporting the synthesis of diverse existing map products that represent ecosystems. Level 3 of the Global Ecosystem Typology (ecosystem functional groups) was identified as an appropriate classification scheme for the development of a global map of ecosystems, particularly given recommendations to countries to use ecosystem functional groups when reporting globally on GBF indicators and SEEA ecosystem accounts[55]. Importantly, ecosystem functional groups provide a ‘common language’ needed to support the synthesis of regional, national and subnational ecosystem maps that were developed with diverse methods and specifications[42]. Therefore, with the Global Ecosystem Typology as a basis, the Phase 1 of the Global Ecosystems Atlas initiative was collaboratively designed with a vision of providing mapping all ecosystems at the planetary scale (Figure 2), following the five design principles described below.

3.1 Integrating knowledge across scales

Local knowledge and mechanistic understanding of ecosystems link expertise, often informed by field work, local monitoring programs, or deep familiarity with particular ecosystems, with larger global efforts to map ecosystems[56]. In contrast, earth observation derived maps of biodiversity are often developed using globally-applicable approaches that risk disregarding local knowledge and ownership, relevant finer grain classifications, and therefore forego the well-reported benefits of working in smaller spatial domains[14,39,57]. Developing a map of all ecosystems requires representation of ecosystem functional groups across the four core Realms of the Global Ecosystem Typology (Terrestrial, Marine, Freshwater and Subterranean), which no single top-down mapping approach is likely to achieve. Therefore, in developing the Global Ecosystems Atlas initiative, it was critical to seek approaches to identify and integrate ecosystem map data previously developed over a range of spatial scales (from regional to national to global). The principle of integrating knowledge across scales is consistent with most ecosystem interventions, which are generally implemented at sub-global administrative scales. For these reasons, the initiative was designed to build upon locally developed spatial data that are already used to underpin these types of interventions worldwide[58], rather than follow a top-down global development pathway.

3.2 Mobilising existing data

Significant unquantifiable investments have already been made in developing maps of ecosystems at a variety of spatial scales and for a broad range of purposes. These include multi-ecosystem mapping programmes developed at national scales, such as those developed for South Africa[11], Italy[59], Myanmar[60], Chile[61] and many other regions (e.g., Western Europe[62], Antarctica[63], Tiwi Islands[64]). A number of global-scale ecosystem specific ecosystem map datasets are also available, including those mentioned above, as well as for many other ecosystem functional groups, such as croplands[65] and plantations[66,67]. Additionally, maps developed for other purposes, such as vegetation maps (e.g., China’s National Vegetation Map [68], the Arctic Vegetation Map[69]) and land cover map products, some of which scale local expertise into transnational initiatives (e.g. the MapBiomas network[70]), frequently include individual classes that are conceptually consistent with and can be cross-referenced to the Global Ecosystem Typology, following guidelines recently developed by the IUCN[38]. Additionally, land cover mapping networks that scale local expertise into transnational initiatives—such as the MapBiomas network, which produces multi-temporal, high-resolution datasets across 18 countries through local institutional collaborations—frequently include classes that can be cross-referenced to the Global Ecosystem Typology. The Global Ecosystems Atlas has much to gain from these large historical investments in diverse environmental mapping programs and therefore sought to develop an organisational framework and data model that could build on existing data, rather than function in parallel or in addition to existing mapping efforts (Figure 2; Table S1).

3.3 Promoting data standards

Developing ecosystem maps to support the monitoring and management of ecosystems requires data standards that promote the development, use, and reuse of quality data. However, many map data products fail to provide adequate information about quality control and validation practices in their documentation or metadata, and are therefore unable to be quickly evaluated for their ability to represent the features they claim to represent[71]. This issue means that propagating known uncertainties in map datasets into ecosystem extent estimates derived from them, which is common in the remote sensing field, is generally not possible[72,73]. To counteract this issue and focus on serving quality spatial data for ecosystems, the atlas initiative has developed an ecosystem spatial data standard that enables a structured approach to the selection of datasets for the initiative. The standard also acts to document provenance of all data in the initiative's outputs to ensure these issues are transparent, while also providing credit and direct links to dataset contributors and the datasets themselves.

3.4 Filling spatial data gaps

Despite decades of ecosystem mapping activity, there are still vast regions where no suitable data for representing the Global Ecosystem Typology's ecosystem functional groups exists, inhibiting our ability to develop a global map of ecosystems through data compilation and synthesis alone. The Global Ecosystems Atlas initiative aims to target these shortfalls by promoting new mapping of globally underrepresented regions and rare, fragmented or unmapped ecosystems. One way of supporting new mapping activity is through the development of critical resources, such as open-access training and validation datasets. These can stimulate mapping activity and be used broadly to distribution mapping of ecosystem functional groups (e.g. to train supervised classification models or for supporting independent map validations) and assist in the development of new mapping workflows that yield new ecosystem maps. Additionally, the provision of training activities, user network building, expert guidance, local iteration and making useful mapping software freely available can enable teams to develop new ecosystem maps that would improve their quality and coverage, while retaining ownership of mapping pipelines and their outputs. Thus, a core design principle of the Atlas was to work to promote new ecosystem mapping activity by a large and diverse range of actors.

3.5 Accessibility and interoperability

To promote trust in the Global Ecosystems Atlas initiative, the initiative is governed by an open access data policy that requires all code and data outputs to be made publicly available with unrestrictive licences. As such, existing datasets that do not meet this condition are unable to be included in the Atlas. However, efforts have been made to mobilise those data by advocating for their conversion to less restrictive licenses and promoting their use for conservation[74]. The initiative is also committed to the Findable, Accessible, Interoperable and Reusable (FAIR) guiding principles[9] through the provision of structured metadata to enable discovery and use of the Atlas geospatial data products (Figures 2 and 3). Similarly, building on the efforts of diverse contributors worldwide, the Atlas is committed to CARE principles (Collective Benefit, Authority to Control, Responsibility, Ethics) and thus includes appropriate attribution to the organisations and authors of source datasets, and provides spatially-aware data attributions within the data themselves. These features are provided through an online web application to enable continued ownership of any data contributed to the initiative. Lastly, to promote appropriate use and enhance trust in the initiative, the Atlas is broadly supported by documentation that explains the methods and operating procedures of the different work units (including field data procedures, data search and synthesis procedures, and training data procedures).

4. Global Ecosystems Atlas: structure

Following design workshops held in 2023, the Global Ecosystems Atlas initiative was structured into four major work packages to enable (i) discovery and curation of existing geospatial data that represents or can be cross-referenced to ecosystem functional groups, (ii) cross-referencing and processing of existing data into a single 'synthesis' geospatial data product that represents ecosystem functional groups, (iii) development of new maps of ecosystem functional groups for regions around the world where little or no spatial data are available, and (iv) engagement, training, and resource development to support and promote ecosystem mapping activities by diverse groups worldwide (Figure 2). A Technical and Scientific Committee oversees all development and active management of the Atlas initiative, with representation from a broad range of scientific and technical fields of research.

