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Standards, methods and guidelines for cross-referencing ecosystem classifications and maps to the IUCN Global Ecosystem Typology

IUCN Commission on Ecosystem Management
Red List of Ecosystems Thematic Group

Version 1.0

INTERNATIONAL UNION FOR CONSERVATION OF NATURE

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Edited by David A. Keith, Anisha Dayaram, Amanda Driver, José Ferrer-Paris, Roxane Francis, Sylvia Hay, Nicholas J. Murray, Emily Nicholson, Julianna Santos, Andrew L. Skowno and Mark G. Tozer

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Summary

The IUCN Global Ecosystem Typology (GET) is a framework for synthesis and sharing of knowledge to support ecosystem conservation, management and sustainable use from global to local scales. An array of different ecosystem inventories (classifications and maps) exist around the world to support local, national and regional decision making for ecosystems in different socio-political and cultural contexts. These valuable inventories are often the outcome of considerable, ongoing investment and locally-based expertise. Their independent development has often resulted in inconsistencies between different ecosystem classifications, for example across national borders. The GET provides a means of embedding these different systems into a globally consistent classification for ecosystems, while maintaining the integrity of the source classifications. To this end it has been adopted as the agreed framework for monitoring progress on targets under the Kunming-Montreal Global Biodiversity Framework and as the reference classification for ecosystem assets in the System for Environmental Economic Accounting – Ecosystem Accounting.

These and other applications underpin the urgent need for technical guidance on cross-referencing local, national and regional ecosystem classifications and associated maps to the GET. Scientifically sound relationships between classifications, with transparent representation of inherent uncertainties, are essential to support effective ecosystem management and reporting. This publication establishes a structured, rigorous standard for cross-referencing ecosystem types to the GET. It first reviews the need for reliable interoperability among ecosystem classifications and the role of the GET as a framework for synthesis. Second, it reviews the conceptual foundations of ecosystem classifications and introduces the structure of the GET. Third, the guidelines introduce key principles for cross-referencing the units of other ecosystem classifications to GET Ecosystem Functional Groups. In particular, it identifies the range of land and water classifications that may be suitable for cross-referencing to the GET. The next section describes the steps, methods and guidance for defining membership relationships to GET Ecosystem Functional Groups. Finally, it foreshadows emerging tools to assist users in cross-referencing tasks with example applications.

Glossary

Term	Definition
Classification	Any arrangement of entities into internally consistent groups. Different types of groups may be hierarchically arranged in levels, or else non-hierarchical.
Ecological process	Any kind of temporal change, transfer, transformation or interaction within or between ecosystems that involves biota (including humans). These transfers and interactions may also involve the non-living environment, for example, through water and nutrient cycling, fire regimes, etc.
Ecosystem concept	A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit (UN CBD, 1992).
Ecosystem property	A feature of the function, structure or composition of an ecosystem type. Keith et al. (2022) elaborate as follows, *"Defining attributes of ecosystem types and their component biota that result from assembly processes (i.e. properties are outcomes of filtering). They include aggregate ecosystem functions (stocks and fluxes), ecological processes (e.g. trophic networks), structural features (e.g. 3-D spatial structure, diversity), and species-level traits of characteristic organisms that influence their performance (e.g. fitness)."*
Ecosystem type	A type of ecosystem distinguished from other types by its characteristic functional, structural and compositional properties.
Entity	Any unit within a classification, a member of a group, placed in that group on the basis of its shared properties with other entities, e.g. an ecosystem type, species, food item, vehicle, etc. As applied here, an entity can itself be a group of finer units (e.g. a species is a group of individuals – both can be entities grouped in classes).
Functional property	An ecosystem property (see above) that relates to ecological processes or their outcomes, rather than properties that relate only to composition or structure.
Map	A representation of the spatial expression of one or more entities. An ecosystem map represents the distribution of ecosystem types within a given ecosystem classification.
Membership	The relationship of an entity to a group. Uncertainty in membership of a given entity to a specified group may be expressed as a value from 0 (full certainty that entity *does not* belong to the group) to 1 (full certainty that entity *does* belong to the group).
Relationship	A general term describing how different entities connect and interact within a domain of knowledge. Membership is one type of relationship or relatedness.
Unit	A general term referring to any class or group (including entities) at any hierarchical level in a classification or any legend category on a map.

Introduction

The IUCN Global Ecosystem Typology (GET) provides a hierarchical framework for global synthesis of the many ecosystem classification schemes in use across different countries and user communities. These schemes are often developed independently of one another to serve the needs and purposes of particular user communities and consequently, they may not be directly compatible or comparable with one another. Table 1 summarises examples of nationally or regionally scoped ecosystem classifications from around the world.

Table 1. Examples of independently developed national, subnational and regional ecosystem classifications suitable for cross-referencing to the IUCN Global Ecosystem Typology

Jurisdiction (land area)	Number of units	Unit name	Source
Chile (748,800 km^2)	125 terrestrial	Vegetation domains, each with several communities	Luebert & Pliscoff (2017)
Colombia (1,038,700 km^2)	81 terrestrial 20 marine	Ecosystem types Ecosystem types	Etter et al. (2020); Uribe et al. (2022)
South Africa (1,221,037 km^2)	458 terrestrial 357 freshwater 150 marine [905 total]	Vegetation types Ecosystem types Ecosystem types	Dayaram et al. (2021)
Mozambique (801,590 km^2)	162 terrestrial	Vegetation units	Lötter et al. (2023)
Europe* (4,233,255 km^2)	233 terrestrial & freshwater 257 marine	Habitat types (based on EUNIS level 3) Habitat types (based on EUNIS level 4)	EEA (2021-22)
Finland (338,145 km^2)	414 terrestrial, freshwater, marine	Habitats (388 types and 26 groups)	Kontula & Raunio (2019)
Italy (301,230 km^2)	107 terrestrial	Ecosystem types	Capotorti et al. (2023)
United States of America - 48 conterminous states (8,080,464 km^2)	6,244 terrestrial	Vegetation associations (within 1,450 alliances)	USFGDC (2022)
Myanmar (676,578 km^2)	64 terrestrial	Ecosystem types	Murray et al. (2020)
Queensland, Australia (1,729,742 km^2)	1,435 terrestrial	Regional ecosystems (within 98 broad vegetation groups)	Queensland Herbarium (2024)

Source: Editors. * An example of regionally aggregated classification units. Finer resolution units are defined at lower levels of the EUNIS classification and within European countries (see examples for Finland and Italy).

The GET facilitates synthesis of these different systems by grouping functionally similar ecosystem types together in the upper levels of its hierarchy, worldwide across land, oceans, inland waters and below ground (see v2.1 in Keith et al., 2022). These function-based groupings are suitable for synthesis because they provide a 'common ecological language' at an informative level of granularity about ecosystem properties and because they can be cross-referenced reliably to other ecosystem classifications and maps without the need for species-level expertise.

The need to cross-reference different classification systems arises frequently in ecology and conservation applications. In Europe for example, where habitat classification is equated with ecosystem classification, most countries maintain their own national habitat classifications (e.g. Kontula & Raunio, 2019), which they cross-reference to the EUNIS classification scheme (EEA, 2021-22) to support scientific and policy interactions and regulatory processes within the European Union. In southern Africa, neighbouring countries undertake collaborative conservation programmes (e.g. https://www.sanbi.org/biodiversity/building-knowledge/biodiversity-monitoring-assessment/the-sbapp-regional-project/; Keith et al., 2024) and need to identify corresponding ecosystem types in their respective national classifications that span their borders. Federated nation states, such as Australia and the United States of America, have independently developed jurisdictional classifications that require national synthesis. In Australia, for example, state classifications of terrestrial ecosystems are entered into a National Vegetation Information System, with a preliminary cross-reference to the GET developed to support the first national ecosystem accounts (MacFarlane et al., 2024).

Despite these needs and activities, to date, the conceptual foundations for cross-referencing classifications are poorly developed. Moreover, recent attempts at cross-referencing independently derived classifications to the GET have limited or no documentation of methods and appear to be based on unstructured, qualitative, expert opinion (e.g. Capotorti et al., 2023; DHI, 2024; MacFarlane et al., 2024). The lack of consistent methods and standards for cross-referencing makes the relationships between units difficult to reproduce and update when more information becomes available, and may lead to divergent or erroneous interpretations of relationships between classifications.

Structured, quantitative methods exist for comparing classifications (e.g. Williams & Clifford, 1971; Wiser & de Cáceres, 2013; Tharwat, 2021; Tozer & Keith, 2023), but in their traditional form, they require systematic quantitative data on the entities classified. In contrast, the information available to compare units between alternative ecosystem classifications is often limited, inconsistent (even among units of one classification), and multi-modal, comprising different types of information spanning quantitative measurements, qualitative information, images and experiential knowledge. Flexible approaches are needed to accommodate these diverse inputs, but in a structured, scientifically rigorous and reproducible form.

These technical guidelines aim to promote understanding of essential aspects of ecosystem classification and to establish a structured, rigorous standard for cross-referencing ecosystem types to the IUCN GET. Their primary audience includes ecosystem managers, scientists and conservation planners who will carry out cross-referencing. However, the guidelines also address relevant issues for policy makers and managers including why cross-referencing is beneficial, why only certain types of classifications are eligible for it, and the collaborative engagement with scientists necessary to achieve a rigorous outcome. The guidelines first review the need for reliable interoperability among ecosystem classifications and the role of the GET as a framework for synthesis. Second, they review the conceptual foundations of ecosystem classifications and introduce the structure of the GET. Third, the guidelines introduce key principles for cross-referencing the units of other ecosystem classifications to GET Ecosystem Functional Groups (EFGs). The next section describes the steps, methods and guidance for defining membership relationships to GET EFGs. Finally, these guidelines review emerging tools to assist users in cross-referencing tasks.

The need for interoperability and role of the Global Ecosystem Typology

Many ecosystem classifications and associated maps are developed for specific territories (e.g. states, countries, regions) independently of those developed in other territories. These locally scoped classifications and maps are often the outcomes of significant local expertise, investment and ownership during their development for use in a range of important regional, national and local applications, including on-the-ground ecosystem management and conservation planning. However, their local scoping and development independently of one another typically results in inconsistencies across jurisdictions, which hampers broader applications and appropriate management outcomes that transcend jurisdictional boundaries. The GET recognises these valuable and detailed descriptive systems explicitly within Level 6 of its hierarchy, while enabling the benefits of integration across jurisdictional borders, terrestrial and aquatic environments and research disciplines into a framework that offers greater consistency and comparability on a global scale (Keith et al., 2022).

Establishing scientifically robust links, particularly across national classification schemes, via the GET provides major benefits and efficiencies related to access, management and use of ecosystem information, while maintaining the integrity of the national classifications and maps. The benefits of embracing national and other ecosystem classifications and maps within the GET span multiple policy, research, management and monitoring imperatives from global to local scales, including key applications summarised in Box 1. For all applications, the units of local or national ecosystem classifications need to be rigorously cross-referenced to Ecosystem Functional Groups (Level 3) of the GET. In some cases, cross-referencing with the GET may bring forth opportunities to improve local classifications and maps.

Many national and regional ecological classifications are broadly consistent with the ecosystem concept (see examples in Table 1), but vary in geographic scope, focal biota, structure (number and organisation of groups and levels), descriptive detail and spatial specifications. Many of them are deeply embedded within national and local applications and instruments for decision-making on ecosystem management. Given these legacies and varied purposes, it is not practical or desirable to impose a uniform classification on all users in order to resolve inconsistencies. Instead, this underscores the need to achieve the benefits for broader applications (Box 1) through enhanced interoperability by cross-referencing the units of different classifications to a common global framework, while maintaining the integrity of each individual classification system as far as possible.

The IUCN Global Ecosystem Typology

The GET was developed in a major international collaboration of ecosystem specialists over several years and continues to evolve with version-controlled updates to accommodate advances in knowledge. The GET was endorsed as the global standard for ecosystem classification by IUCN with the publication of version 2.0 (Keith et al., 2020). An update (v2.1) was published with an account of the approach and methods in 2022 (Keith et al., 2022). The latest version and update process is accessible on the GET web application at https://global-ecosystems.org/. The update process is managed by the GET Scientific Committee. Box 2 summarises some general classification concepts relevant to the development, interpretation and use of the GET.

Box 1. Applications requiring cross-referencing of local, subnational, national or regional ecosystem types to IUCN GET Ecosystem Functional Groups

1. **Implementing and monitoring international agreements.** The 196 parties to the United Nations' Convention on Biological Diversity (UN CBD) have agreed on biodiversity conservation targets for 2030 and broader goals for 2050 under the Kunming-Montreal Global Biodiversity Framework (KMGBF). Countries have agreed to report progress towards ecosystem targets based on agreed Headline Indicators (including A.1 Red List of Ecosystems, A.2 Extent of natural ecosystems) using high-quality national data. Recognising the need for consistent reporting across national borders, the Monitoring Framework invites countries to report progress on ecosystem targets by cross-referencing their nationally recognised ecosystem types to Level 3 (Ecosystem Functional Groups) of the IUCN GET (UN CBD, 2024a,b; Nicholson et al., 2024). Similarly, the UN System of Environmental-Economic Accounting (SEEA) Ecosystem Accounting standard (UN SD, 2024) adopts the GET as the reference classification for ecosystem types and recommends accounts based on high-quality national data aggregated to Level 3 of the GET for global reporting of accounts. Both frameworks, as well as the UN Family of Statistical Classifications, adopt the GET to implement an internationally consistent statistical methodology for reporting on ecosystems from diverse information systems that exist across the parties to the agreements.
2. **Enhancing cross-border cooperation and planning.** Cooperative ecosystem management, including protected area design and management and measures to protect threatened ecosystem types, is likely to produce stronger outcomes for biodiversity and people. For example, cross-referencing to the GET Level 3 may help countries identify like-for-like types at Levels 4 and 5 which can support regional Red List of Ecosystems assessments (RLE, Keith et al., 2024). Without cross referencing, the inevitable inconsistencies between independently developed national ecosystem classifications and maps may pose barriers to cooperation. Attribution of all classification units to GET EFGs, as an agreed international framework, respects and maintains national information infrastructure while providing a common language to facilitate cooperative ecosystem management across and beyond jurisdictional borders.
3. **Contributing high-quality data to open-source global data platforms.** A partnership led by the Group on Earth Observations (GEO) is developing a Global Ecosystem Atlas (https://globalecosystemsatlas.org/). The vision for the Atlas is to produce trusted, spatially and thematically comprehensive, harmonised maps of the world's ecosystems. The developing Atlas is an integrated repository of high-quality sub-global and global maps of ecosystems, which is expected to support a wide range of policy and research applications. It will use the GET as its framework for synthesis to support country engagement and the development of national ecosystem maps aligned with the GET. Rigorous cross-referencing of national ecosystem classifications to Level 3 of the GET will enable the highest-quality maps for each country to be incorporated into this emerging global platform. These guidelines enable consistent application of recommended cross-referencing protocols by the multitude of mapping teams developing ecosystem classifications and maps worldwide.
4. **Enhancing knowledge transfer to inform on-ground ecosystem management and nature-based solutions.** Effective ecosystem management is often hampered by limited understanding of ecosystem ecology and management needs. Level 3 of the GET groups together ecosystem types that share similar mechanisms of response to environmental change and management action. By enabling generalisations across functionally similar ecosystem types, the use of GET groupings, particularly at Level 3, empowers local actors to leverage research, experience and lessons learnt about approaches to ecosystem management and restoration that has been implemented in areas beyond their immediate jurisdictions of interest.
5. **Supporting comparative research.** Research in conservation biology and other disciplines produces major insights and advances in understanding about the global and regional status of ecosystems, their ecology and responses to environmental change. The GET is providing a vital interpretive framework for these efforts, for example, by disentangling tree-dominated savannas from superficially similar forest ecosystems and highlighting their contrasting ecology and management needs (Bond, 2020). Attribution or framing of research studies to GET EFGs facilitates appropriate applications of research to ecosystem management, and provides a rigorous method for aggregating data into global overviews of ecosystem properties, integrity and change.