4.1 Data search and evaluation

The data search and evaluation stream aims to find, document, and evaluate existing maps from all

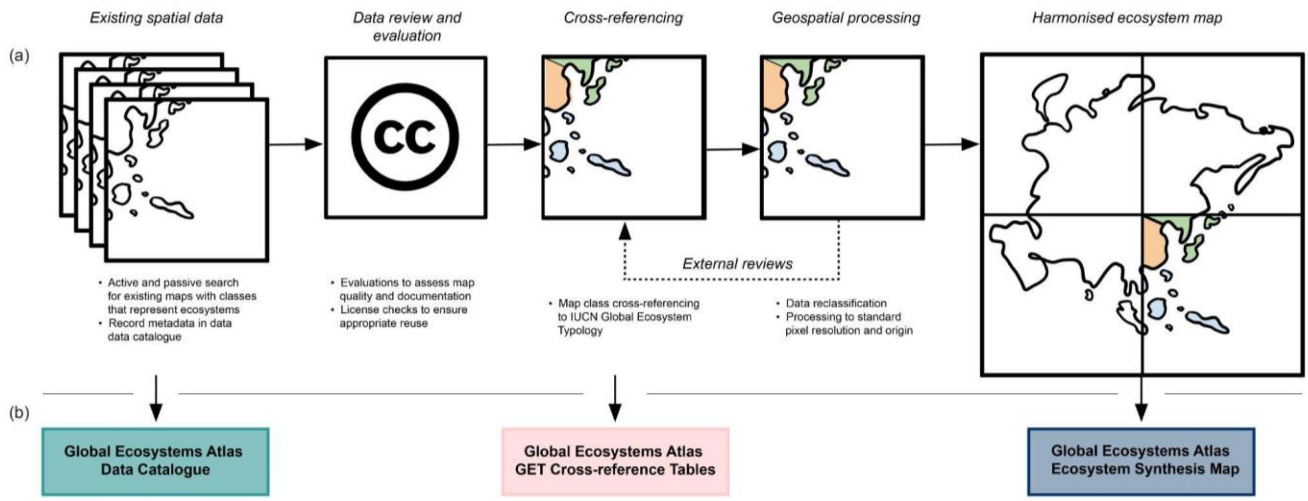

Fig. 3. Data search and evaluation unit of the Global Ecosystems Atlas Initiative. (a) Datasets with map classes suitable for representing ecosystem functional groups are discovered through active and systematic searches of the literature and data repositories, and through outreach to relevant mapping organisations and science teams. Each dataset is evaluated for accuracy, recency, adequacy of documentation, and license conditions. The data are then cross-referenced to the Global Ecosystem Typology and processed through a geospatial pipeline for reclassification and data harmonisation (including resampling to a consistent 100-m spatial resolution), and integrated into the Global Ecosystems Atlas synthesis map, and (b) Outputs of the Global Ecosystems Atlas initiative.

available sources that either directly represent the spatial distribution of ecosystem functional groups or can be processed to robustly represent those groups (Figure 3). Data searches and ongoing monitoring of publication channels for new spatial data are conducted using both active and systematic search methods, supported by active engagement activities focused on map developers and governments (both national and non-national mapping teams). All data discovered during the data search are compiled and documented in the Global Ecosystems Atlas Data Catalogue (Figure 3, Supplemental Table S1), which serves as a central repository of existing spatial data regarding the world's ecosystems and is a freely available output (see data and code availability).

Following initial review, each map dataset documented in the Atlas Data Catalogue is formally evaluated for inclusion into the Atlas synthesis map. The evaluations focus on (i) data licences, to confirm that reuse of the data in the Atlas synthesis map is possible under the conditions of the licence, (ii) spatial resolution of the dataset, ensuring that data are of sufficient resolution to be integrated into the synthesis map (a 100-m resolution data product, see Section 4.2), (iii) alignment with the Global Ecosystem Typology to confirm the map and its classification comply with cross-referencing guidelines developed by the IUCN[38], (iv) provision of adequate documentation and validation information, and (v) recency of the data, to enable decisions regarding whether the data are appropriate for developing a coherent map of the current distributions of the world's ecosystems. Over 400 datasets are already recorded in the Data Catalogue with more than 60 currently forming the pre-publication version of the ecosystem synthesis map (Supplementary Table S1).

4.2 Geospatial synthesis

To integrate select datasets from the Atlas Data Catalogue into a single geospatial data product, termed the *Ecosystems Synthesis Map*, we developed a cross-referencing and data-integration pipeline that reconciles the varied classification schemes of the existing maps with the IUCN Global Ecosystem Typology Ecosystem

Functional Group classification (Figure 3). In many cases, existing datasets (termed 'source data') submitted to the Atlas already represent ecosystem functional groups. These account for approximately 5% of the data catalogue. However, datasets that do not directly represent ecosystem functional groups, such as those following alternative classification schemes or developed to represent different features (e.g. land

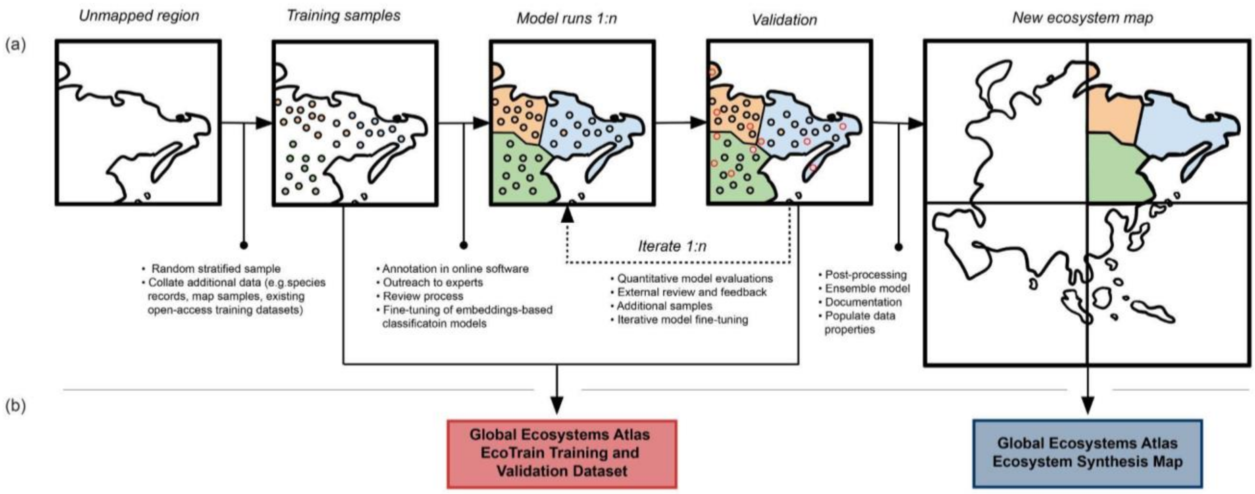

Fig. 4. Overview of the spatial modelling unit of the Global Ecosystems Atlas. (a) The spatial modelling unit seeks to develop new maps of ecosystem functional groups in places where no map data is available. The pipeline involves training geospatial foundation model-based classification models with the *EcoTrain* global training and validation dataset developed by the Atlas initiative. The results are classified maps at the 100-m scale that are submitted directly to the map synthesis unit, and (b) outputs of the Global Ecosystems Atlas initiative.

cover classes), are reviewed by the Atlas team class-by-class against the defining properties of the ecosystem functional groups, following the principles outlined in the IUCN cross-referencing guidelines[38]. This cross-referencing procedure uses information from class definitions, spatial context, and expert judgements to determine whether each map class in the source data can be reliably assigned to a single ecosystem functional group. Map classes that only partially match (assessed as <50% alignment) or are incompatible with the Global Ecosystem Typology are considered ineligible for cross-referencing and excluded from further processing. Classes that are evaluated as having >50% alignment with an ecosystem functional group are retained, and the results of this process are used to reclassify source data map classes into map classes that represent ecosystem functional groups. Datasets are then compiled into the official *Ecosystems Synthesis Map* dataset (Figure 6) following assembly rules that are dictated by an 'overlap index'. This is developed using metadata collected during dataset evaluations and supplemented by an expert assessment where required. The Synthesis Map is designed as a set of four cloud-optimised GeoTIFF files to represent the four main classes of spatial data derived from this process (Figure S1), including: (i) the multiclass maps of ecosystem functional groups, biomes, and realms, (ii) maps of 'standalone' ecosystem functional groups that cannot be represented within the multi-class map due to being co-located in three-dimensions with other ecosystems (e.g., caves, pelagic ecosystems), (iii) data regarding the sources used to develop ecosystem data layers, including per-pixel identification of source data and the year that the data represents, and (iv) a data mask that depicts areas of disagreement among the source maps and counts of datasets used to develop the ecosystems synthesis map.