Source: Editors

Box 2. Classification concepts and the Global Ecosystem Typology

In the most general sense, classifications are groupings of entities based on similarities of their properties. Entities in the same group should thus be more similar to one another than entities placed in different groups. This makes ***classifications useful tools for storing, retrieving and communicating information about variation among entities and for generalising about their properties***. Moreover, classifications are fundamental to the way that people think about, describe and communicate the world around them – we have a deep psychological tendency to generalise by grouping similar phenomena. Classifications may be structured hierarchically or non-hierarchically. A hierarchy of groupings allows relationships among entities to be represented at different levels of similarity or to represent similarities in different kinds of properties at different levels of the hierarchy. These conceptual properties of classifications make them potentially powerful tools for managing and communicating information about complex entities such as ecosystems. With spatial representation on maps, they have become powerful resources for informing conservation and resource use in the modern era (Margules & Pressey, 2000).

It is possible to construct different classifications of the same set of entities, depending on how the properties are interpreted and weighted, how finely differences are distinguished and the number of groups to which the entities are assigned. Different classifications also emerge when object properties are uncertain – improvements in knowledge (e.g. discovery of new entity types, or new understanding of object properties) may be reflected in changes to classification structure. Thus, it is very common for different classifications to exist for sets of similar entities, specifically ecosystems, in part because different design decisions reflect different application needs and different levels of understanding about the diversity and properties of ecosystems to be grouped.

The ecosystem concept is foundational to the GET, whose fundamental unit of classification, 'an ecosystem', is defined in the Convention on Biological Diversity as "*a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit*" (UN CBD, 1992). Rigorous cross-referencing between different classifications must be founded on comparisons of like-for-like units (see Principle 1 in Cross-referencing principles for ecosystem classifications). Therefore, only classification units that align with the ecosystem concept, can be cross-referenced to EFGs of the GET. As a 'reference classification' adopted by the United Nations (https://unstats.un.org/unsd/classifications/Family), the GET frames the international standard for reporting on ecosystems.

It should be noted that biological (and other) classifications are dynamic in both their fundamental units of classification and overall structure as knowledge develops for the entities that they classify (Keith et al., 2015). Species taxonomy, for example, is continually adapted as the species concept develops, and as rapidly accumulating molecular data improve insights into evolutionary relationships (e.g. Zuntini et al., 2024). Lags in adjustments to new knowledge result in a contemporary species taxonomy that reflects a mixture of morphological, biological and phylogenetic species concepts and alternative interpretations of evolutionary pathways.

Source: Editors

The GET provides a consistent, scientifically robust and widely agreed reference classification that serves as a 'common language' for synthesis, discourse and knowledge transfer on ecosystems from around the world. It has a hierarchical structure with six formal levels (Figure 1). The three upper levels differentiate functional groupings, and three lower levels accommodate differences in biotic composition among functionally convergent ecosystem types (Table 2). The granularity of ecosystem classes increases from Level 1 to Level 6. For clarity, the following sections describe the functional component of the typology (Levels 1–3) from the top down and the compositional component (Levels 4–6) in reverse order.

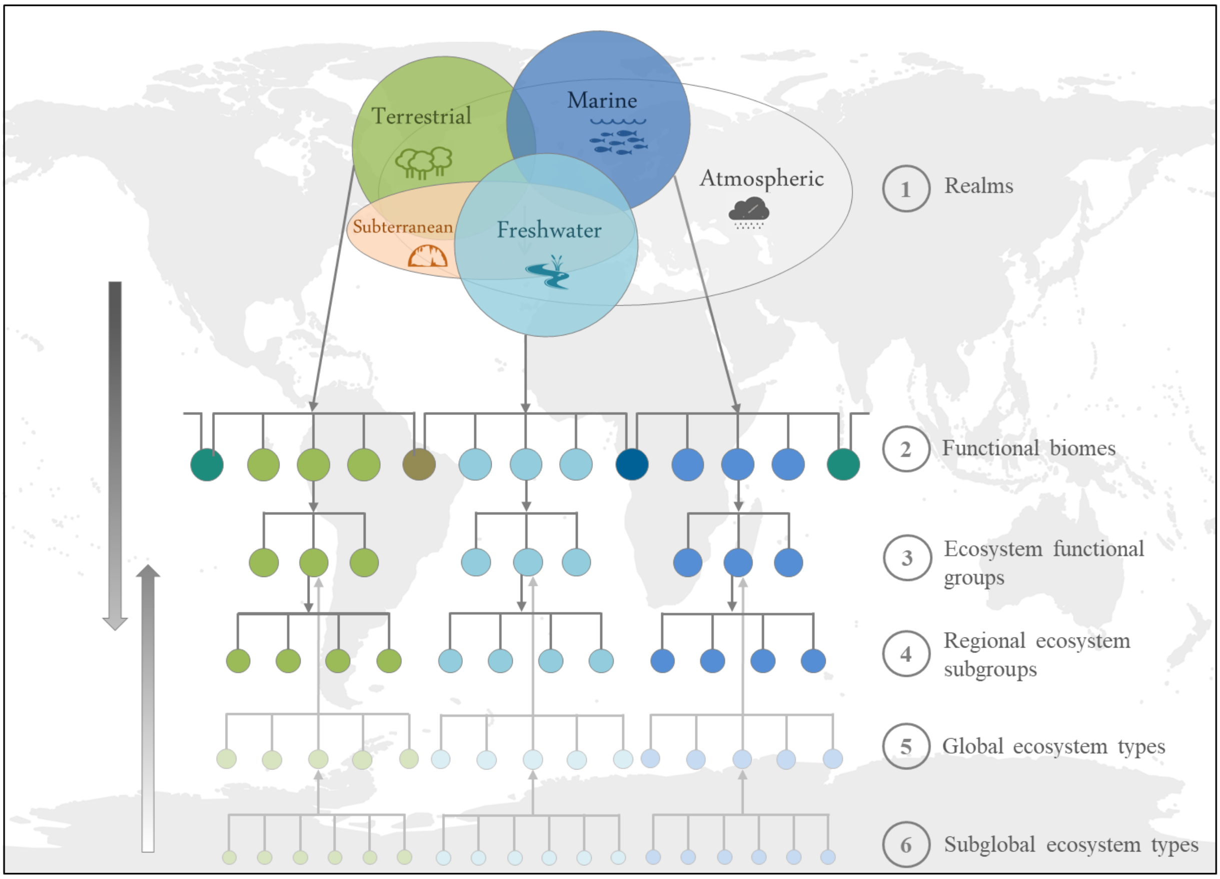


Figure 1. Hierarchical structure of the IUCN Global Ecosystem Typology. *Source: Reproduced from Fig S3.1, Keith et al., 2022. Note: Level 6 may comprise multiple sublevels (see Table 2)*

The functional component (Levels 1–3)

In Level 1 of the GET hierarchy, the biosphere is divided into four 'core' realms (Figure 1)[1]. Additional 'transitional' realms accommodate continuous variation of ecosystems across the interfaces between the core realms. The realms are divided into two to seven functional biomes, as well as nine transitional biomes, 25 in Level 2 of v2.1 of the GET, that recognise differences between the major drivers (or assembly filters) that shape ecosystem properties within a realm.

Ecosystem Functional Groups (EFGs, Level 3 units of the GET) are a key level of classification defined on the basis of shared functional properties, irrespective of the identity of biota that contribute to those functions. For example, tropical lowland forests of Africa, Asia, Australia, the Pacific and the Americas are grouped within a single functional group (T1.1 Tropical and subtropical lowland rainforests) because of their convergence in ecological properties, even though relatively few species are shared between forests in those different regions. The functional basis of these upper levels is fundamental to generalisations and predictions about ecosystem responses to environmental change, and a key reason why Level 3 of the GET is the agreed reference classification for ecosystem accounting (UN SD, 2024) and framework for synthesis of national reporting on Headline Indicators of the KMGBF (Nicholson et al., 2024). Lower levels of classification involve additional complexity (more classes) to accommodate regional to local variation in ecosystem composition, while Levels 1 and 2 are too broad to support the granularity of generalisations on ecosystem status needed for international reporting.

[1] A fifth core realm, the atmospheric realm, currently remains unresolved in its typological structure at Levels 2-6 of the GET due to the poorly developed understanding of atmospheric ecosystems.

Table 2. Definitions of hierarchical levels within the Global Ecosystem Typology

Level	Definition		
1 Realm	One of four major components of the biosphere that differ fundamentally in ecosystem organisation and function: terrestrial, freshwater, marine, and subterranean, with potential to add the atmosphere.	Functional properties – global context	Increasing specificity ↓
2 Functional biome	A component of a realm united by one or a few common major ecological drivers that regulate major ecosystem functions and ecological processes, derived from the top-down by subdivision of realms (Level 1).		
3 Ecosystem Functional Group (EFG)	A group of related ecosystems within a biome that share common ecological drivers promoting convergence of ecosystem properties that characterise the group. Derived from the top-down by subdivision of biomes.		
4 Regional ecosystem subgroup	An ecoregional expression of an EFG derived from the top-down by subdivision of EFGs (Level 3). They are proxies for compositionally distinctive geographic variants that occupy different areas within the distribution of a functional group.	Compositional properties – local data	Increasing specificity ↓
5 Global ecosystem type	A complex of organisms and their associated physical environment within an area occupied by an EFG. Global ecosystem types grouped into the same EFG share similar ecological processes, but exhibit substantial difference in biotic composition. Within the GET classification, they are derived from the bottom-up, either directly from ground observations, by evidence-based ecosystem proxies informed by local ecological knowledge, or by aggregation of sub-global ecosystem types (Level 6).		
6 Sub-global ecosystem type	A subunit or nested group of subunits within a global ecosystem type (Level 5), which therefore exhibit a greater degree of compositional homogeneity and resemblance to one another than global ecosystem types. These represent units of established classifications (e.g. at national level), in some cases arranged in a sub-hierarchy of multiple levels, derived directly from ground observations or, in data-poor situations, by finer resolution ecosystem proxies informed by local ecological knowledge.		

Source: Table S3.1 of Keith et al., 2022

The compositional component (Levels 4–6)

Level 6 of the GET (Sub-global ecosystem types) includes the finest available units of ecosystem classification. In essence, they represent the units from many local, national and regional classifications that cover different parts of the Earth's surface. These classifications, may, themselves, comprise multiple hierarchical levels, which are enveloped within GET Level 6. In essence, Level 6 is where national classifications are recognised as part of the GET. Potentially these classifications sum to many thousands of Level 6 units worldwide (Table 1), so establishing explicit relationships with Level 3 EFGs (i.e. cross-referencing Level 6 units to Level 3 units) simplifies complexity, resolves inconsistencies, and also facilitates access to information on functional properties that are sometimes poorly documented in sources that describe Level 6 units.

Level 5 of the GET (Global ecosystem types) provides the opportunity to rationalise some of the inevitable inconsistencies among Level 6 units from different jurisdictions by broadening and aggregating sub-global ecosystem types with very similar properties, whether these originate from different local classifications or the same one. Rationalisation may be informed by analyses of quantitative data, where available, and/or by expert opinion, preferably via structured elicitation methods to reduce cognitive bias (Hemming et al., 2018).

Level 4 of the GET (Regional ecosystem subgroups) offers an alternative pathway from the top down (i.e. by subdividing Level 3 units, rather than aggregating Level 6 units; Figure 1) to develop proxies for global ecosystem types. Development of Level 4 subtypes is predicated on the assumption that global-scale geography is informative about biotic composition, i.e. occurrences of the same EFG (Level 3 unit) in different geographic areas are assumed to comprise different assemblages of biota (Smith et al., 2018). Where this assumption holds, Level 4 provides a more rapid pathway to compositional units but as global-scale proxies, they may be expected to show inferior representation of biota compared to Level 5 types, which are derived directly from observations of the biota or evidence-based ecosystem proxies informed by local ecological knowledge.

Cross-referencing principles for ecosystem classifications

Four key principles underpin scientific standards for cross-referencing the units of an independent ecosystem classification to GET Ecosystem Functional Groups.

Principle 1. Comparison of like classifications

The first principle for cross-referencing classifications is to ensure that their units are based on like concepts (i.e. whether they are the same kinds of entities). Cross-referencing can elucidate relationships between the units of classifications that classify the same types of entities. Cross-referencing is not informative about relationships between classifications that classify qualitatively different kinds of entities. As a trivial example, fruits and desserts are different kinds of entities that may be grouped into structurally different classifications based on different properties. Nevertheless, partial relationships may exist between these classifications; some of their groups may be related. Many desserts include fruit, and in some cases multiple fruits can be included in a dessert type. Thus, some dessert types are unrelated to fruit types and vice versa, while some are related in a way that permits cross-referencing. These kinds of partial relationships may arise between classifications of ecosystem types, and classifications of conceptually different entities, such as land use types or land cover types, and warrant rigorous evaluation in cross-referencing.

To be cross-referenced to the GET, it follows that the units of another classification must be aligned with the ecosystem concept. These guidelines adopt the definition agreed in the UN CBD (1992) (see Box 2), following Tansley's (1935) original concept: *"a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit"*.

Principle 2. Group membership based on entity properties

The task of cross-referencing units from different ecosystem classifications may be viewed more generally as defining the *relationships* between *entities* (Chen, 1976). For example, two entities that share most or all of their key properties may be interpreted as having a one-to-one relationship. More complex relationships are possible, such as one to many or even many to many. The relationships between groups defined in different classifications can be elucidated by a comparison of entity properties.

Applying this general model to the GET, the entities of interest are most commonly ecosystem types (represented in Levels 5 and 6 of the GET) and EFGs (Level 3 of the GET). EFGs are groups (entity types), i.e. they are a set of ecosystem types sharing common properties that distinguish them from ecosystem types in other EFGs (Keith et al., 2022). The *relationship* of interest in this case is the *membership* of a particular ecosystem type to an EFG.

Similarly, users of the GET may need to determine EFG membership for singular observations of an ecosystem at a specific place and time (e.g. in the field for management purposes, or to compile training data for mapping). Figure 2 posits a simplified model of membership relationships. An inference (or diagnosis) of membership is based on a comparison of properties of a given ecosystem type (or singular ecosystem observation) with those of candidate EFGs.

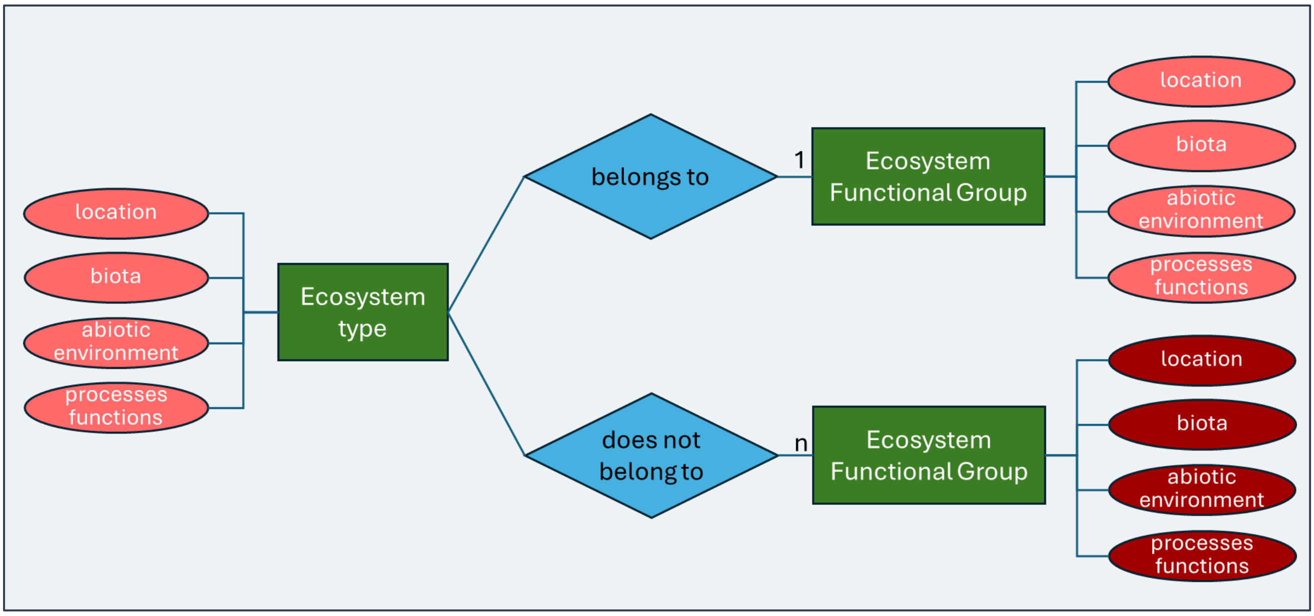


Figure 2. Simplified conceptual model of deterministic binary membership relationships of an ecosystem type to Ecosystem Functional Groups (rectangles). Membership (diamond) is inferred from a comparison of four groups of ecosystem properties (ellipses). If the properties of the type fall within the range of values described for a candidate EFG (shown where ellipses on left and right are the same colour), then the type is inferred to 'belong to' that EFG. If the properties of the type fall outside the range of values described for 'n' other candidate EFGs, then it is inferred that the type 'does not belong to' those EFGs. Property mismatches are indicated by a darker shade of ellipse. The model shows relationships for a single ecosystem type, however, multiple ecosystem types (not shown to simplify) may belong to a single EFG. Note: Labels of ellipses are abbreviated. For example, refer to properties of biota (e.g. function, life form), rather than identity of biota. Processes and functions involve biota and/or the abiotic environment and may vary between sites within the ecosystem distribution. *Source: Editors*

Principle 3. Weight of evidence

While principle 2 establishes the concept of group membership, principle 3 describes how membership should be estimated. An essential pre-requisite for cross-referencing is to access and interpret all information on relevant properties for both the ecosystem type(s) in the source classification and the candidate EFGs to which they could be assigned. Figure 2 lists four groups of diagnostic properties (in ellipses) that are the defining features of ecosystem types (Keith et al., 2013; IUCN, 2024). All relevant lines of evidence on group membership should be considered, documented and weighted according to relevance and reliability. Descriptive profiles summarise this information for all EFGs (Keith et al., 2022; https://www.global-ecosystems.org). Similar profiles may be available for the classification that is to be cross-referenced (e.g. Mucina & Rutherford, 2006; Luebert & Pliscoff, 2017; Kontula & Raunio, 2019; Murray et al., 2020; EUNIS; USFGDC, 2022). However, much of the ecosystem data relevant to cross-referencing may be disconnected from the classifications, and needs to be accessed from other sources (e.g. remote sensing, environmental spatial data, databases of field observations, etc.). Assessments based on limited descriptive information are unlikely to support robust cross-referencing outcomes.

Relevant lines of evidence that inform comparisons of ecological properties may be derived from direct in situ observations of ecosystems, or may be inferred from indirect sources, such as remote sensing, maps or models. The weight assigned to evidence on each property in estimating membership should consider:

i) The diagnostic value of the property for discriminating candidate EFGs,
ii) The reliability of the evidence on the property for the classification unit, and
iii) Corroboration of independent lines of evidence.

Other things being equal, evidence on more ecosystem properties supports stronger membership inferences than evidence based on few properties or little detail, multiple lines of evidence should be weighted more highly than a single line of evidence, and direct evidence should be weighted more highly than indirect evidence. All lines of evidence evaluated, their weightings and associated justification should be cited or documented as part of the cross-referencing output to ensure a standard of transparency and repeatability. Where large numbers of ecosystem types are cross-referenced to the GET (e.g. for some national classifications with many units, Table 1), the documentation may be compiled efficiently in an overall 'Methods' statement, with additional detail for particular ecosystem types added where necessary to a cross-referencing table.

Principle 4. Representing uncertainty

Membership of entities to groups may be uncertain. Uncertainty is not unique to ecology, but pervades all disciplines of all knowledge (Burgman, 2005). Although dealing with uncertainties is challenging and sometimes inconvenient, ignoring them in decisions and reporting may lead to adverse outcomes or even catastrophic consequences (Burgman, 2005). The first step towards transparent reporting and future-proof decisions is to identify and quantify uncertainties. In statistics, for example, it is standard practice to summarise data by reporting means and confidence intervals or some other measure of variation about the mean. Where quantitative data are lacking, similar methods can be used to produce bounded estimates from expert elicitation (Burgman, 2015). The bounds or confidence intervals provide additional information for future-proofing decisions than best estimates or means alone.

Levels of uncertainty vary depending on the nature of evidence available, as well as the definitional boundaries (circumscription) of ecosystem types and EFGs in their respective classifications. Sources of uncertainty that affect membership inferences for cross-referencing may include:

i) Incomplete or poor-quality information about ecosystem properties,
ii) Disagreement between different sources of evidence,
iii) Spatial or temporal variation in ecosystem properties (e.g. dynamic forest or wetland mosaics),
iv) Properties that may be intermediate or shared between those of two or more EFGs, and
v) Methodological or subjective differences between analysts in interpretation of the same evidence.

Some sources of uncertainty (e.g. source i) may be resolved by assessing additional information, or by applying standard guidelines for interpretation (e.g. source v), while other sources of uncertainty may not be reducible (e.g. source iv).

Thus, uncertainty inevitably exists in classifications and should be represented transparently, not ignored. The simplistic binary deterministic membership model in Figure 2 ignores uncertainty, i.e. it assumes that each ecosystem type (and by extension all of its occurrences) can be uniquely attributed to a single EFG without doubt. Alternatively, a fuzzy (graduated) membership concept (Figure 3) recognises that membership attribution can be uncertain and that there may be more than one plausible alternative candidate EFG for membership of a given ecosystem type. This uncertainty can be quantified by estimating membership values that sum to a value of one across all candidate EFGs. Interpreters should document not only the best-fit membership of an ecosystem type to an EFG, but also the uncertainty in the relationships, by including plausible alternative EFGs and a membership estimate that indicates their relative plausibility. This is analogous to providing confidence intervals around a mean estimate. Transparent estimation, systematic treatment of, and clear communication of, uncertainty will provide users with options to deal with them, rather than ignore it in applications and decisions. Users may still use the most likely EFGs (i.e. those with the highest membership value of all candidates) in decisions. However, identifying plausible alternative EFGs and membership estimates enables ecosystem policy makers and managers to examine the implications of alternative scenarios for the decisions, as well as make informed adjustments to membership relationships when new information becomes available (see Box 6).

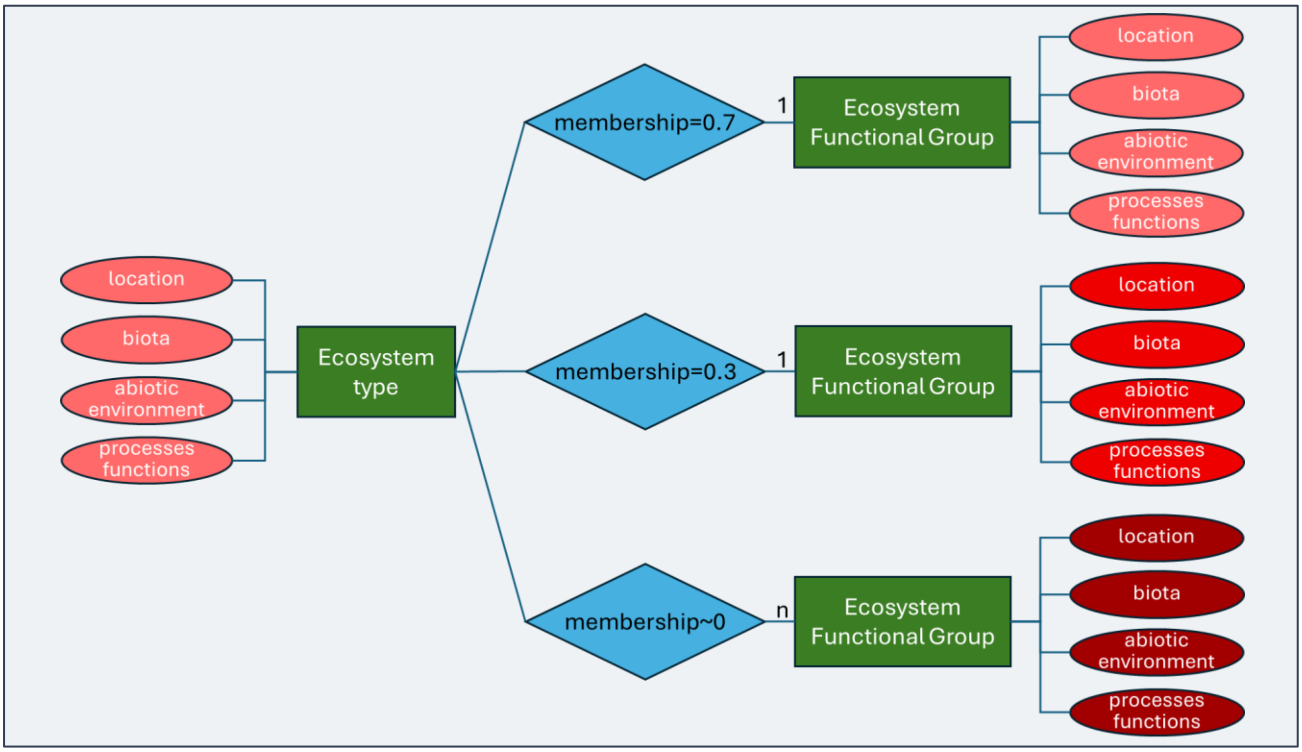


Figure 3. Simplified conceptual model of quantitative membership relationships of an ecosystem type to Ecosystem Functional Groups (rectangles) based on fuzzy sets. Membership (diamond) takes on values ≤1, summing to 1 (with rare exceptions <1) based on a comparison of four groups of ecosystem properties (ellipses). If the properties of the type fall largely within the range of values described for a candidate EFG, then the membership value is high for that EFG (top rectangle on right). If some properties of the type fall outside the range of values described for another candidate EFG(s) but membership is plausible, then the membership value(s) is/are smaller but non-zero for that EFG(s) (middle rectangle on right); and membership values are zero for remaining EFGs with significant mismatches in properties with those of the type (bottom rectangle on right). Darker shades of ellipse represent decreasing resemblance of properties between the ecosystem type and candidate EFG(s). This example shows two candidate EFGs with non-zero membership values, one more than twice as likely as the other to include the ecosystem type in its fuzzy set. Numbers to the right of blue diamonds indicate one EFG with a membership value of 0.7, one with a value of 0.3, and 'n' (all remaining EFGs) with zero membership values. The model shows relationships for a single ecosystem type, however, multiple ecosystem types (not shown for simplicity) may belong to a single EFG. *Source: Editors*

Stepwise cross-referencing protocol

The principles for cross-referencing may be implemented in a stepwise diagnostic process (Figure 4), either manually or with the aid of diagnostic tools to assess available evidence. The process described here assesses ecosystem types one-by-one, in a systematic manner that progressively eliminates alternative EFGs whose properties are not consistent with those of the ecosystem type being assessed. The list of candidate EFGs to which the ecosystem type could belong is progressively narrowed until one or a few plausible candidates remain. Membership values are then assigned to these remaining candidates according to the weight of evidence across relevant properties and membership uncertainty. In the absence of large, balanced quantitative data sets on multiple ecosystem properties, estimation of membership is at least partly a subjective process, engagement of multiple interpreters is recommended in a structured elicitation process. In the final step, membership estimates from multiple interpreters are combined to produce the robust cross-referencing relationships, with uncertainty quantified and methods documented. Stepwise manual diagnosis can help new users build familiarity with the diagnostic process, as well as the properties of EFGs, but can be adapted to a batch workflow with the aid of diagnostic software. Commentary on each of the five steps is given below (Table 3).

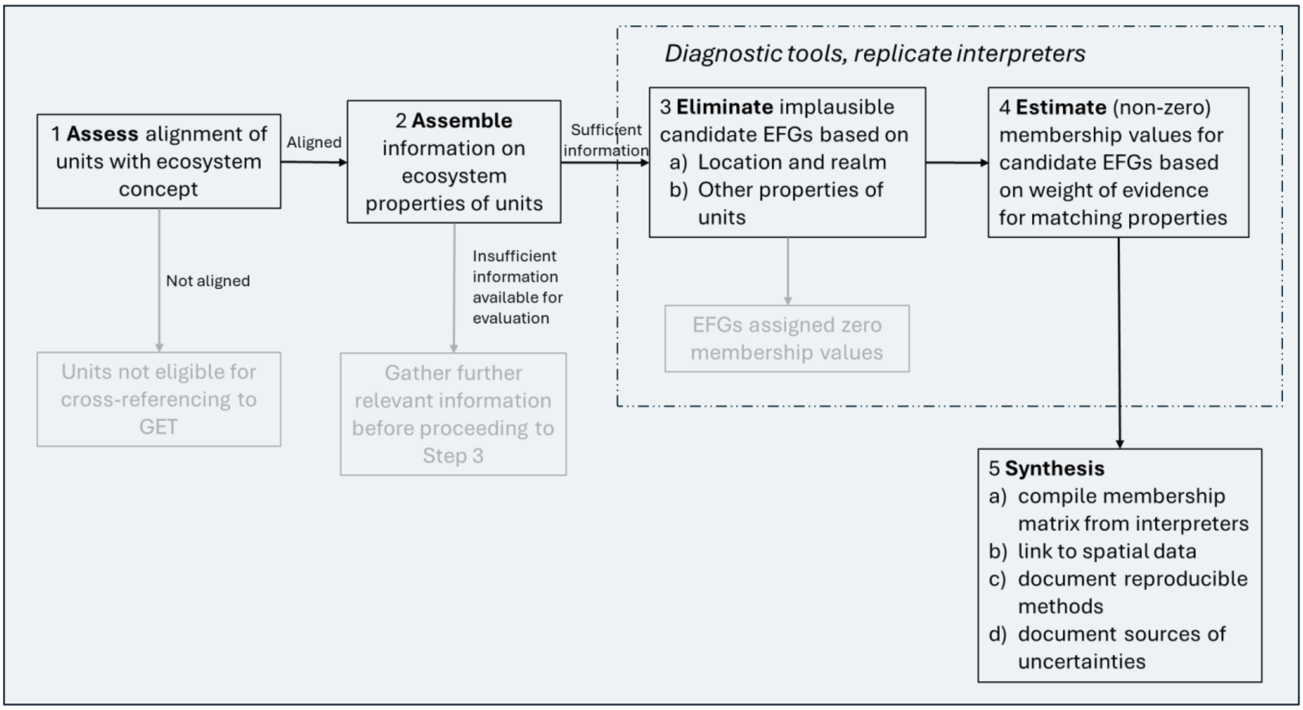


Figure 4. Sequential diagnostic steps for estimating the membership of an ecological classification unit to GET Ecosystem Functional Groups. *Source: Editors*

Table 3. Summary of diagnostic steps for cross-referencing ecosystem types to Ecosystem Functional Groups

Step	Guidance
1. Assess alignment with ecosystem concept	See Principle 1. Is the entity a functional unit defined by distinguishing biotic and abiotic features and/or with descriptive information that enable its ecological processes and interactions to be identified and compared? If yes, the classification unit is 'within scope' for cross-referencing, proceed to step 2.
2. Assemble available information	See Principle 2. Diagnostic properties of ecosystem types include those related to location, biotic features, abiotic features and ecological processes and interactions (see Step 2. Assembling information on the properties of ecosystem types for elaboration). Information on diagnostic properties may be obtained from descriptions (published or unpublished reports), research literature, or compiled from field observations, remote sensing and other spatial data, in situ images (photos), or expert advice. If the information is assessed as reliable and of sufficient scope for comparison with GET EFG descriptions, proceed to step 3.
3. Eliminate implausible candidate Ecosystem Functional Groups	Use appropriate information on location and environmental realm for the ecosystem type to identify and eliminate implausible candidate EFGs from further consideration. Other informative diagnostic ecosystem properties may be considered in further reducing the number of plausible candidate EFGs. This interpretation should be made by multiple experts who read and understand available information (including descriptions of EFGs). Membership estimates for EFGs identified with certainty as implausible candidates for the ecosystem type should be set to '0' and may be excluded from step 4.
4. Estimate membership values for remaining candidate EFGs	Each of the multiple interpreters should ensure familiarity with descriptions of candidate EFGs and their key diagnostic properties (https://global-ecosystems.org/explore). Estimates of membership values for the remaining (i.e. plausible) candidate EFGs should be based on the weight of evidence using all available information on all relevant properties. Based on Principle 3, the weight assigned to each property in estimating membership values should consider: i) The diagnostic value of the property for candidate EFGs, ii) The reliability of the evidence on the property for the classification unit, and iii) Corroboration of independent lines of evidence. Specific guidance and rules for estimating membership values is given in Table 4.
5. Synthesis	To reduce cognitive bias and other subjective effects on membership estimates, steps 3 and 4 should be completed by multiple interpreters, including at least one expert familiar with the classification being assessed and its area of coverage and at least one expert familiar with the GET and the global context of the study area. The estimates should be developed using structured elicitation methods (Appendix 1) in which interpreters: i) Are provided with information from steps 1–3 and briefed on the membership rules and elicitation process, ii) Independently make initial membership estimates, iii) Share summaries of their initial estimates and discuss issues of interpretation, and iv) Independently revise their initial estimates. The final best estimates of membership are calculated by averaging the revised estimates across all interpreters, with bounds represented by the lowest and highest among interpreters.