4.3 Spatial models and inference

To account for regions where no existing data representing ecosystem functional groups can be found, a dedicated spatial modelling project for developing new maps of ecosystem functional groups was developed (Figure 4). We model and map areas worldwide where data searches and country engagement efforts suggest that, without a dedicated effort to develop new maps of ecosystems, they will remain unmapped into the near-term future (over a 5–7-year time frame).

To support the development of new maps of ecosystems, the initiative is developing an open-access labelled training and validation dataset of ecosystem functional group occurrences. The *EcoTrain* dataset was developed as a set of 92,000 random location samples spatially stratified by ecoregion[75] for use in spatial models tasked with estimating the distribution of ecosystem functional groups. Each sample is labelled to ecosystem functional groups in one of two ways. Where no existing ecosystem map data are available, seven ecology-trained image analysts annotate each sample with the primary and secondary ecosystem functional group within 10-m and 100-m bounding boxes, confidence estimates, the date of observation, and over 10 other properties. Data labelling is conducted in the *OlmoEarth* online mapping platform[76], and is supported by an expert system that supports attribution of training points to ecosystem function group on multiple information sources including time series of satellite images, existing landcover, climate, or topological datasets, images taken on the ground, guidance by regional or ecosystem experts, scientific publications, and reference to species records from the Global Biodiversity Information Facility. Samples that occur within existing maps of ecosystems are intersected with those maps, cross-referenced to an ecosystem functional group, and populated with properties that align with the human labelled samples[38].

Fig. 5. The Global Ecosystems Atlas synthesis map. The Global Ecosystems Atlas synthesis map is a Cloud-optimised GeoTIFF that represents the distribution of IUCN ecosystem functional groups. The figure below shows the current extent of development of the Global Ecosystems Atlas synthesis map, which has reached 73% coverage of Earth and continues to grow with the inclusion of new geospatial datasets that represent the distribution of different ecosystem types.

To predict the distribution of ecosystem functional groups, the Atlas team has developed supervised classification pipelines that employ geospatial foundation models and embedding datasets to map the distribution of ecosystem functional groups (Figure 4). Labelled records from *EcoTrain*, supplemented with additional open-access occurrence records where possible, are used to train spatial classification models that estimate the most likely ecosystem functional group for every pixel in the regions that they are applied to, yielding new maps of ecosystem functional groups (Figure 4). The outputs of the spatial modelling work package therefore includes the *EcoTrain* training and validation dataset published as an open-access data product (Figure 2) and new maps of ecosystem functional groups, which are submitted directly to the synthesis pipeline to be integrated into the Ecosystems Synthesis Map (Figure 4).

4.4 Training and engagement

The Global Ecosystems Atlas aims to play a key role in building capacity for map production by diverse mapping teams worldwide[57]. New guidelines[77] for developing national scale ecosystem maps, reviewed by CBD parties in an open review period, focus on problem definition, core concepts for mapping and classifying ecosystems, and a suggested framework for developing national ecosystem maps. A key message from the guidelines is that institutional and social processes, together with collaboration and access to the analytical tools and skills required to operate them, are

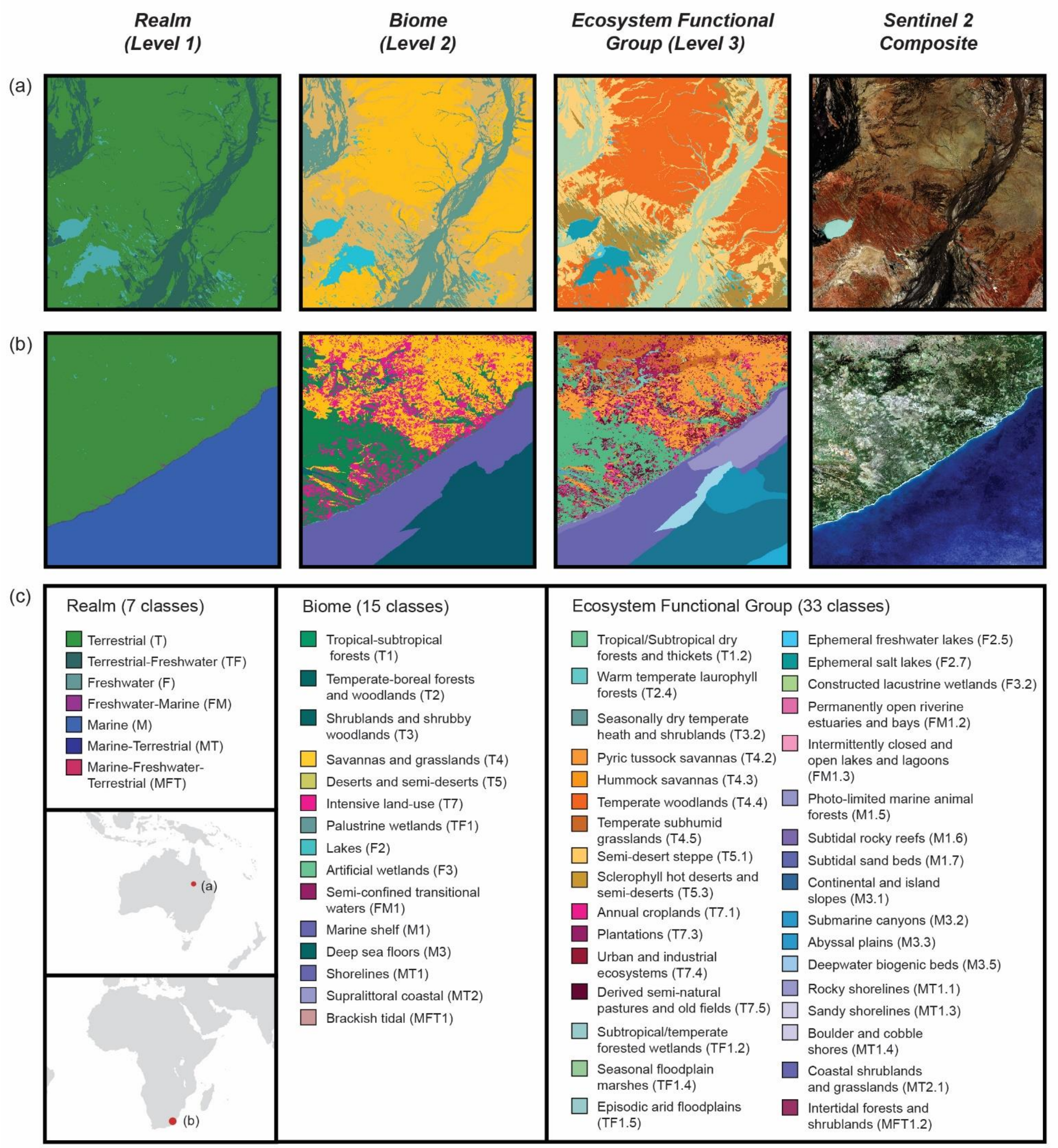

Fig. 6. Representative examples of source spatial data representing ecosystems to a globally consistent resource. Panel plot showing the Realm, Biome and ecosystem functional groups data bands from the Global Ecosystems Atlas synthesis map for (a) Australia and (b) South Africa. Realm, Biome and ecosystem functional groups are levels 1, 2 and 3 of the IUCN Global

Ecosystem Typology, respectively. The panel (c) indicates the Realm, Biome and ecosystem functional group map classes shown in the panels above following the hierarchical naming scheme of the IUCN Global Ecosystem Typology and colour palette of the Global Ecosystems Atlas (see Table S2).

necessary to successfully develop new maps of ecosystems. All of these aspects are included in the Atlas 'accelerator' initiative, which is a national-scale training and implementation program designed to provide structured support to countries developing ecosystem maps from the ground-up. The Republic of Maldives has been the first accelerator country for the Atlas initiative, which, through collaborative workshops and co-developed program of field work, is expected to result in a nationally owned ecosystem map to underpin national reporting and management.