Source: Editors

Step 1. Assessing alignment of units with the ecosystem concept

An interpreter must first determine eligibility for cross-referencing to the GET by assessing whether the units (entities) of interest align with the ecosystem concept (Principle 1). To assess this requirement, these guidelines adopt the definition of an ecosystem used in the Convention on Biological Diversity (see Glossary).

Alignment with the ecosystem concept is predicated on whether units of eligible classifications are *explicitly described and distinguished from one another* on the basis of three main elements of the ecosystem definition (UN CBD, 1992):

i) A biotic complex (plants, animals, micro-organisms),
ii) An abiotic complex (the non-living environment), and
iii) The interactions within and between them that underpin process and function (i.e. interacting as a functional unit).

In some cases, there may be insufficient information to assess whether the units of a classification align with the ecosystem concept based on elements i–iii of its definition (UN CBD, 1992). In general, the assessment of alignment should be based on explicit information from the source and associated information (e.g. descriptive profiles, methods of derivation, see Box 3). To a limited degree, assessors may use well-justified inferences and assumptions about the properties of the entity to fill gaps in information needed to complete step 1 with reasonable certainty. Conversely, for example, a text label in a map legend, of itself, will generally contain insufficient information to assess whether an entity is aligned with the ecosystem concept, as well as subsequent diagnostic steps in cross-referencing. Indeed, this level of information is generally inadequate for applications such as international reporting because users are unable to obtain a minimal understanding of the entities reported. Classifications and maps that lack basic documentation describing the ecological properties of their units will therefore be difficult to cross-reference to the GET and also of limited utility for reporting at any scale. Improving their fitness-for-purpose rests with their custodians and authors, with further development required to document the properties and description of their units.

Step 2. Assembling information on the properties of ecosystem types

Information on the diagnostic properties of ecosystem types (their location, biotic features, abiotic features and ecological processes) is essential for cross-referencing them to the EFGs of the GET (Figure 3). Examples of relevant information include:

i) Location (sets of point coordinates, georeferenced polygons, or pre-defined areas of occurrence, e.g. countries, ecoregions, etc.),
ii) Biotic properties (abundant or important species, dominant life forms, phenological, behavioural and movement traits of dominant biota, structural properties, trophic components, etc.),
iii) Abiotic properties (terrestrial/freshwater/marine/subterranean setting, climate variables, substrate features, topographic features, disturbance regimes, etc.), and
iv) Ecological processes and interactions (e.g. structure of trophic webs, dependencies and competitive relationships among biota, seasonal dynamics and cues, disturbance regimes, mechanisms of energy capture and biomass production, resource cycling, spatial processes such as resource flows or movement of biota, key life history processes and biotic turnover, etc.).

Relevant sources of evidence on these properties may include descriptions (published or unpublished reports), research literature, or compilations from in situ field observations, images (photos), remote sensing and other spatial data, or expert advice. Other things being equal, detailed and reliable evidence on more ecosystem properties supports stronger membership inferences than less detailed evidence based on few properties. Therefore, *all reasonable effort should be made to search for and compile relevant information* on the ecosystem types to be cross-referenced, and the efficacy and scope of the information should be assessed as reliable and sufficient for comparison with GET EFG descriptions (https://global-ecosystems.org), before proceeding to step 3.

Box 3. Alignment with the ecosystem concept

Certain types of land or water classification align with the ecosystem concept (UN CBD, 1992), while others do not. For example, vegetation classifications based on ecological properties are often effective surrogates for ecosystems (e.g. Dayaram et al., 2021) because vegetation plays important structural and functional roles in terrestrial ecosystems. In contrast, classifications of land use or land cover (e.g. Di Gregorio & Jansen, 2000) are defined on the basis of human activity or detectable structural features, and may not faithfully represent 'dynamic complexes of biotic communities'. Similarly, classifications or maps constructed from environmental or bioclimatic stratifications (e.g. Sayre et al., 2020) are based on edaphic, substrate, geomorphic or climatic variables but lack direct reference to biota and interactions that define a functional ecosystem unit. Ecoregions are based on biogeographic patterns in biota, but offer limited representation of dynamism or functional interactions. These types of entities are therefore generally ineligible for cross-referencing to the GET because their units are not ecosystem types. However, these other types of classifications and associated maps may contain useful information about some ecosystem types (e.g. Driver & Botts, 2025).

Habitat or vegetation type classifications
Many classifications of terrestrial or aquatic habitat types or vegetation types have ecological foundations (e.g. Table 1) and meet the basic requirements for alignment with the ecosystem concept, and are therefore eligible or 'within scope' for cross-referencing to the GET.

Classifications based on abiotic features
Classifications based only or largely on stratifications of generic abiotic features from global data sets (climate, landcover, substrate, etc.) would not usually be 'within scope' for cross-referencing to EFGs unless biotic features and interactions explicitly identify them as distinctive 'functional units' (UN CBD, 1992). For example, certain benthic topographic features serve as sufficient indicators of ecosystems and contain unique biota that are associated with hadal trenches and troughs (EFG M3.6). Relationships between fine scale abiotic features (e.g. soil) and biotic features (e.g. vegetation) based on local evidence may also be important information sources to describe distributions of local and national ecosystem types with appropriate spatial models or rules.

Land use and land cover type classifications
Classifications and maps of land use types and land cover types may not be well aligned with the ecosystem concept because, in part, they are generally not described or distinguished in terms of biotic assemblages or ecological interactions and processes that characterise them as functional ecosystem units (Driver & Botts, 2025). Exceptions may include certain land use types that represent anthropogenic ecosystem types in which humans directly introduce and maintain the biota and shape its interactions in particular environments (e.g. wheatfields). In such cases, their defining features align well with the elements i–iii of the ecosystem concept (Driver & Botts, 2025).

Ecoregions
Ecoregions (Olson et al., 2001; Spalding et al., 2007; Abell et al., 2008; Dinerstein et al., 2016) are another type of ecological unit that does not align directly with the ecosystem concept. These are mapped areas that share common macro-environmental or biogeographical features and contain complexes of contrasting, but co-occurring ecosystem types. For example, a single marine ecoregion may include occurrences of mangrove, rocky shores, seagrass, coral reef and other ecosystems characterised by different biotic assemblages, environments and ecological processes (Spalding et al., 2007; Keith et al., 2022). The heterogeneity of ecoregions therefore makes them unsuitable for cross-referencing to EFGs.

Source: Editors

Step 3. Identifying plausible candidate Ecosystem Functional Groups by elimination

Membership of any given ecosystem type to a particular EFG (Principle 2) is determined by the degree to which its properties are shared with those of the EFG (described at https://global-ecosystems.org). Initially all EFGs are candidates for membership. Identifying the subset of plausible candidates may be viewed as a process of elimination, in which EFGs with a negligible membership value (~0, Figure 3) can be excluded from further consideration. This should be based on the weight of evidence in comparing ecosystem properties between the ecosystem type and candidate EFGs (Principle 3), however many implausible candidates can rapidly be eliminated with reference to a few key properties.

The location of an ecosystem type and its realm in Level 1 of the GET (Figure 1: terrestrial, subterranean, freshwater, marine or transitional) warrant evaluation at an early stage in step 3 due to their high diagnostic value in discriminating between large numbers of candidate EFGs. Care should be taken in considering ecosystem types that may occur on the interfaces among the core realms of the GET to ensure that plausible options are not eliminated erroneously. Location information is also an important means of excluding implausible candidates, and critical evaluation of spatial relationships that is cognisant of spatial granularity can reduce errors in inferences about candidate EFGs (Box 4). After information on location and environmental realm is evaluated, interpreters should consider other ecosystem properties that provide greatest discrimination (high diagnostic value) among remaining candidate EFGs.

To illustrate the elimination process, locational information that an ecosystem type occurs in China, for example, reduces the number of candidate EFGs from 110 to 68, excluding those from other parts of the world. Reliable information that this ecosystem type occurs on dry land further reduces the number of candidate EFGs to 20 excluding those of the aquatic (freshwater and marine) and transitional GET realms. More detailed environmental information that the ecosystem type occurs only in high alpine environments further reduces the number of plausible candidates to 3 EFGs. Thus, with country-level information on location, and broad information about two abiotic properties (terrestrial realm and alpine environment) 107 EFGs can be identified as implausible candidates and assigned zero membership without the need for further consideration of other properties.

Where the properties of the ecosystem type are well known and cross-referencing interpreters are highly familiar with EFG profiles, the identification of candidate EFGs (or exclusion of many non-candidates) can be done rapidly on a subjective basis. Nonetheless, attention to detail is essential to ensure accuracy in reducing the candidate EFGs to a small number. Interpreters must read and understand the descriptions of both the ecosystem type and the candidate EFGs to critically evaluate and compare their key diagnostic properties. Several tools are in development to support a systematic approach to cross-referencing (see Analytical tools for cross-referencing).

Step 4. Estimate membership and uncertainty for the remaining candidate Ecosystem Functional Groups

By interpreting group membership as a fuzzy concept (Principle 4, Figure 2), rather than as a deterministic binary concept (Figure 1), interpreters can indicate the degree of uncertainty about the membership of any ecosystem type to a GET EFG. This can be done by estimating a fuzzy membership value (range 0–1) for each pairwise combination of ecosystem type and EFG, whereby '1' represents full certainty of membership to an EFG and 0 represents full certainty of non-membership. Table 4 gives guidance for estimating fuzzy membership values. To ensure that membership values can be interpreted logically as subjective probabilities (Burgman, 2015), for any given ecosystem type they should sum to '1' for all candidate EFGs. Thus, the sum of membership values for an ecosystem type should never exceed '1'. In exceptional cases, membership values may sum to '<1' if the ecosystem type could belong to a distinctive undescribed EFG that cannot be interpreted as intermediate among other EFGs (i.e. interpreters should always try to ensure summation to '1' except where there is no other option or a certain gap that is not filled by existing EFGs).

Box 4. Assessing location information to identify plausible candidate Ecosystem Functional Groups

If the location of the ecosystem type is outside the spatial distribution of a particular EFG, it cannot be a member of that EFG. The implementation of this logic is limited by the quality of information on the spatial distribution of both the ecosystem type and the EFG. Indicative distribution maps on the GET website (https://global-ecosystems.org) provide a relatively inclusive and coarse-resolution representation of global EFG distributions that can be used for this comparison. Spatial information on the ecosystem type of interest will generally offer finer granularity, but there are limitations associated with both high- and low-resolution spatial data and spatial intersections should not be used rigidly to eliminate implausible candidate EFGs without critical appraisal of independent information appropriate to the context. If the granularity of spatial information on ecosystem occurrence is too fine (e.g. a point location or small grid cell or polygon), a lack of spatial overlap with an indicative EFG map could result from small locational errors in the former or small errors of omission in the latter. For example, indicative EFG maps may omit small occurrences of ecosystems on mountain tops beyond the main envelope of occurrence. Conversely, if spatial information for both entities is very coarse, a comparison may not eliminate many implausible candidate EFGs, i.e. the diagnostic value of the comparison is low.

A simple but informative comparison of location information can be made by identifying the country(ies) or marine region(s) in which the ecosystem type occurs and comparing it with the list of countries in which a candidate EFG is recorded based on its indicative global distribution map. A list of EFGs mapped within a given country or marine region can be obtained from the Analyse function (select predefined region) on the GET web application (https://global-ecosystems.org/analyse). Although this relatively coarse granularity is usually sufficient to eliminate many implausible EFGs from further consideration with confidence, there may be spatial errors of omission or commission for EFGs at the country level.

Source: Editors

Table 4. Rules for estimating fuzzy membership values, also known as degrees of belief or subjective probabilities, that ecosystem type 'A' belongs to a particular Ecosystem Functional Group (EFG) 'X' of the Global Ecosystem Typology. All membership estimates for type 'A' across all Ecosystem Functional Groups must sum to no more than 1.

Strength of evidence that ecosystem type 'A' is a member of Ecosystem Functional Group 'X'	Membership estimate
Virtually certain (properties are a strong match, no plausible alternative EFGs)	1
Very likely (properties are a strong match and all plausible alternative EFGs are very unlikely)	0.90–0.99
Likely (properties are a good match and all plausible alternative EFGs are unlikely)	0.66–0.89
More likely than not (properties are a good match, but other plausible EFGs could be almost as likely)	0.50–0.65
Almost as likely as not (properties are a reasonable match, but alterative EFGs could be as likely)	0.33–0.50
Unlikely (properties show limited degree of match, but alternative EFGs could be more likely)	0.10–0.33
Very unlikely (properties show very limited match, and alternative EFGs should be more likely)	0.01–0.10
Exceptionally unlikely (key diagnostic properties do not match, membership is implausible)	0

Source: Concept adapted from Mastrandrea et al. (2010)

For an ecosystem type with properties that are strongly aligned with those of one particular EFG (i.e. within the bounds of variation documented in the EFG description) and there is no plausible alternative EFG to which that type could plausibly belong, interpreters should estimate a membership value of '1' for that EFG and '0' for all others (Table 4). A membership value of '1', means that it is virtually certain that an ecosystem type is part of the fuzzy set for one particular EFG (i.e. within its range of variation) to the exclusion of other candidates, not that it is a perfect example of that EFG. For example, the properties of fynbos vegetation types described and mapped on the Cape Peninsula (Mucina & Rutherford, 2006) are within the range of variation for the same properties documented in the description of EFG *T3.2 Seasonally dry temperate heath and shrublands* (Keith et al., 2022) and there are no plausible alternative EFGs to which fynbos vegetation types could belong. These fynbos vegetation types should therefore be assigned a membership estimate of '1' to EFG T3.2 and an estimate of '0' to all other EFGs.

Membership values must be estimated for each candidate EFG for each ecosystem type that is cross-referenced to the GET. It should be noted that, for virtually all ecosystem types, most EFGs will have zero membership values and only a few (usually <4) will have non-zero values. Table 5 describes interpretations for exemplar scenarios for membership estimates where there is uncertainty about the membership of an eligible ecosystem type to one or more plausible candidate EFGs. In most of the scenarios presented, one EFG (with the largest membership estimate) is clearly identifiable as the most plausible candidate. Other scenarios where the membership estimates are low or where two or more EFGs have very similar membership estimates indicate uncertain relationships. For applications that require the most plausible candidate to be identified, tied membership values may be resolved by including additional interpreters in the elicitation, providing additional information to interpreters on the properties of respective entities, or by instructing interpreters to resolve the most plausible candidate by revising their membership estimates.

Table 6 provides interpretive commentary on EFG membership estimates for three real examples of terrestrial, freshwater and marine ecosystem types. Similar reasoning is applicable to ecosystem types from transitional realms.

Table 5. Example scenarios for estimating fuzzy membership values based on a comparison of ecosystem properties of an ecosystem type with those of candidate Ecosystem Functional Groups (EFGs) (see Step 4)

Membership scenario	Interpretation	Guidance on membership estimates
Definitely within scope of at least one EFG	A local ecosystem type 'A' is without doubt a member of one or more EFGs	Sum to 1 for one or more EFGs
Only one plausible EFG	A local ecosystem type 'A' is, without doubt, uniquely a member of EFG 'X'	1 is assigned to group 'X' and 0 to all other EFGs
Two plausible EFGs, one three times more likely than the other	Membership of a local ecosystem type 'A' to EFG 'X' is three times as likely as membership to EFG 'Y' and membership to all other EFGs is exceptionally unlikely	0.75 is assigned to EFG 'X', a value of 0.25 is assigned to EFG 'Y', and 0 assigned to all other EFGs
Two plausible EFGs, one twice as likely as the other	Membership of a local ecosystem type 'A' to EFG 'X' is twice as likely as membership to EFG 'Y' and membership to all other EFGs is exceptionally unlikely	0.67 is assigned to EFG 'X', a value of 0.33 is assigned to EFG 'Y', and 0 assigned to all other EFGs
Two plausible and equally likely EFGs	Membership of a local ecosystem type 'A' to EFGs 'X' and 'Y' is equally likely and membership to all other EFGs is exceptionally unlikely	0.5 is assigned to each of EFGs 'X' and 'Y', and 0 assigned to all other EFGs
Three plausible and equally likely EFGs	Membership of a local ecosystem type 'A' to EFGs 'X', 'Y' and 'Z' is equally likely and membership to all other EFGs is exceptionally unlikely	0.33 is assigned to each of EFGs 'X', 'Y' and 'Z', and 0 assigned to all other EFGs
One plausible EFG, but may not be a member of any EFG	The local ecosystem type 'A' could belong to EFG 'X', but it is equally likely that it does not belong to any currently recognised group*	0.5 is assigned to EFG 'X' and 0 to all other EFGs
Possibly no plausible EFG	A local ecosystem type 'A' may belong to two or more EFGs (e.g. 'X' or 'Y') but also may not be a member of any EFG*	Estimates for 'X', 'Y' and all other EFGs sum to <1 (low values indicate less likelihood of membership to any EFG)
Definitely no plausible EFG	A local ecosystem type 'A' definitely does not belong to any currently recognised EFG*	0 is assigned to all groups

Source: Editors. *This scenario is very rare in practice, given that the GET is intended to cover Earth's entire biosphere.