To further support ecosystem map development, the Atlas has worked with partners to develop new mapping tools and resources that build on our previously developed online ecosystem mapping applications that were designed to improve access to cutting-edge ecosystem mapping approaches[78]. These include code-free remote sensing classification applications, developed in collaboration with Google and Ai2, that enable training data collection and labelling functionality to the ecosystem functional group classification scheme and the ability to run interactive map classifications (Supplementary Figures S2a and S2b). Additionally, all code, data, guidelines, standard operating procedures, Global Ecosystem Typology membership matrices (i.e. cross-referencing tables), and other resources are openly available via a public GitHub to promote the application of FAIR principles. Lastly, to enable direct access and allow a range of standard analyses of the Atlas data products, such as estimates of ecosystem functional group extents per region or proportion of each ecosystem functional group under protection, the Global Ecosystems Atlas has developed an online web-application and API (https://www.globalecosystemsatlas.org/).

5. Next steps towards a global ecosystem monitoring system

5.1 Known challenges

The Global Ecosystems Atlas initiative has made considerable progress in organising and providing ecosystem maps. However, developing and integrating maps of some ecosystems remains a technical challenge that will require years of dedicated research and development to resolve. Firstly, there are several ecosystems that occur beyond the detection limits of earth observation, including benthic marine ecosystems that occur at depths where *in-situ* survey effort and the advancement of novel spatial models are essential. These include all seven ecosystem functional groups of the Deep Sea Floors Biome and the majority of the Marine Shelf Biome, although we note that significant recent progress on shallow coral reefs [79], seagrass[25] and, to a lesser extent, kelp forests [80]. Similarly, subterranean ecosystems such as Aerobic caves (S1.1; Global Ecosystem Typology) and endolithic systems (S1.2) are among the most data poor ecosystems on Earth and require fundamentally different approaches to mapping, such as developing data catalogues and inventories of cave entrances. Freshwater ecosystems are also particularly challenging, because they frequently require detailed information on water chemistry (F2.6 Permanent salt and soda lakes), temperature (F2.9 Geothermal pools and wetlands), freeze-thaw dynamics (F2.4 Freeze-thaw freshwater lakes), or lake size (F2.1 Large permanent freshwater lakes). Lastly, developing ecosystem mapping pipelines that can distinguish ecosystems that are differentiated by extremely subtle and often unobservable processes requires continued methods development, such as savanna and dry forest ecosystems that are strongly influenced by the incidence of herbivory or fire, even in the era of geospatial foundation models.

5.2 Future expansions

The development of the Global Ecosystems Atlas and the resources already available represents an important step towards building a rigorous evidence base on ecosystem distributions to meet a wide range of scientific, conservation, and management needs. To supplement these resources, a range of extensions of the Atlas initiative are foreseen that aim to build on the first-phase foundations described in this manuscript, which are listed below.

5.2.1 Change in ecosystem extent

High-temporal and spatial resolution monitoring are already available for some specific ecosystems, including mangroves[16], and several land cover and land use classes[81,82] and different types of forest cover (e.g. tropical humid forests[83], defined as 5m tall trees with a canopy closure exceeding 60% that occur in the tropics). These monitoring systems have been shown to have a significant impact on reducing loss and degradation and have been instrumental in building a synoptic understanding of land cover change[84]. To expand this type of extent monitoring to other ecosystem functional groups, the Atlas plans to advance ecosystem change detection and extent monitoring for a greater number of the world's ecosystem types. The geospatial data model of the Ecosystems Synthesis Map (Fig S1) was designed to enable the two most commonly applied Earth observation monitoring approaches, (i) regular updates of a versioned base map that is updated with new data, and; (ii) change detection systems that identify and characterise loss, gain or ecosystem transitions at higher temporal cadence than can be achieved through updates to a base map[85].

5.2.2 Ecosystem types at levels 4-6 of the IUCN Global Ecosystem Typology.

Many applications of ecosystem maps demand finer thematic classifications of ecosystems than the synthesis map currently provides, which typically correspond to Levels 4 and 5 of the Global Ecosystem Typology. To achieve maps of ecosystem regional subgroups (Level 4 of the Global Ecosystem Typology, Regional Subgroups), an approach that geographically 'splits' maps of ecosystem functional groups, has already been well advanced and is proven in global Red List of Ecosystems assessments for mangroves and coral reefs, and for geographical regions such as Antarctica[63]. This approach to achieve Level 4 maps typically requires spatial analysis of the Level 3 units against relevant biogeographical boundaries guided by local and regional thematic experts[42]. Levels 5 (Global Ecosystem Types) and 6 (Sub-global Ecosystem Types) are far more challenging, because these levels of the Global Ecosystem Typology require detailed information on biota and extensive expert knowledge to account for regional differences in biotic composition[42]. Activities already underway in the Atlas address Level 6, which are extremely diverse units of classification that are already represented in established ecosystem classifications and map datasets, such as those developed to support national and local applications. The compilation of existing map data now documented in the data catalogue (Table S1) suggests that the total number Level 6 units worldwide is likely to exceed ten thousand different Sub-global Ecosystem Types. On the other hand, developing the Level 5 maps will require extensive effort, probably through regional or thematically focused workshops, to define each Level 5 unit and enable cross-referencing of the Level 6 units in our database. Regardless, the geospatial data model developed for the synthesis map, where Realm (Level 1), Biome (Level 2) and Ecosystem Functional Group (Level 3) are served as separate data bands in a single cloud-optimised geotiff, could easily be extended to include additional data bands that represent Regional Subgroups (Level 4), Global Ecosystem Types (Level 5), and Sub global Ecosystem Types (Level 6). Furthermore, the synthesis model developed for the Atlas, which allows for continuous submission of ecosystem map data, would also enable Levels 4, 5, and 6 of the Global Ecosystem Typology to be progressively populated as suitable data becomes available. With the structure of the Atlas in place, we consider this a logical expansion of Atlas data products over a 5–10-year period.

5.2.3 Ecosystem condition

Global conservation initiatives, including the GBF and the IUCN Red List of Ecosystems, require estimates of the distribution and severity of decline in ecosystem condition, as well as an ability to track the extent and impacts of ecosystem restoration efforts. A range of protocols and initiatives have been developed to support this need[86-88], though some have attracted criticism in the scientific literature[89]. Ecosystem condition analyses should account for the exceptionally diverse and often synergistic or multiplicative relationships between multiple drivers of ecosystem degradation[90] and the response of ecosystems[2]. Consequently, condition metrics are most effectively custom-developed for specific ecosystem types or groups of ecosystem types that share common responses to environmental change and management[42,91]. The Global Ecosystems Atlas can support these efforts by providing the foundation for ecosystem-specific condition models, whereby spatially explicit ecosystem condition estimates can be informed by the distribution of ecosystem functional groups. For instance, ecosystems as diverse as Polar Tundra and Deserts (T6.3), Ice Sheets, Glaciers and Perennial Snowfields (T6.1), Seasonally Dry Tropical Shrublands (T3.1) and Coastal Saltmarshes and Reedbed (MFT1.3) could all be treated differently, either through development of spatial data for key ecosystem indicators that represent different dimensions of degradation, or through an overarching spatial model that accounts for underlying ecosystem types. Representation of ecosystem diversity in this way will enable advances on the one-size-fits-all approaches that have typically been applied in this area of research. Similarly, the Atlas approach of developing open-access occurrence data to support modelling of the distribution of ecosystems could be expanded to develop a similar set of spatially and temporally explicit reference data on the condition of ecosystems or relevant indicators, through a bottom-up expert derived process[91]. Such a resource would enable diverse ecosystem condition data products to be reliably assessed against independent data.