Table 6. **Exemplar reasoning to support fuzzy membership estimates based on comparisons of ecosystem properties observed in situ to those documented for Ecosystem Functional Groups (EFGs).** Diagnostic steps 1–4 (Figure 4) were applied by a single expert, with output to be combined with those of other experts in step 5. Numbers in parentheses in each row for step 3 indicate number of remaining candidate EFGs in a process of elimination top to bottom. EFG codes: F2.1 Large permanent freshwater lakes; T1.1 Tropical-subtropical lowland rainforests; T1.3 Tropical-subtropical montane rainforests; M1.2 Kelp forests; M1.6 Subtidal rocky reefs.

Diagnostic steps	Lake Geneva (freshwater)	Virunga mountains forests (terrestrial)	Alaskan rocky reefs (marine)	Rangeland (terrestrial)
1. Aligned with ecosystem concept	Yes	Yes	Yes	No – rangelands describe a land use, which is not aligned with the ecosystem concept. Many ecosystem types are used for grazing livestock (tundra-alpine-desert-forest), thus 'rangelands' do not have a characteristic biota, abiotic environment or ecological processes as required by the ecosystem concept
2. Available information	Lake area polygon, summary of species composition	Elevation, temperature and rainfall, field observation of vegetation structure and composition, presence of iconic animal species	Species composition and trophic networks	Maps and brief descriptions
3a. Candidate EFGs: Location	Switzerland (33 candidate EFGs)	Democratic Republic of the Congo, Rwanda, Uganda (44 candidate EFGs)	Gulf of Alaska (34 candidate EFGs)	N/A
3b. Candidate EFGs: Most distinctive biotic/abiotic properties	Freshwater lake (3 EFGs); No winter freeze (2 EFGs); Surface area 580 km^2 (1 EFG)	Tree-dominated (5 EFGs); Evergreen closed tree canopy (2 EFGs); Mild temperatures 14–24°C (1 EFG)	Marine shelf benthic (8 EFGs); Rocky substrate (3 EFGs); algal macrophytes present but sparse (2 EFGs)	N/A
3c. Candidate EFGs: Supplementary diagnostic properties	Permanent surface water, large fish and local endemism support membership of F2.1 over alternative EFGs	Altitude 2,500–3,500 masl; diurnal temperature range 12°C, annual rainfall >2,000 mm, often misty, dry season <3 mths, canopy tree diversity <10 per 0.1 ha, and large primates support membership of T1.3 over T1.1	Presence of giant kelp (>10 m), with epiflora and epifauna, sea otters, benthic macroinvertebrate herbivores and detritivores, including abundant urchins suggest degraded expression of M1.2 rather than M1.6	N/A
4. Membership estimate	One plausible EFG: F2.1 membership = 1.0	One plausible EFG: T1.3 membership = 1.0	Two plausible EFGs: M1.2 membership = 0.8; M1.6 membership = 0.2	Not eligible for membership of an EFG

Source: Editors.

Examples in Table 6 show that a relatively small number of steps and observed properties can often narrow the plausible candidates to one or two EFGs. Membership estimates for multiple ecosystem types within a classification can be summarised in a membership matrix (see Membership matrix template).

As well as linking other ecosystem classifications to EFGs of the GET, membership concepts are useful for identifying EFGs in the field. A similar stepwise elimination process may be deployed, but applied to direct field observations in steps 3–4.

Step 5. Synthesis

Consistent with Principle 4, uncertainties in cross-referencing should be evaluated and incorporated into estimates so they can be considered transparently and appropriately in applications that scale up from ecosystem types to EFGs. A basic level of documentation is needed to ensure a standard of transparency and repeatability in the cross-referencing output. This may be included in a general 'methods statement' that describes the workflow, and the interpretation and weight applied to sources of information considered in estimating membership of ecosystem types to EFGs. Where necessary, specific details should be added for particular ecosystem types. This will enable efficient batch processing of updates when there is agreement that source information should be interpreted or weighted differently.

For individual interpreters, many sources of uncertainty can be incorporated into their estimates of membership values based on guidance in Table 4. As noted above, some uncertainty stems from subjective judgements that may vary between experts. To reduce cognitive bias and other subjective effects on membership estimates, steps 3 and 4 should be completed by multiple interpreters using structured elicitation methods. See Structured expert elicitation and Appendix 1 for detailed guidance on elicitation methods and standards.

Where multiple interpreters have provided membership estimates, the results should be combined for application. This should generally be done by taking the average of final membership estimates across all interpreters, including zero values, for each element (cell) of the membership matrix. Interpreters may be weighted differently where justified. Finally, a check should be carried out to ensure that membership values sum to '1' across all EFGs for each ecosystem type. The combined membership values are compiled into a final membership matrix of ecosystem types (rows) by EFGs (columns) (see Membership matrix template).

Documentation of the cross-reference should include:

i) A summary of cross-referencing in a membership matrix (Box 5), enabling the relationship to be joined to spatial data (Box 6);
ii) A methods statement, including input data sources (e.g. published or unpublished sources of descriptions and maps), ecosystem properties assessed, analytical tools and workflows, expert elicitation methods, number and identity of experts, and relevant details of interpretations;
iii) Appraisal of sources and magnitude of uncertainties; and
iv) Any additional information specific to the interpretation of particular ecosystem types.

Analytical tools for cross-referencing

This section explores three different types of analytical tools that may assist implementation of a cross-referencing workflow through consistent systematic methods and documentation. Of these, the membership matrix template is currently available on the GET website (https://global-ecosystems.org/page/resources), while the identification key and diagnostic tools are under exploratory development, with completion dependent on resourcing.

Although quantitative multivariate methods are available to compare properties of entities and assign them to classification groups (e.g. De Cáceras et al., 2010; Wang et al., 2012; Tozer & Keith, 2023), in many cases their use for cross-referencing ecosystem types to EFGs is precluded by two significant constraints. First, insufficient or unevenly distributed quantitative data on properties often requires subjective intervention to fill gaps. Second, the multimodality of information on ecosystem properties creates challenges for mathematical synthesis, including context-dependent property weightings, which have not yet been fully resolved. Therefore, most cross-referencing will rely on subjective comparisons of ecosystem properties. The analytical tools discussed below offer approaches to support rigorous, subjective evaluations of evidence on cross-referencing relationships between entities and groups defined in different classifications.

Membership matrix template

Outcomes from the stepwise protocol for interpreting membership relationships outlined in Figure 3 should be documented in a membership matrix, which contains all pairwise combinations of the ecosystem types (i.e. from a national or other classification) and EFGs (Box 5). A spreadsheet template for standard documentation is available at https://global-ecosystems.org/page/resources. It includes a membership matrix, summary tables and basic logical checking procedures to ensure validity of membership estimates in summing to no more than '1', and a 'notes' field for documenting reasoning behind estimates.

A basic level of documentation is needed for the cross-referencing output to ensure a standard of transparency and repeatability. The 'notes' field should contain sufficient information for an independent user to understand the reasons and evidence that underpin the membership estimates for respective ecosystem types. For some national classifications, large numbers of ecosystem types need to be cross-referenced to the GET (e.g. Table 1). Where this is the case, cross-referencing may be documented efficiently in 'notes' by referring to a general 'methods statement' that compiles relevant information for all ecosystem types. This statement should include the workflow, the sources of information considered, the interpretation of information within those sources (e.g. where particular features mentioned in descriptions are taken as indicative of a particular EFG) and how the weight of evidence was determined. Where necessary, specific details should be added to 'notes' for particular ecosystem types.

The format of the membership matrix itself is suitable for joining to the table of digital geospatial data that maps the distribution of ecosystem units (Box 5). This allows the spatial configuration to be displayed and analysed for both the primary units of classification (ecosystem types) and the EFGs to which they belong, while also accounting for uncertainty in the membership relationships. Box 5 provides further explanation of a membership matrix and an example.

Box 5. Constructing and populating a membership matrix

A membership matrix is a type of confusion matrix in which rows represent the units of an eligible ecosystem classification, the columns represent EFGs, and the cells contain fuzzy membership estimates for each unit in the ecosystem classification to each respective EFG.

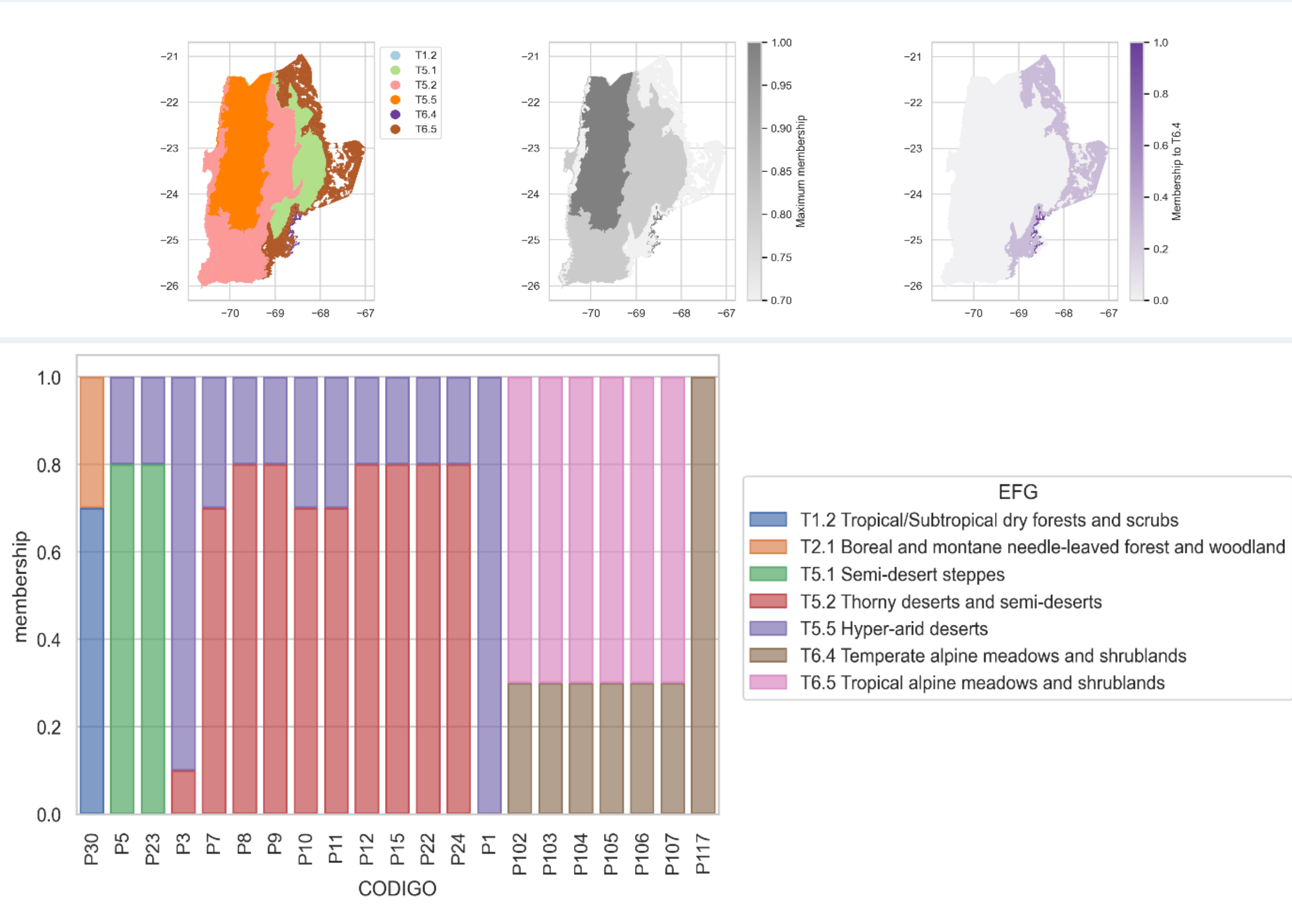
The example below is an excerpt taken from a membership matrix that cross-references ecosystem types of the South African national terrestrial ecosystem classification (Dayaram et al., 2019, 2021) with the EFGs of the GET (Keith et al., 2022). Ecosystem types were derived from vegetation types of Mucina and Rutherford (2006) (see Dayaram et al., 2019). Cells with single zero values indicate agreement between experts that a unit does not belong to an EFG. Dual non-zero estimates in black and red font represent subjective estimates by different experts based on their respective comparisons of ecosystem properties using available information. Note that estimates in red (expert 2) sum to 1 across all rows, indicating an opinion that all units (rows) are members of an EFG. In contrast, some estimates in black (expert 1) sum to less than one, indicating an opinion that some units might not be a member of any currently described EFG.

C	D	F	G	K	L	N	O	P	S	T	W	X	Y	Z	AB
SA Ecosystem Class (vNVM2018)	Functional group	T1.2 Tropical/Subtropical dry forests and scrubs	T1.3 Tropical/Subtropical montane rainforests	T2.3 Oceanic temperate rainforests	T2.4 Warm temperate rainforests	T2.6 Temperate pyric sclerophyll forests and woodlands	T3.1 Seasonally dry tropical shrublands	T3.2 Seasonally dry temperate heaths and shrublands	T4.1 Trophic savannas	T4.2 Pyric tussock savannas	T4.5 Temperate grasslands	T5.1 Semi-desert steppes	T5.2 Thorny deserts and semi-deserts	T5.3 Sclerophyll deserts and semi-deserts	T5.5 Hyper-arid deserts
Sundays Valley Thicket		[0.8, 0.6]	0	0	0	0	0	0	0	0	0	0	[0.1, 0.4]	0	0
Albany Mesic Thicket		[0.9, 0.9]	0	0	0	0	0	0	0	0	0	0	[0, 0.1]	0	0
Southern Mistbelt Forest		0	[0.8, 0.1]	0	[0, 0.9]	0	0	0	0	0	0	0	0	0	0
Ironwood Dry Forest		[0.4, 0.6]	0	0	0	0	0	0	0	[0.3. 0.4]	0	0	0	0	0
Northern Afrotemperate Forest		0	[0, 0.1]	0	[0.9, 0.9]	0	0	0	0	0	0	0	0	0	0
Loerie Conglomerate Fynbos		0	0	0	0	0	0	[0.95, 1]	0	0	0	0	0	0	0
Kango Conglomerate Fynbos		0	0	0	0	0	0	[0.95, 1]	0	0	0	0	0	0	0
Limpopo Sweet Bushveld		0	0	0	0	0	0	0	[0.9, 0.9]	[0, 0.1	0	0	0	0	0
Western Sandy Bushveld		0	0	0	0	0	0	0	0	[0.9, 1]	0	0	0	0	0
Lesotho Highland Basalt Grassland		0	0	0	0	0	0	0	0	[0, 0.1]	[0.9, 0.9]	0	0	0	0
Klawer Sandy Shrubland		0	0	0	0	0	0	0	0	0	0	0	[0.9, 1]	0	0
Namaqualand Spinescent Grassland		0	0	0	0	0	0	0	0	0	0	0	[0.9, 0.4]	[0, 0.6]	0
Western Gariep Hills Desert		0	0	0	0	0	0	0	0	0	0	0	0	0	[0.8, 1]

Source: Editors

Box 6. Representing and using information about uncertainty in maps

A fuzzy membership matrix can be linked to the attribute table of spatial data to display and analyse uncertainty in the spatial patterns and extent of ecosystem types. Membership relationships of ecosystem types to EFGs is just one of several sources of uncertainty that can be incorporated in this way. In the example below, a membership matrix has been developed to link the national vegetation classification of Chile (Luebert & Pliscoff, 2017) with EFGs (Table S3.3 in Keith et al., 2022). The maps below give examples of how uncertainties in EFG membership can be displayed and interpreted. A traditional deterministic map (left panel) shows the best estimate of distribution of EFGs (i.e. those with maximum membership value) in Codigo region of central Chile. The membership values associated with those EFGs (middle panel) show spatial patterns of EFG uncertainty in the same area (dark shades indicate higher certainty in the identity of the mapped EFG). Finally, the uncertainty in mapped extent of any EFG can be explored individually. The right panel shows a small area in which T6.4 is virtually certain to occur (dark shade), a larger area in which it is unlikely (intermediate shade), and an even larger area in which it is exceptionally unlikely to occur (pale shade). The bottom panel shows the variation in membership values among map units for each EFG.