6. Summary

The Global Ecosystems Atlas was designed as a dynamic set of data products that will grow over time, given newly available datasets and growing contributions from the global ecosystem mapping community. We are aware that the Global Ecosystems Atlas would not be possible without the dedicated effort and investments made by ecologists, mapping teams, field biologists, technology organisations, and governments around the world. We expect that the technological advances made possible in the Atlas will also catalyse ecosystem mapping efforts by more diverse actors around the world, enabling map submissions to the Atlas from a broader range of contributors and for regions on earth where there is little knowledge about the ecosystems that occur within them. We hope that through integration into the Global Ecosystems Atlas, these efforts can lead to improved conservation and management of ecosystems globally and ultimately contribute to halting and reversing worldwide biodiversity loss.

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Author Contributions

All authors contributed to the conceptualization and formulation of the Global Ecosystems Atlas initiative. N.M., B.C., T.L, A.Y. developed the first draft of the paper. All authors participated in review and editing the manuscript.

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Supplemental Information

Fig. S1. The Global Ecosystems Atlas Ecosystem Synthesis Map geospatial data model. The Global Ecosystems Atlas ecosystem synthesis map is delivered as a set of 4 cloud-optimised GeoTiff files designed to serve the needs of a broad range of use cases. Data files are structured to represent (i) multi-class maps of Levels 1, 2, and 3 of the IUCN Global Ecosystem Typology (3 data bands: Realm, Biome, Ecosystem Functional Group), (ii) standalone ecosystems that cannot be represented in the multiclass maps due to their legitimate co-occurrence with other ecosystems (e.g. Sea ice), (iii) data masks showing areas of valid data, data richness, and areas of disagreement (3 data bands), and (iv) sources data to propagate information about the datasets that were included in the Atlas, including citations (3 data bands). Green data bands indicate those that represent the distribution of ecosystems, biome or realms, while grey data bands indicate those that provide spatial metadata about the green data bands.

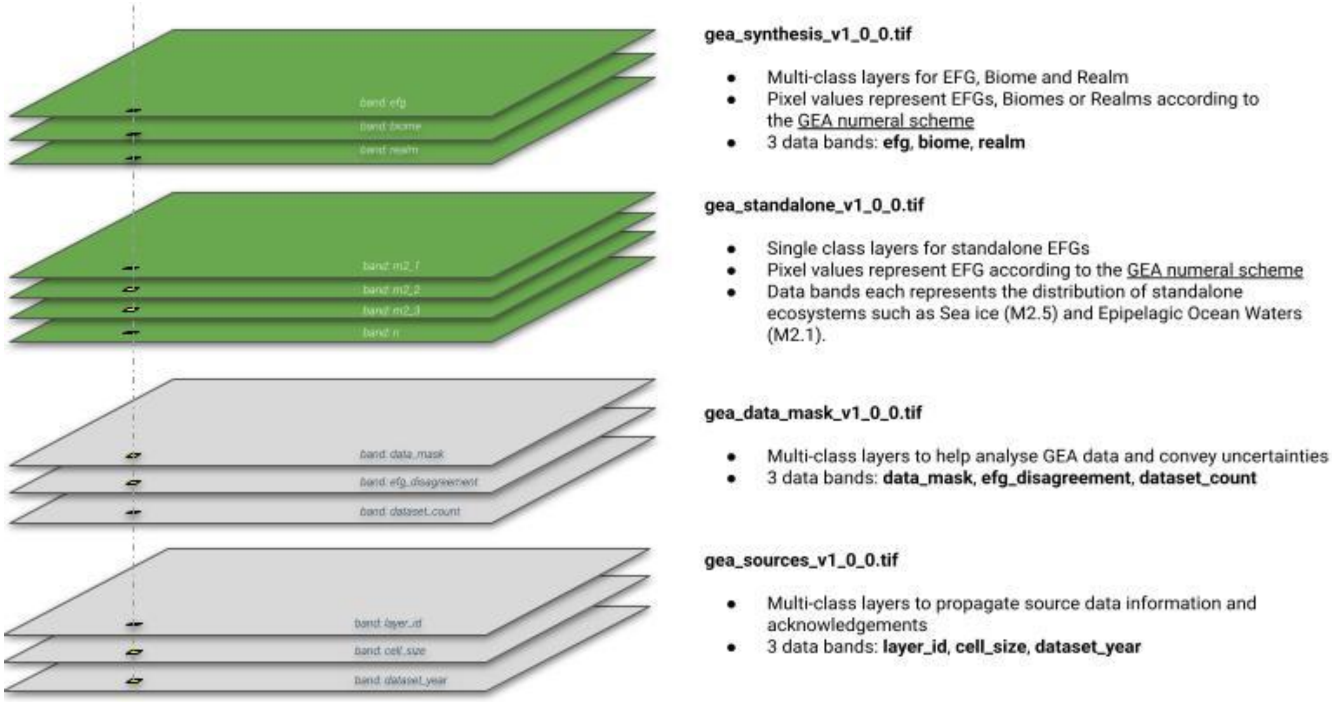
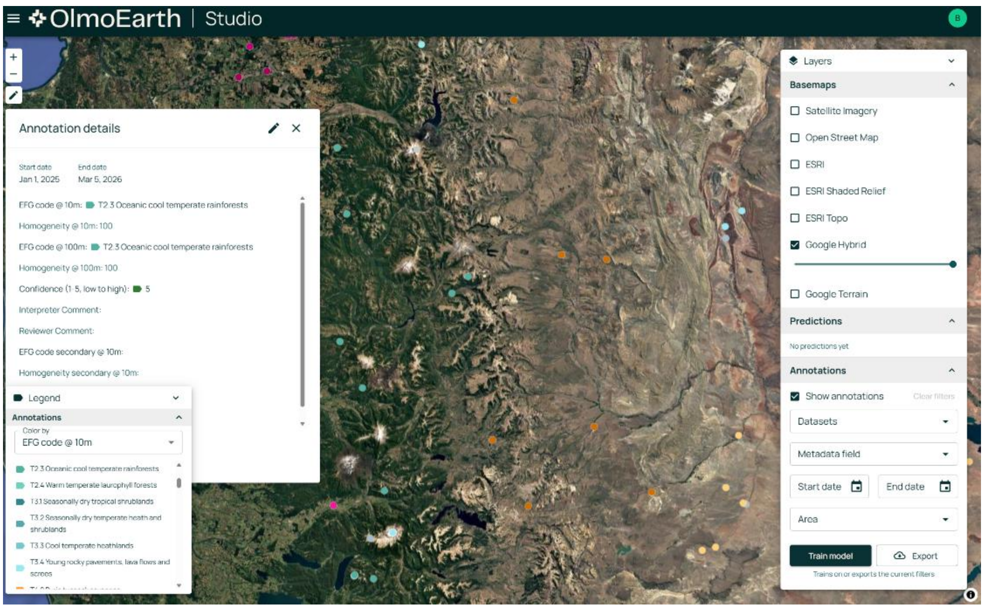


Fig. S2. Examples of resources developed in collaboration with the Global Ecosystems Atlas to support ecosystem mapping. (a) Google Earth enables land classification according to the IUCN GET Level 3 to encourage ecosystem experts with local knowledge to contribute to the Global Ecosystems Atlas, enabling continuous improvement of the resulting maps. The tool uses the Satellite Embedding dataset powered by AlphaEarth Foundations and Google Earth Engine. (b) The OlmoEarth Platform, developed by Ai2 (2025), enables annotations of the *EcoTrain* dataset with reference to a broad range of imagery and direct application of OlmoEarth classification models. Both of these online applications have been used in national ecosystem mapping training workshops held in Maldives, Indonesia and Philippines. (c) The Global Ecology Lab EcoViewer Interface, developed to assist with ecosystem identification while conducting annotations of the EcoTrain training and validation dataset. The figure shows the point statistics such as slope, elevation and ecoregion (top left), Global Biodiversity Information Facility (GBIF) occurrence records mapped as ecosystem indicator species within a 25 km radius of the selected point. (top right, wetland and waterbody distribution, including hydrological statistics for nearby rivers (bottom left), and landcover and vegetation characteristics surrounding the area of interest.

(a)

(b)



(c)

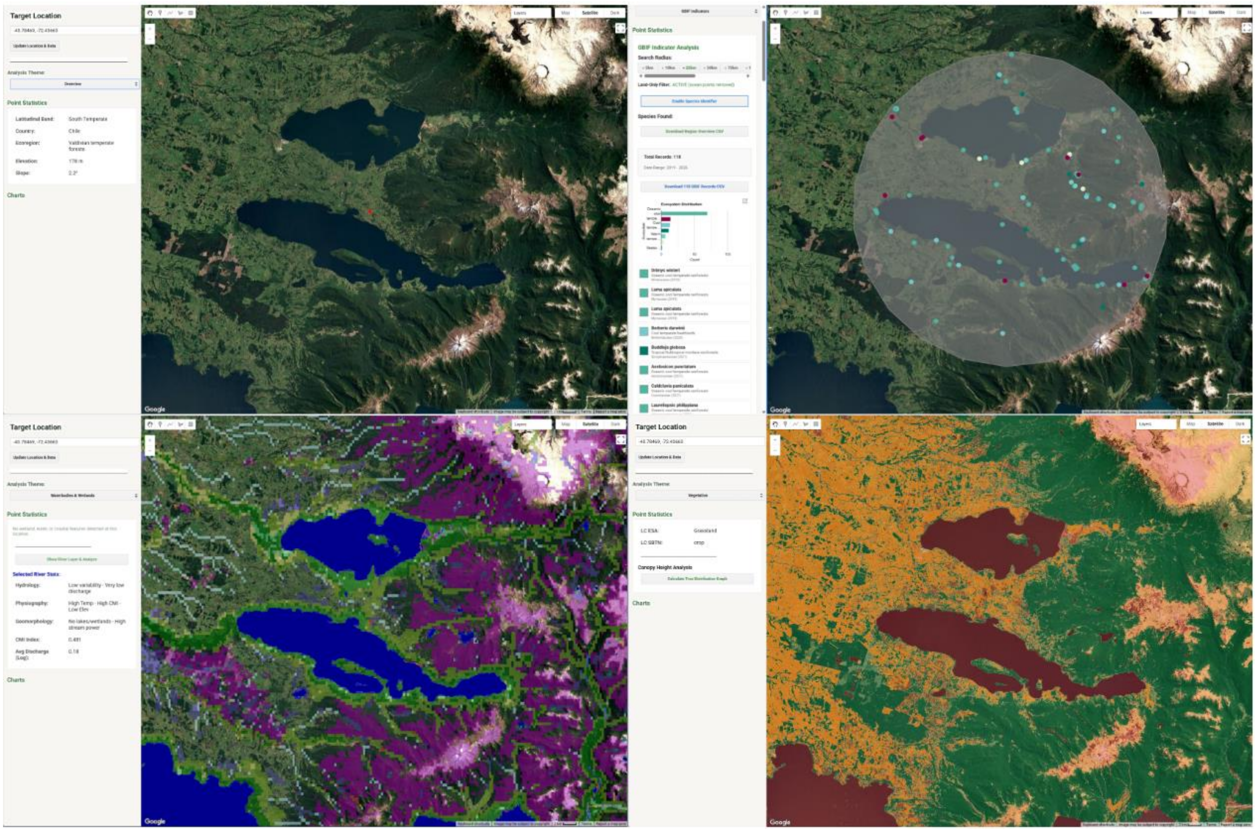

Target Location
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Table S1. Examples of existing spatial datasets that represent ecosystems, drawn from an extract of the Global Ecosystems Atlas Data Catalogue. Rows represent individual datasets summarised by the spatial domain that they were developed at. The complete data catalogue is available on Github and periodically archived on Zenodo[71].

Dataset Reference	URL
Raynolds, Martha; Walker, Donald (2022), Raster Circumpolar Arctic Vegetation Maps, *Mendeley Data*, Version 2.	https://data.mendeley.com/datasets/c4xj5rv6kv/2
Selkirk, P., Adamson, D. and Harris, U. (1999) Macquarie Island Vegetation and Drainage Structure Data Set, Version 1, *Australian Antarctic Data Centre.*	https://data.gov.au/data/dataset/aad-mivegmap
Murray, Nicholas; Keith, David A.; Tizard, Robert; Duncan, Adam; Htut, Win Thuya; Hlaing, Nyan; et al. (2020). Map of the Terrestrial Ecosystems of Myanmar, Version 1.0. *Figshare.*	https://figshare.com/articles/dataset/Map_of_the_terrestrial_ecosystems_of_Myanmar_Version_1_0/12364067/5
Department of Environment and Science (2021), Remnant 2021 broad vegetation groups - Queensland. State of Queensland, Australia.	https://qldspatial.information.qld.gov.au/catalogue/custom/search.page?q=%22Remnant%202021%20Broad%20Vegetation%20Groups%22
Allen Coral Atlas (2022). Imagery, maps and monitoring of the world's tropical coral reefs.	https://allencoralatlas.org/atlas/#1.45/6.7737/-141.8664
Navarro, A., Canto, R., M., Lyons, M. & Murray, N.J. (2023) Australian saltmarsh and sparsely vegetated saltmarsh map version 1.0. James Cook University, Townsville.	https://figshare.com/articles/dataset/Australian_saltmarsh_and_sparsely_vegetated_saltmarsh_map_version_1_0/24021465/1
Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R., Thomas, N., Tadono, T., Worthington, T., Spalding, M., Murray, N., & Rebelo, L.-M. (2022). Global Mangrove Watch (1996 - 2020) Version 3.0. *Zenodo*.	https://zenodo.org/records/6894273
Murray, Nicholas; Phinn, Stuart; Fuller, Richard; DeWitt, Michael; Ferrari, Renata; Johnston, Renee; et al. (2022). High-resolution global maps of tidal flat ecosystems from 1984 to 2019. *figshare.*	https://springernature.figshare.com/collections/High-resolution_global_maps_of_tidal_flat_ecosystems_from_1984_to_2019/5884598/1
Worthington, T. A., Spalding, M., Landis, E., Maxwell, T. L., Navarro, A., Smart, L. S., & Murray, N. J. (2023). The distribution of global tidal marshes from earth observation data. *bioRxiv*, 2023.2005.2026.542433	https://zenodo.org/records/8420753
Luebert, F. & Pliscoff, P. (2017) Sinopsis bioclimatica y vegetacional de Chile. Segunda edicion. Editorial Universitaria, Santiago.	https://zenodo.org/records/60800
C. Blasi, G. Capotorti, S. Bonacquisti, R. Copiz, E. Del Vico, L. Facioni, L. Zavattero (2021) Carta Degli Ecosistemi di Italia, Ministero della Ambiente e della Sicurezza Energetica.	https://download.mase.gov.it/Natura2000/Lista%20Rossa%20degli%20Ecosistemi%20Italiani/_prodotto_D/
Lotter, M., Burrows, J., Jones, K., Duarte, E., Costa, H., McCleland, W., Stalmans, M., Schmidt, E, Darbyshire, I., Richards, S., Soares, M., Grantham, H., Matimele, H. Sousa, C., Alves, T., Zolho, R., Nicolau, D., Ribeiro, N., Macamo, C., Massingue, A., & Bandeira S. (2023) Historical vegetation map and red list of ecosystems assessment for	NA