Source: Editors

Structured expert elicitation

Comparisons and evaluations of ecosystem properties using available knowledge necessarily involve a degree of subjective interpretation. To reduce cognitive bias and other subjective effects on membership estimates, it is recommended that steps 3 and 4 of the cross-referencing protocol should be replicated by multiple interpreters in a structured elicitation protocol (Appendix 1). The elicitation protocol first requires an orientation of expert interpreters, then independent estimation, a discussion of interpretive issues, then an opportunity to independently adjust initial estimates in the light of discussions, and finally a synthesis of estimates across experts (Appendix 1; Burgman, 2015; Hemming et al., 2018; Courtney Jones et al., 2023). The steps are as follows:

i) Interpreters are provided with information from Step 1 and Step 2 and briefed on the membership rules and elicitation process;
ii) Interpreters independently make initial membership estimates;
iii) Interpreters share summaries of their initial estimates and discuss issues of interpretation;
iv) Interpreters independently revise their initial estimates; and
v) The final estimates of membership are calculated by averaging the revised estimates with bounds estimated by the range of estimates across interpreters. A weighted average may be calculated where there is justification to weight interpreters differently (e.g. based on their performance in elicitation trials).

Membership estimates should be provided by at least two independent expert interpreters familiarised with the ecosystem type(s), the region of interest, and the GET. However, elicitation of three or more experts is strongly encouraged.

Engagement of multiple experts involves trade-offs: greater numbers and diversity of expert interpreters improve robustness of estimates (Burgman, 2015), but numbers may be limited by resources (e.g. the pool of interpreters with relevant expertise, time commitments, etc.). Nonetheless, cross-referencing entirely reliant on a single interpreter involves high risks of interpretative errors and other anomalies that limit the reliability of the output. Novel online platforms, such as Ideacology (https://www.ideacology.com/; Courtney Jones et al., 2023) are likely to improve the efficiency of workflows significantly. Further guidance on structured elicitation is given in Appendix 1 and by Hemming et al. (2018).

Multi-access digital identification key

Automated protocols may increase the efficiency and consistency of the cross-referencing process, with potential co-benefits for repeatability of outcomes, although independent verification of their outputs is essential for quality assurance.

Multi-access digital identification keys are software platforms that automate a sequential logical, diagnostic process of elimination to identify an entity, i.e. to determine its membership to a group from a pre-determined classification of candidate groups (Norton et al., 2000). They are widely used for species identification and are replacing traditional static dichotomous keys in which the user answers a pre-determined sequence of questions about species' attributes.

In traditional static keys, each question is determined by the answer to the preceding question, narrowing the pool of plausible candidates until one or a few candidate(s) remain(s). Although applied mainly to species identification (Norton et al., 2000), a few examples of static identification keys have been developed for ecological entities, including EUNIS Level 1 habitat types (EEA, 2019) and vegetation formations in Australia (Keith, 2004). Multi-access keys offer greater flexibility than traditional dichotomous keys by allowing the user to select questions in any sequence. This provides flexibility to follow alternative identification pathways, according to the varied availability and quality of information on the properties of the entity to be identified.

A multi-access digital identification key in development for the EFGs of the GET is based on a similar workflow to that outlined in Figure 4. It operates from a pre-stored reference matrix of diagnostic ecosystem properties, including locational information, biotic properties, abiotic properties and ecological processes that characterise each EFG. In a stepwise procedure, users are served with a list of these properties from which they may select any property which is sufficiently known. For a given property, users select a value that matches the ecosystem type to be cross-referenced. This enables a subset of candidate EFGs to be eliminated from further consideration (i.e. those whose properties do not match the selected value). The eliminated EFGs may be assigned zero membership values for the ecosystem type if the mismatch in properties is virtually certain (Table 4). The user is then served with a reduced set of properties that discriminate at least some candidate EFGs from the remaining pool of candidates. The procedure iterates until the remaining candidate EFGs cannot be discriminated with confidence based on available information for the remaining diagnostic properties. Non-zero membership estimates may be assigned to the remaining EFGs by the user at this point and entered into the membership matrix, along with the zero values for EFGs that were eliminated earlier in the process.

A prototype (version 0.1) is in development and testing using Lucid software (Lucidcentral, 2024). When performance is satisfactory for general use, the first release will be made available with open access at https://global-ecosystems.org/. The prototype is based on properties drawn from the descriptive profiles of EFGs, with gap-filling by the authors (Keith et al., 2022) to ensure systematic coverage of properties. Range estimates for key climatic variables were drawn from spatial intersections of indicative global distribution maps (Keith et al., 2023) with Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) v spatial layers (Karger et al., 2017, 2021a,b). These climatic range estimates are approximate due to variation in quality of indicative global distribution maps (Keith et al., 2022). The upper and lower limits of each climatic variable for each EFG were drawn from the minimum and maximum values of the distribution of values from respective intersections. When the user-specified value(s) fall(s) outside the maximum-minimum range for a given EFG, that EFG is eliminated from the list of remaining candidates.

Table 7 summarises EFG properties included in the reference matrix for v0.1 of the key. The key currently supports identification and cross-referencing of ecosystem types to EFGs one ecosystem type at a time. Future tools will be designed to accept batch tasks for cross-referencing multiple ecosystem types in a classification.

Table 7. Example set of ecosystem properties (arranged in themes based on the ecosystem concept – see Glossary) for discriminating Ecosystem Functional Groups (EFGs) in a multi-access digital identification key

Ecosystem theme	Example properties for key development
Location	United Nations subregion Country Other spatial data
Abiotic properties	Environmental realm Substrate/benthos type (including soils) Topography Nutrient fertility Climate niche (water balance, thermal regime)
Biotic properties	Dominant life forms Structural variables Representation of life history traits Representation of morphological traits Representation of phenological traits Representation of dietary traits Representation of taxonomic groups

Ecological processes	Flood regimes Fire regimes Storm regimes Trophic structure Life cycle processes Successional processes Biotic interactions
Anthropogenic processes	Tillage frequency Domesticated biota Planting and harvest Resource subsidies (water, nutrients) Built infrastructure

Source: D. A. Keith, J. R. Ferrer-Paris, S. Hay and M. G. Tozer

Appendix 2 shows example outputs of the prototype key.

Artificial intelligence diagnostic tools

Artificial intelligence can potentially be used to suggest membership relationships in response to user-supplied information. Although yet to be developed for ecosystem classifications, they can operate with a range of alternative artificial intelligence or machine learning algorithms. These algorithms require a bank of training observations that document the properties of GET EFGs and accept new information on ecosystem types supplied by the user. Artificial intelligence or machine learning algorithms could undertake a comparison of the properties of the ecosystem type to the training data set for each EFG and return a ranked list of candidate EFGs based on the degree of resemblance of their properties to those of the ecosystem type under consideration.

A prototype text-based diagnostic tool is currently under evaluation. The prototype is based on Large Language Models with a simple Retrieval Augmented Generation implemented through a commercial tool (ChatPDF) and allows users to engage with the content of the source document in a conversational format. This tool performs two steps: analysing the input document; and answering a question. For the analysis step, it generates a semantic index over all paragraphs of the document (PDF) that describes the reference entities (EFGs). For the answer step, this tool finds the most relevant paragraphs from the document and uses the ChatGPT Application Programming Interface (API) from OpenAI to generate an answer. The source document is based on the profiles for all EFGs and has been customised with contextual information to enhance accuracy of the response.

Although the tool will respond to any user prompt, a structured approach produces the most informative answers. Users can submit the name and description of the ecosystem using a suite of standard questions:

i) I have the following description for an ecosystem type in [country/jurisdiction] known as [name of ecosystem type]. Provide me with a list of three to five candidate Ecosystem Functional Groups to which it could belong and a brief summary of the matching features. Here is the description: "…".
ii) Of these candidates, which one is the closest match to the description?
iii) What is the source of your answer and where can I find more information.

An example application is given in Appendix 2 and the tool is currently available for testing at: https://www.chatpdf.com/share/nlWIjvieG9n0nXhC459WT.

Initial trials of the text-based Large Language Model indicated that its performance, in terms of inferred membership relationships, varied depending on the available detail in ecosystem descriptions. The correct EFG was more likely to be among a small set of candidate EFGs identified by the algorithm if it was supplied with detailed information on the properties of the ecosystem type of interest.

Despite the moderate performance of the text-only Large Language Model, a particularly promising aspect of Artificial Intelligence algorithms is their capability to accommodate multi-modal data on ecosystem properties. This includes diverse forms of information such as text descriptions, in situ observation data, spatial information (occurrence points, polygons), photographic images, as well as reference to remote sensing archives and environmental spatial data. Exemplary tools include citizen science platforms for species observations, such as iNaturalist (https://www.inaturalist.org), which offer users the capability to identify species with information on observation location and date, a photographic image, and crowd-sourced expert review. An adaptation of this platform for assessing the ecological condition of vegetation types is currently under evaluation in South Africa (https://www.inaturalist.org/projects/vegmaphoto-s-afr). Users capture landscape images tagged with custom fields specifying the vegetation type, standard score for ecological integrity and observed pressures. The data captured contribute to a training archive and ultimately enable the algorithm to learn to distinguish different levels of degradation for each vegetation type.

Building capacity for interoperable ecosystem classifications and maps

Cross-referencing to the IUCN GET provides a pathway for data custodians and users of national and other jurisdictional ecosystem classifications and maps to make their data sets interoperable with a common language for international reporting and information sharing. This requires initial investments to establish the relationships between the source classifications (local, national, regional) and Level 3 of the GET, but once these are established and refined, little ongoing maintenance should be required beyond activities already directed at updating the national data.

Cross-referencing between classifications inevitably involves some uncertainties and diagnostic errors. These can be reduced either at the outset or over time by the following measures:

i) Ensure that entities (map units) for cross-referencing to GET units are aligned with the ecosystem concept;
ii) Identify and assess all information relevant to comparisons of ecosystem properties of ecosystems to be cross-referenced and candidate EFGs;
iii) Eliminate implausible candidate EFGs by first evaluating information on location and environmental realm, and then information on other properties with high discriminatory value for remaining EFGs;
iv) Use membership values to transparently represent uncertainty among plausible candidates, rather than binary attributions of ecosystem types to Ecosystem Functional Groups; and
v) Document workflows and methods as well as outcomes of cross-referencing to ensure transparency and enable consistent updates.

Both multi-access digital identification keys and Artificial Intelligence diagnostic tools have the potential to improve efficiency and accuracy of cross-referencing, yet both may generate diagnostic errors. Whether generated by diagnostic tools or from expert elicitation, the outputs of cross-referencing should therefore be critically evaluated, rather than accepted without further scrutiny. The following practices are recommended to minimise diagnostic errors in cross-referencing units of different classifications:

i) Include a diverse set of ecosystem properties in reference matrices and training data;
ii) Interpret properties of ecosystems in a manner that considers their natural spatial and temporal variability;
iii) Include a large and representative set of observations in the reference/training data;
iv) Apply rigorous standards for input data with regard to the impact on output quality;
v) Expose outcomes of cross-referencing to expert review; and
vi) Contribute new information to reference matrices and training data, building capacity for further improvements to the GET and its applications.

Future establishment of a GET cross-reference repository should facilitate these practices.

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Appendix 1

Guidance on structured expert elicitation for estimating fuzzy membership of ecosystem types to Ecosystem Functional Groups (EFGs) in the IUCN Global Ecosystem Typology (GET)

The ecosystem types within a classification may be regarded as 'entities that belong to a group based on similarities of their ecological properties. Group membership may be uncertain or 'fuzzy' due to a number of reasons outlined in Principle 4, including cases where ecosystem properties are not well known and where they appear to be intermediate between alternative groups.

Inevitably, estimation of EFG membership relies heavily on expert judgement to synthesise and contextualise diverse evidence types, fill gaps (where possible) in the documented evidence base, and the relative veracity of different information sources. Expert judgement is unavoidably subject to contextual biases, which can be reduced and quantified by engaging multiple experts in a structured elicitation protocol. In this standard, the IDEA protocol (Investigate-Discuss-Estimate-Aggregate) is recommended for this purpose, as testing indicates reliable results (Hemming et al. 2018; Courtney Jones et al. 2023). It treats the elicitation of expert judgements in the same regard as empirical data, by using repeatable, transparent methods and addressing scientific questions (not value judgements) in the form of probabilities and quantities (Hemming et al. 2018).

While Hemming et al. (2018) provide detailed guidance, key elements of the protocol include:

i) Selection of experts. These should include diverse participants familiar with the problem area, representing diverse backgrounds, career stages, geographic locations, cultures and gender. Hemming et al. (2018) recommend 10–20 experts for the most robust results, however for cross-referencing ecosystems, the pool of available experts will often be limited. While the experts should be well replicated, they should include at least two independent interpreters familiarised with the ecosystem type(s), the region of interest, and the GET. However, use of three or more experts is strongly encouraged.
ii) An 'Investigate' phase in which experts are orientated to the problem of cross-referencing ecosystem types to EFGs, fuzzy membership concepts and the rules of elicitation. This may include compilation of available information sources and feedback to uncover additional relevant sources.
iii) Initial round of membership estimation. Experts must make estimates in this initial round independently of one another to reduce cognitive and social biases. The estimates should be bounded to represent the plausible range of membership values, given the sources of uncertainty (Principle 4) and plausible scenarios. See further guidance under 'Estimating uncertain membership' below.
iv) An analysis and feedback step in which the first round elicitation of membership estimates is collated, summarised (e.g. graphics, tables) and made available to experts for feedback.
v) A 'Discuss' phase in which experts discuss interpretations, counterfactuals and plausible scenarios on which membership estimates are based.
vi) An 'Estimate' phase in which experts may (or may not) adjust their initial membership estimates independently of one another based on insights from the 'Discuss' phase.
vii) An 'Aggregate' phase in which membership values are checked for errors (e.g. mathematical inconsistencies), aggregated into group estimates (e.g. by averaging) and returned to experts for final review and approval.

Membership values should be estimated by matching observed features of an entity to those in the descriptions of alternative candidate groups. For each ecosystem type, experts should first eliminate the implausible candidate EFGs from further consideration (membership value = 0), then estimate non-zero values summing to '1' for the remaining candidates. See Protocol steps 3 and 4, and instructions for populating a membership matrix template under Analytical tools. Interpreters may use diagnostic tools to assist their judgements as they become available, but outputs should be critically evaluated by interpreters for diagnostic errors and corrected where necessary.

ALWAYS: membership values sum to a total of 1 or less for each ecosystem type

ALWAYS: check membership outputs from automated diagnostic tools

Estimating uncertain membership

When estimating uncertain membership values, the degree of uncertainty can be represented by the breadth of bounds around a best estimate: narrow bounds represent high confidence in the best estimate; broad bounds indicate considerable uncertainty. When making a bounded estimate, four values need to be estimated in the order shown in Figure 5.

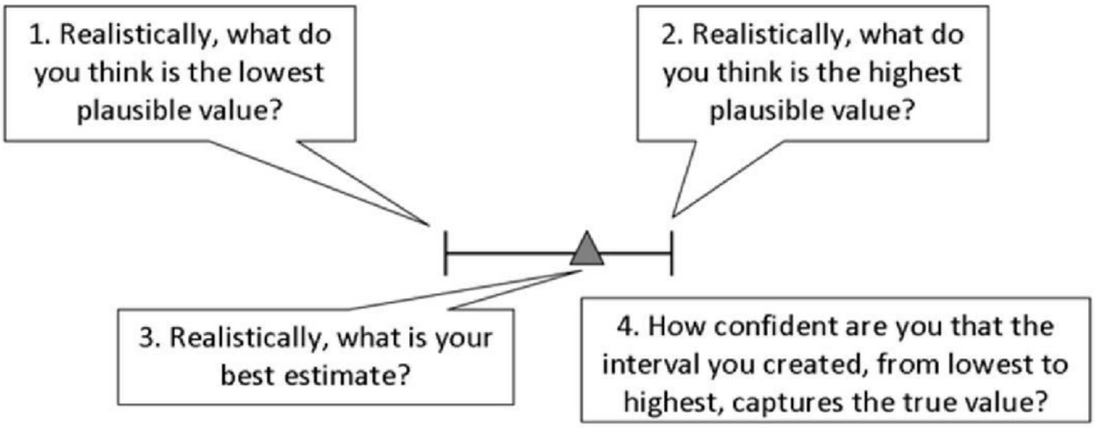


Figure 5. The four ordered steps in making a bounded estimate. *Source: Editors*

It is important to specify bounds ***before*** estimating the best estimate to consider extreme values and avoid anchoring the best estimate. To estimate a plausible lower bound realistically (Figure 5, question 1), consider *all of the data and reasons why the value may be small.* The second question is similar, but for a plausible upper bound. Then make the best estimate – the one considered to be closest to the truth. The bounds do not have to be symmetrical around the best estimate. That is, a person may be more confident about an upper bound than they are about a lower bound, or vice versa.

Finally, question 4 (Figure 5) asks how confident the assessor is that the true value falls within the bounds. A value of 0.9 means that an assessor is 90% confident that the true value lies between the lower and upper bounds. Statistically, this means that when an expert makes 20 similar estimates, he/she expects the true value will be within the bounds for 18 estimates, less than the lower bound once and greater than the upper bound once out of twenty times that they make a bounded estimate. A confidence value less than 0.5 indicates that the assessor believes that his/her true value is more likely to be outside the bounds of their estimate than within them. Consequently, assessors should make their bounds broad enough to be reasonably confident that the true value lies within them.

ALWAYS: lower bound first, then upper bound, then best estimate

ALWAYS: lower bound ≤ best estimate ≤ upper bound

Appendix 2

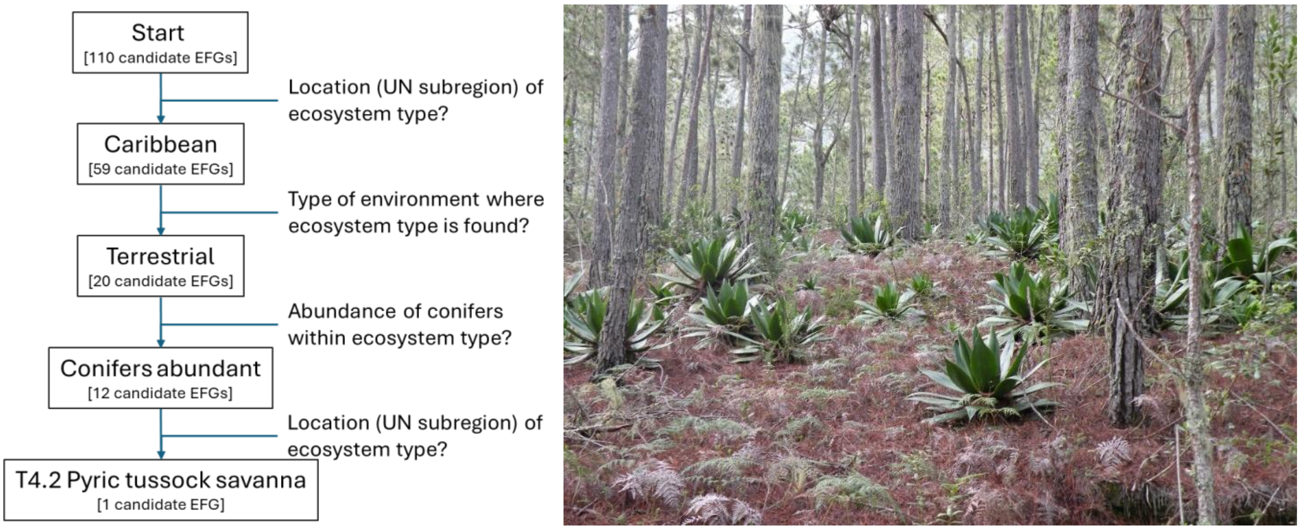
Example applications of analytical tools in development for cross-referencing ecosystem types to the Global Ecosystem Typology (GET) Ecosystem Functional Groups (EFGs)

These analytical tools for cross-referencing ecosystem types to the GET are currently under exploratory development and testing. Completion of development is dependent on resourcing. The tools and user guidance will be available on the GET website (https://global-ecosystems.org/page/resources) when suitable for open use.

Multi-access digital identification key

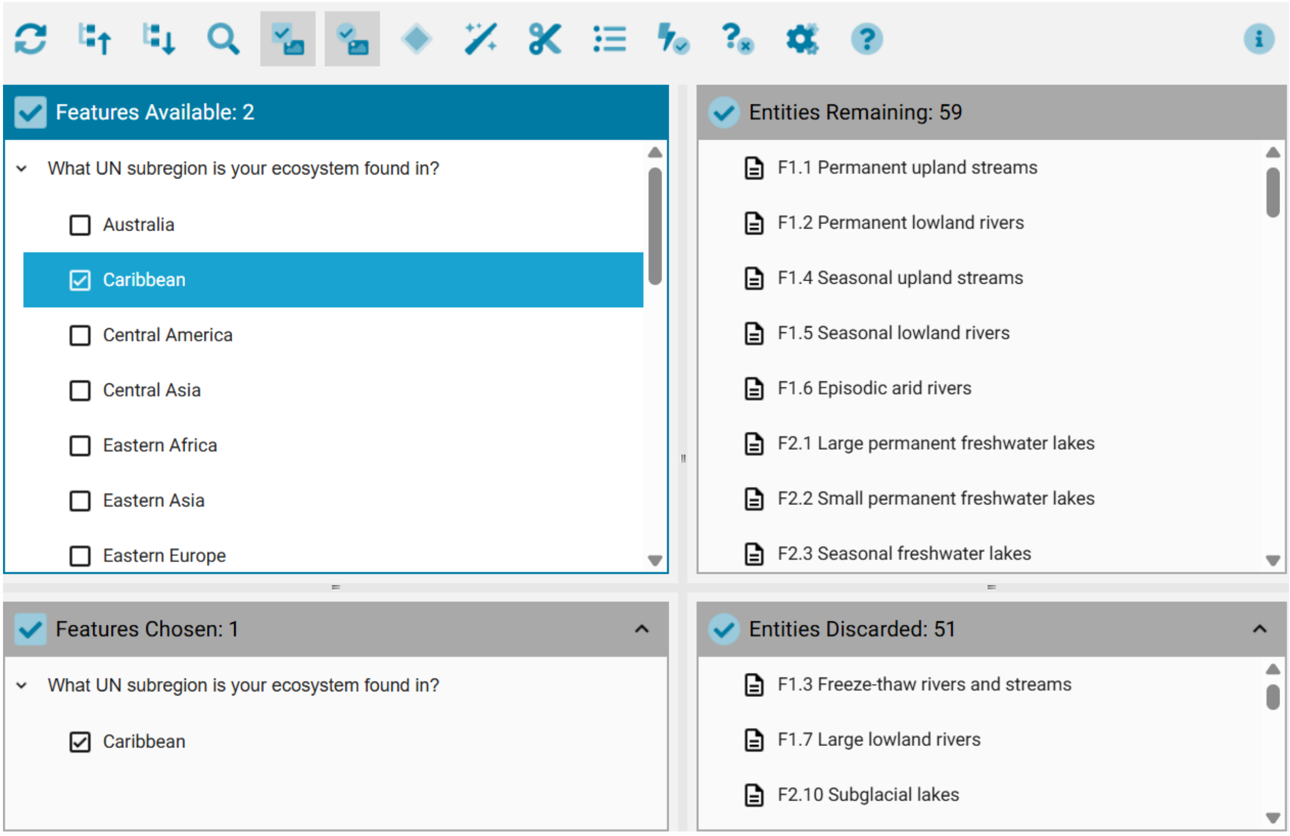
Two examples below illustrate the operation and output of a prototype (version 0.1) digital multi-access identification key to EFGs. The prototype was developed in Lucid software (Lucidcentral 2024), which displays dynamic lists of key questions on diagnostic ecosystem properties and the remaining and eliminated candidate EFGs.

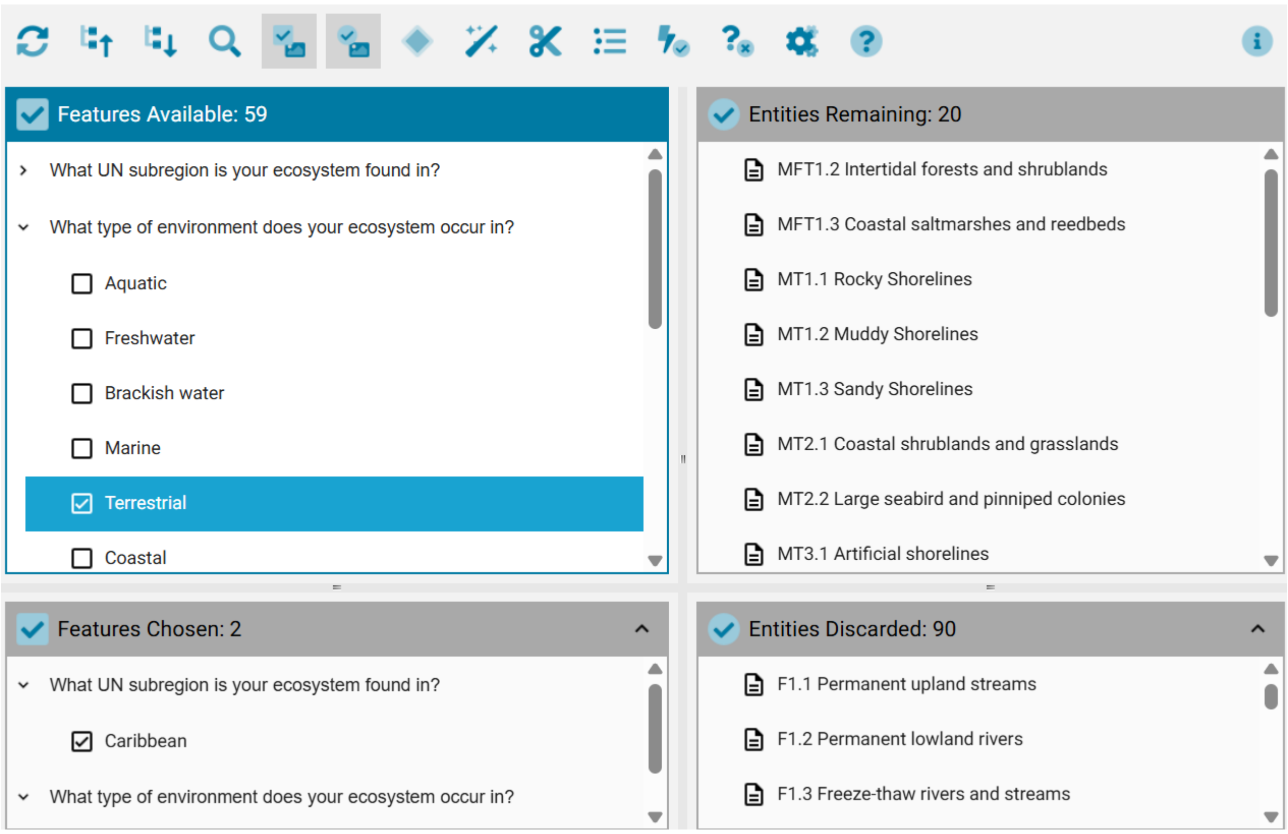
Example 1: The diagrammatic representation of workflow below is an example application of the *Ecosystem Functional Group Identification Key* for a pine savanna on Hispaniola in the Caribbean region. User-selected key questions on right-hand side of workflow, answers in boxes on left. Features for selected questions are determined from information based on the location and image of the ecosystem type (fire incidence from local expert).

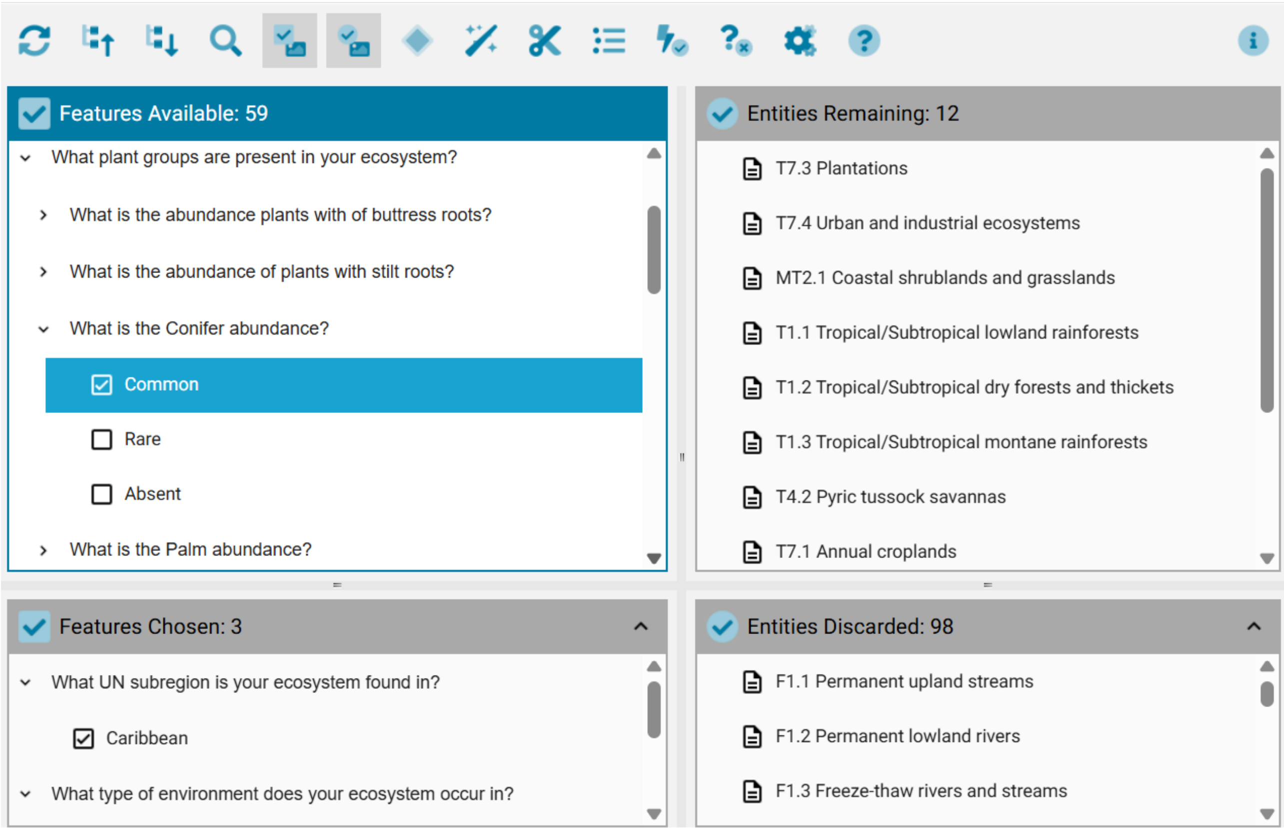


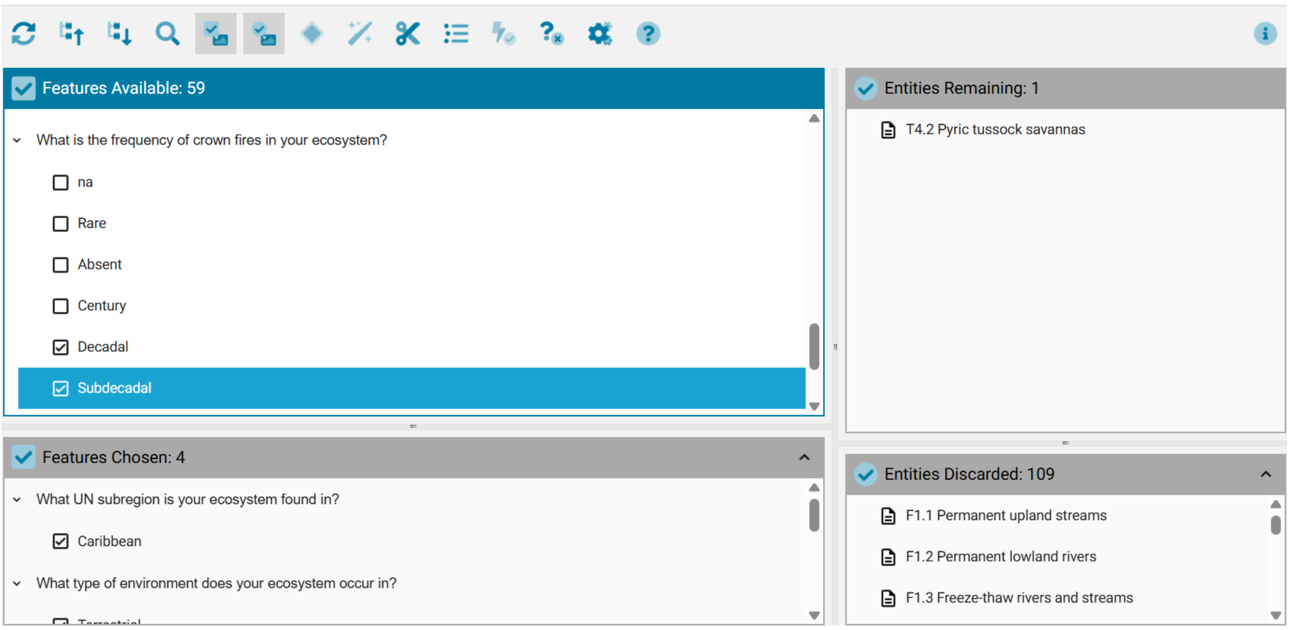
Source: D. A. Keith, J. R. Ferrer-Paris, S. Hay & M. G. Tozer. Image credit: Jane Franklin.