Mozambique" Version 2.0 Final report. USAID / SPEED+, AFD/FFEM. Maputo. 481pp.	
Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. (2017). Sea Ice Index, Version 3 [March 24]. Boulder, Colorado USA. National Snow and Ice Data Center. (accessed 13/05/2024)	https://nsidc.org/data/seaice_index
Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. (2017). Sea Ice Index, Version 3 [September 23]. Boulder, Colorado USA. National Snow and Ice Data Center. (accessed 13/05/2024)	https://nsidc.org/data/seaice_index
Kennaway, Todd A.; Helmer, Eileen H. (2023) Puerto Rico, Vieques and Culebra land cover and forest formations circa 2000. Fort Collins, CO: Forest Service Research Data Archive.	https://www.fs.usda.gov/rds/archive/catalog/RDS-2023-0022
Descals, A. (2024). Global oil palm extent and planting year from 1990 to 2021 (v1.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11034131	https://zenodo.org/records/11034131
Floyd, M., East, H., Traganos, D., Musthag, A., Guest, J., Hashim, A., Evans, V., Helber, S., Unsworth, R., & Suggitt, A. (2024). Maldivian seagrass aerial extent raster layers 2021 - 2000 [Data set]. In Scientific Reports. Zenodo.	https://zenodo.org/records/11144240
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Instituto Brasileiro de Geografia e EstatÍstica (2021) Mapeamento de Recursos Naturais À" Base conti-nua de Vegetação do Brasil - Escala 1:250 000. (accessed 09/07/2024)	https://bdiaweb.ibge.gov.br/#/consulta/vegetacao
Federal Statistical Office of Germany (2023) Ecosystem Atlas Germany.	https://www.destatis.de/EN/Themes/Society-Environment/Environment/Environmental-Economic-Accounting/ecosystem-account/_node.html#584336
Roelfsema et al. (2021). How Much Shallow Coral Habitat is there on The Great Barrier Reef. *Remote Sensing*.	https://www.arcgis.com/home/item.html?id=d1c58d71667d490ba650c8fd07d6f7ee#overview:~:text=of%20downloads%3A%20102-,Download,-Description
Toth, A., Terauds, A., Chown, S. L., Hughes, K. A., Convey, P., Hodgson, D. A., Cowan, D. A., Gibson, J., Leihy, R. I., Murray, N. J., Robinson, S. A., Shaw, J. D., Stark, J. S., Stevens, M. I., van den Hoff, J., Wasley, J., & Keith, D. A. (2024). Antarctic Ecosystem Inventory: Spatial data for Ice-free lands v1.0. *Zenodo*.	https://zenodo.org/records/11629115
Brown, C.F., Brumby, S.P., Guzder-Williams, B. et al. Dynamic World, Near real-time global 10 m land use land cover mapping. *Sci Data* 9, 251 (2022). doi:10.1038/s41597-022-01307-4	https://developers.google.com/earth-engine/datasets/catalog/GOOGLE_DYNAMICWORLD_V1#description
Song, XP., Hansen, M.C., Potapov, P. et al. (2022) Soy Planted Area, Global Forest Watch.	https://data.globalforestwatch.org/datasets/gfw::soy-planted-area-/about

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Punalekar, S.M., Hurford, C., Lucas, R. M., Planque, C., Chognard, S. (2024) Habitat (detailed) 2023, available from: https://livingearthhub.org/tools/interactive-map	https://earthtrack.aber.ac.uk/livingwales/maps.html
Wildlife Conservation Society (2021) Ecosystem Map - Ecosistemas Marinhas	https://wcs-global.maps.arcgis.com/apps/webappviewer/index.html?id=b8aa324c46294cd8a685c50771b05828
Ferrer-Paris, J. R., & Keith, D. A. (2021). Indicative distribution map for Ecosystem Functional Group M2.1 Epipelagic ocean waters (M2.1.web.orig v2.1) *Zenodo*.	https://zenodo.org/records/5090911
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M2.2 Mesopelagic ocean water (M2.2.web.orig v2.0) *Zenodo*.	https://zenodo.org/records/5090913
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M2.3 Bathypelagic ocean waters (M2.3.web.orig v1.0). *Zenodo*.	https://zenodo.org/records/5090915
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M2.4 Abyssopelagic ocean waters (M2.4.web.orig v1.0) *Zenodo*.	https://zenodo.org/records/5090917
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M3.1 Continental and island slopes (M3.1.web.orig v1.0). *Zenodo.*	https://zenodo.org/records/5090975
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M3.2 Submarine canyons (M3.2.web.orig v1.0) *Zenodo.*	https://zenodo.org/records/5090977
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M3.3 Abyssal plains (M3.3.web.orig v1.0). *Zenodo.*	https://zenodo.org/records/5090979
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M3.4 Seamounts, ridges and plateaus (M3.4.web.orig v2.0). *Zenodo.*	https://zenodo.org/records/5090981
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M3.5 Deepwater biogenic beds (M3.5.web.orig v1.0). *Zenodo.*	https://zenodo.org/records/5090983
Keith, D. A., & Ferrer-Paris, J. R. (2021). Indicative distribution map for Ecosystem Functional Group M3.6 Hadal trenches and troughs (M3.6.web.orig v1.0). *Zenodo.*	https://zenodo.org/records/5090985
State Government of NSW and Office of Environment and Heritage (2024) Vegetation Classes of NSW (version 3.03 - 200m Raster) - David A. Keith and Christopher C. Simpson. VIS_ID 3848	https://datasets.seed.nsw.gov.au/dataset/vegetation-classes-of-nsw-version-3-03-200m-raster-david-a-keith-and-christopher-c-simpc0917

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Natural Resources Institute Finland (2021), The Multi-source National Forest Inventory Raster Maps of 2021.	NA
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Eswatini national map of ecosystems (2025) The Eswatini National Trust Commission.	NA
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Lesotho national map of ecosystems (2025) Lesotho Department of the Environment.	NA
Earth Observation Research Center (Japan Aerospace Exploration Agency) (2023), High-Resolution Land-Use and Land-Cover Map of Vietnam for 2020	https://www.eorc.jaxa.jp/ALOS/en/dataset/lulc_e.htm
Xiaoqing Xu, Chong Liu, Caixia Liu, et al. (2022) Circumpolar Arctic Land Cover for circa 2020 (CALC-2020). V1. *Science Data Bank.*	https://www.scidb.cn/en/detail?dataSetId=55d041817b184e1d95ae6d7c512b8612#p2
Bernhard Lehner, Penny Beames, Mark Mulligan, Christiane Zarfl, Luca De Felice, Arnout van Soesbergen, Michele Thieme, Carlos Garcia de Laeniz, Mira Anand, Barbara Belletti, Kate Brauman, Stephanie Januchowski-Hartley, Kimberly Lyon, Lisa Mandle, Nick Mazany-Wright, Mathis Messager, Tamlin Pavelsky, Jean-Francois Pekel, Jida Wang, Qingke Wen, Marcus Wishart, Tianqi Xing, Xiao Yang, Jonathan Higgins (2024) Global Dam Watch database version 1.0. *Figshare*	https://figshare.com/articles/dataset/Global_Dam_Watch_database_version_1_0/25988293?file=47913739
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Van Tricht, K., Degerickx, J., Gilliams, S., Zanaga, D., Savinaud, M., Battude, M., Buguet de ChargÃ¨re, R., Dubreule, G., Grosu, A., Brombacher, J., Pelgrum, H., Lesiv, M., Bayas, J. C. L., Karanam, S., Fritz, S., Becker-Reshef, I., Franch, B., Bononad, B. M., Cintas, J.,	https://zenodo.org/records/7875105

Szantoi, Z. (2023). ESA WorldCereal 10 m 2021 v100 (Version v100) *Zenodo*.	
Descals, A., Wich, S., Szantoi, Z., Struebig, M. J., Dennis, R., Hatton, Z., Ariffin, T., Unus, N., Gaveau, D. L. A., and Meijaard, E. (2023) High-resolution global map of closed-canopy coconut palm, *Earth Syst. Sci. Data*, 15, 3991-4010,	https://zenodo.org/records/8128183
Ren, H., Wu, F., Zhou, G. (2024). The 30 m vegetation maps of the Tibetan Plateau (1990-2020). National Tibetan Plateau / Third Pole Environment Data Center. https://doi.org/10.11888/Terre.tpdc.301126.	https://data.tpdc.ac.cn/en/data/0c84a954-435d-45f4-bf42-d561f7c7da2a
Gaw, L. Y.-F., Yee, A. T. K., & Richards, D. R. (2019). A High-Resolution Map of Singapore's Terrestrial Ecosystems. Data [dataset], 4(3), 116. https://doi.org/10.3390/data4030116	https://figshare.com/articles/dataset/A_high-resolution_map_of_Singapore_s_terrestrial_ecosystems/8267510/4
Masolele, R. N., Marcos, D., De Sy, V., Abu, I.-O., Verbesselt, J., Reiche, J., & Herold, M. (2024). Land use following deforestation for Africa. *Scientific reports* (Version v1, Vol. 14, p. 1681). Zenodo.	https://doi.org/10.5281/zenodo.11065705

Table S2. Ecosystem names, codes and pixel values of the map classes in the Global Ecosystems Atlas synthesis map. Ecosystem names and EFG codes are sourced from the IUCN Global Ecosystem Typology website (www.global-ecosystems.org), with pixel values and colour hex codes developed by the Global Ecosystems Atlas initiative. Detailed descriptions of each Ecosystem Functional Group are available as hotlink and from Keith et al (2022).

EFG Code	Pixel Value	Hex Code	Name of Ecosystem Functional Group
N/A	0	FFFFFF	No Data
T1.1	1	32A06B	Tropical/Subtropical lowland rainforests
T1.2	2	52BC85	Tropical/Subtropical dry forests and thickets
T1.3	3	6FD9A1	Tropical/Subtropical montane rainforests
T1.4	4	8DF7BD	Tropical heath forests
T2.1	7	006051	Boreal and temperate high montane forests and woodlands
T2.2	8	329483	Deciduous temperate forests
T2.3	9	54B2A0	Oceanic cool temperate rainforests
T2.4	10	73D1BE	Warm temperate laurophyll forests
T2.5	11	92F0DD	Temperate pyric humid forests
T2.6	12	BBF0E5	Temperate pyric sclerophyll forests and woodlands
T3.1	16	34878E	Seasonally dry tropical shrublands
T3.2	17	57A7AE	Seasonally dry temperate heath and shrublands
T3.3	18	78C8CF	Cool temperate heathlands
T3.4	19	9AEAF1	Young rocky pavements, lava flows and screes
T4.1	22	FFD21C	Trophic savannas
T4.2	23	FFA134	Pyric tussock savannas
T4.3	24	FF9110	Hummock savannas
T4.4	25	FF6B00	Temperate woodlands
T4.5	26	D36E00	Temperate subhumid grasslands
T5.1	30	FFD279	Semi-desert steppe
T5.2	31	EEC471	Succulent or Thorny deserts and semi-deserts
T5.3	32	B38E3E	Sclerophyll hot deserts and semi-deserts
T5.4	33	886716	Cool deserts and semi-deserts
T5.5	34	5E4300	Hyper-arid deserts
T6.1	38	DBDBDB	Ice sheets, glaciers and perennial snowfields
T6.2	39	C7C7C7	Polar/alpine cliffs, screes, outcrops and lava flows
T6.3	40	B8B8B8	Polar tundra and deserts
T6.4	41	A8A8A8	Temperate alpine grasslands and shrublands

T6.5	42	949494	Tropical alpine grasslands and herbfields
T7.1	46	FF14A1	Annual croplands
T7.2	47	CA0079	Sown pastures and fields
T7.3	48	AA005F	Plantations
T7.4	49	8B0047	Urban and industrial ecosystems
T7.5	50	6C0030	Derived semi-natural pastures and old fields
S1.1	54	C0AC14	Aerobic caves
S1.2	55	F2D918	Endolithic systems
S2.1	57	9DBF3D	Anthropogenic subterranean voids
SF1.1	59	D49686	Underground streams and pools
SF1.2	60	FFB5A1	Groundwater ecosystems
SF2.1	62	FB9DC4	Water pipes and subterranean canals
SF2.2	63	C67E8C	Flooded mines and other voids
SM1.1	65	569B49	Anchialine caves
SM1.2	66	008767	Anchialine pools
SM1.3	67	006E79	Sea caves
TF1.1	70	73B898	Tropical flooded forests and peat forests
TF1.2	71	8EE3BB	Subtropical/temperate forested wetlands
TF1.3	72	9FFFD3	Permanent marshes
TF1.4	73	93D699	Seasonal floodplain marshes
TF1.5	74	AFD6B3	Episodic arid floodplains
TF1.6	75	C1F195	Boreal, temperate and montane peat bogs
TF1.7	76	DFF1CF	Boreal and temperate fens
F1.1	81	C4FFBE	Permanent upland streams
F1.2	82	ABF5A3	Permanent lowland rivers
F1.3	83	7EE5AA	Freeze-thaw rivers and streams
F1.4	84	51D4B1	Seasonal upland streams
F1.5	85	47BA9B	Seasonal lowland rivers
F1.6	86	3A9C82	Episodic arid rivers
F1.7	87	2D7763	Large lowland rivers
F2.1	92	D6FBFF	Large permanent freshwater lakes
F2.2	93	B8F8FF	Small permanent freshwater lakes
F2.3	94	85F3FF	Seasonal freshwater lakes
F2.4	95	42ECFF	Freeze-thaw freshwater lakes

F2.5	96	1CD8ED	Ephemeral freshwater lakes
F2.6	97	19BED1	Permanent salt and soda lakes
F2.7	98	009DB1	Ephemeral salt lakes
F2.8	99	007A8A	Artesian springs and oases
F2.9	100	005C6B	Geothermal pools and wetlands
F2.10	101	004252	Subglacial lakes
F3.1	107	C4FFBE	Large reservoirs
F3.2	108	ABF5A3	Constructed lacustrine wetlands
F3.3	109	90DAA0	Rice paddies
F3.4	110	51D4B1	Freshwater aquafarms
F3.5	111	47BA9B	Canals, ditches and drains
FM1.1	115	D43A99	Deepwater coastal inlets
FM1.2	116	F960BA	Permanently open riverine estuaries and bays
FM1.3	117	FF83DC	Intermittently closed and open lakes and lagoons
M1.1	120	F1EBFF	Seagrass meadows
M1.2	121	E9E0FF	Kelp forests
M1.3	122	E0D3FF	Photic coral reefs
M1.4	123	C0B5FF	Shellfish beds and reefs
M1.5	124	A197FE	Photo-limited marine animal forests
M1.6	125	897CFE	Subtidal rocky reefs
M1.7	126	6F66EE	Subtidal sand beds
M1.8	127	5E56D1	Subtidal mud plains
M1.9	128	5653A6	Upwelling zones
M1.10	129	3C3973	Rhodolith/Maërl beds
M2.1	135	CEA8FE	Epipelagic ocean waters
M2.2	136	B781FA	Mesopelagic ocean water
M2.3	137	A474E0	Bathypelagic ocean waters
M2.4	138	9569CC	Abyssopelagic ocean waters
M2.5	139	704F99	Sea ice
M3.1	143	1B7693	Continental and island slopes
M3.2	144	2192B5	Submarine canyons
M3.3	145	27AED8	Abyssal plains
M3.4	146	52BEE0	Seamounts, ridges and plateaus
M3.5	147	9CDAED	Deepwater biogenic beds

M3.6	148	A8EAFF	Hadal trenches and troughs
M3.7	149	DBF7FF	Chemosynthetic-based-ecosystems (CBE)
M4.1	154	994A8E	Submerged artificial structures
M4.2	155	7B2E72	Marine aquafarms
MT1.1	157	8782D2	Rocky shorelines
MT1.2	158	A49EF0	Muddy shorelines
MT1.3	159	C2BAFF	Sandy shorelines
MT1.4	160	E0D7FF	Boulder and cobble shores
MT2.1	163	726BDA	Coastal shrublands and grasslands
MT2.2	164	5651A6	Large seabird and pinniped colonies
MT3.1	166	CEC9FF	Artificial shorelines
MFT1.1	168	AC676D	Coastal river deltas
MFT1.2	169	89474E	Intertidal forests and shrublands
MFT1.3	170	672931	Coastal saltmarshes and reedbeds