The panels below show the identification steps in Lucid Key software. In each step, the top left panel shows the current user selected question and answer, the bottom left panel shows previous questions answered, the top right panel lists remaining plausible candidate EFGs (tally on top bar), and the bottom right panel lists discarded EFGs (tally on top bar).


Features Available: 2
What UN subregion is your ecosystem found in?
Australia
Caribbean
Central America
Central Asia
Eastern Africa
Eastern Asia
Eastern Europe
Entities Remaining: 59
F1.1 Permanent upland streams
F1.2 Permanent lowland rivers
F1.4 Seasonal upland streams
F1.5 Seasonal lowland rivers
F1.6 Episodic arid rivers
F2.1 Large permanent freshwater lakes
F2.2 Small permanent freshwater lakes
F2.3 Seasonal freshwater lakes
Features Chosen: 1
What UN subregion is your ecosystem found in?
Caribbean
Entities Discarded: 51
F1.3 Freeze-thaw rivers and streams
F1.7 Large lowland rivers
F2.10 Subglacial lakes


Features Available: 59
What UN subregion is your ecosystem found in?
What type of environment does your ecosystem occur in?
Aquatic
Freshwater
Brackish water
Marine
Terrestrial
Coastal
Entities Remaining: 20
MFT1.2 Intertidal forests and shrublands
MFT1.3 Coastal saltmarshes and reedbeds
MT1.1 Rocky Shorelines
MT1.2 Muddy Shorelines
MT1.3 Sandy Shorelines
MT2.1 Coastal shrublands and grasslands
MT2.2 Large seabird and pinniped colonies
MT3.1 Artificial shorelines
Features Chosen: 2
What UN subregion is your ecosystem found in?
Caribbean
What type of environment does your ecosystem occur in?
Entities Discarded: 90
F1.1 Permanent upland streams
F1.2 Permanent lowland rivers
F1.3 Freeze-thaw rivers and streams

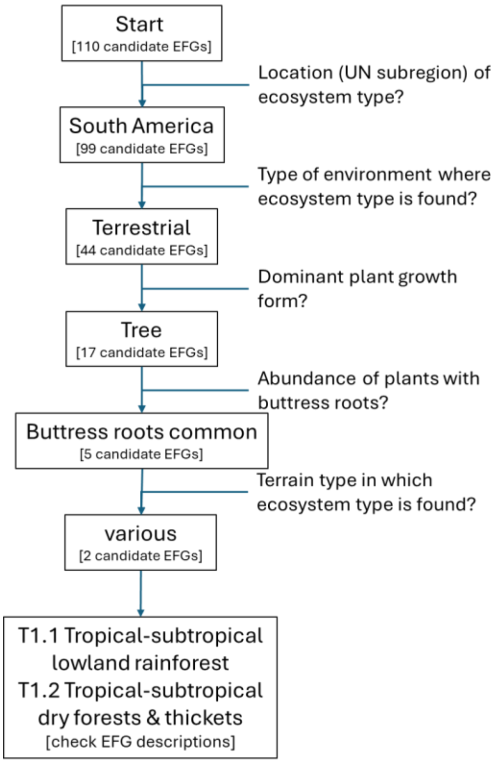




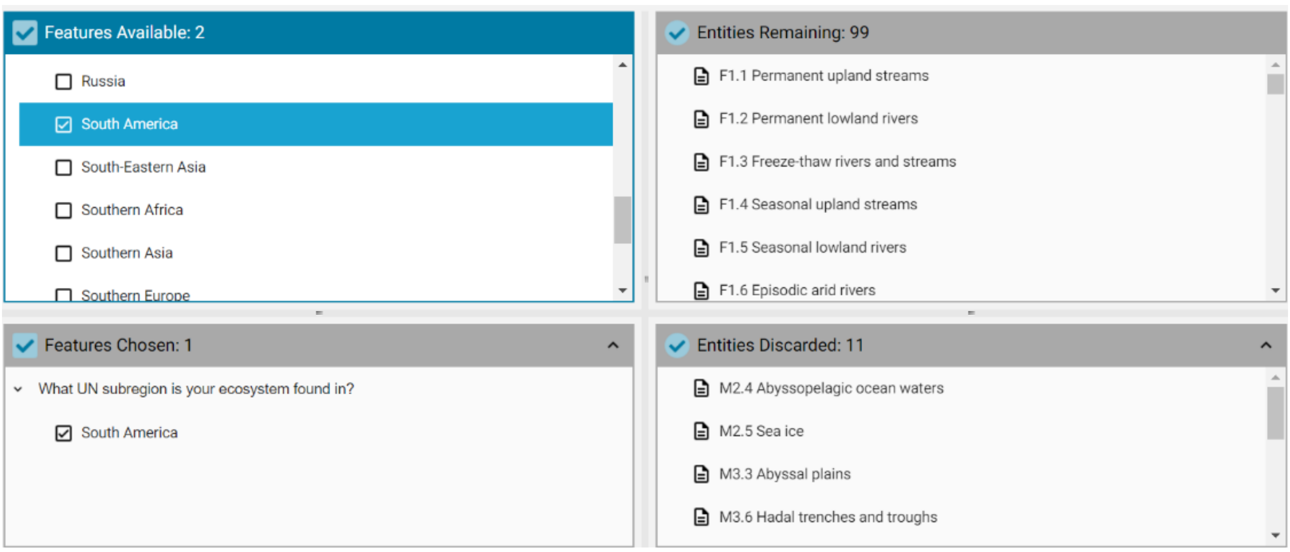
Source: D. A. Keith, J. R. Ferrer-Paris, S. Hay & M. G. Tozer

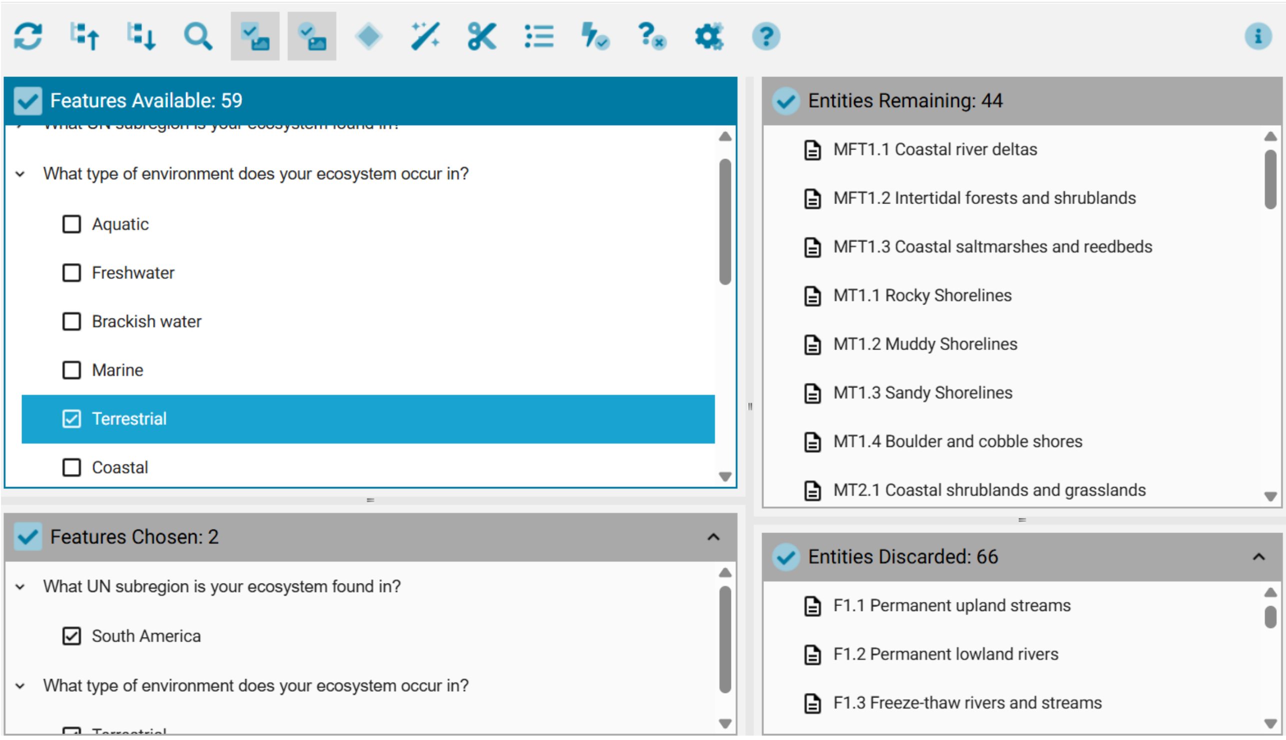
The outcome is *T4.2 Pyric tussock savannas* with high certainty, check EFG description.

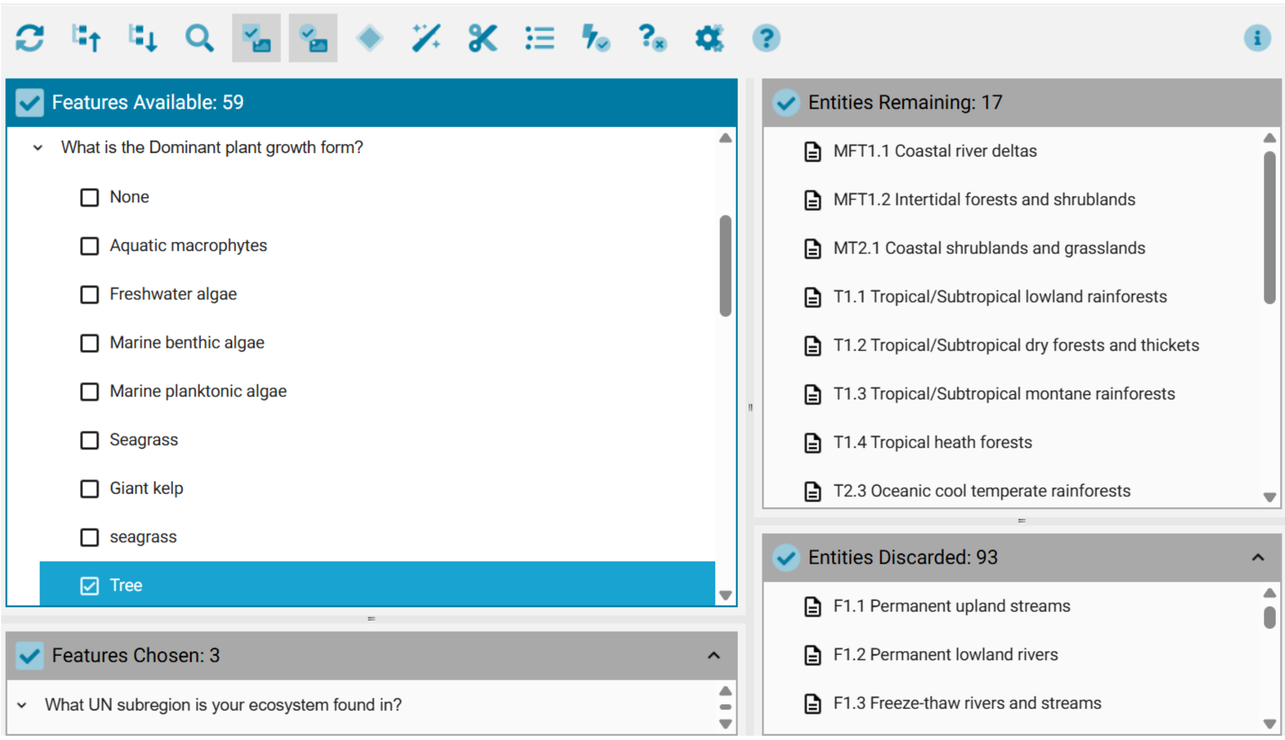
Example 2. A second example workflow for application of the GET multi-access identification key to EFGs examines lowland tropical rainforest in the foothills of Sierra de Santa Marta, Colombia.

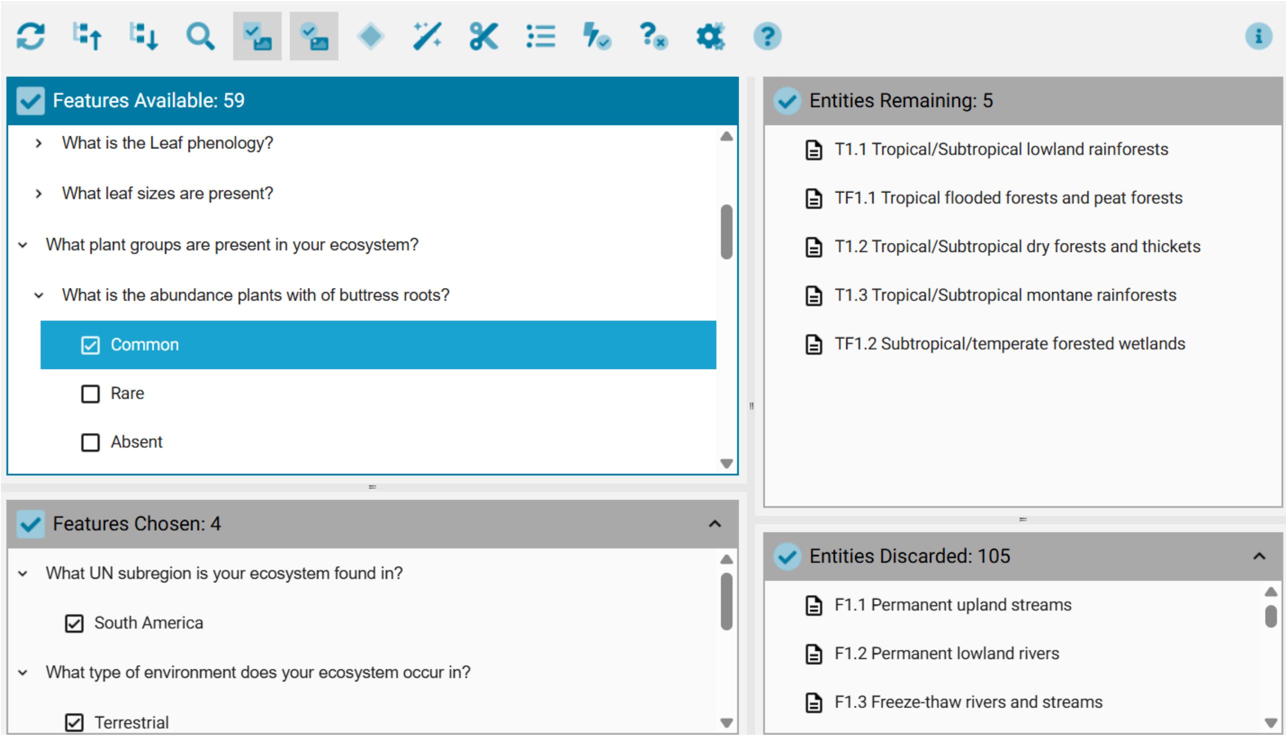


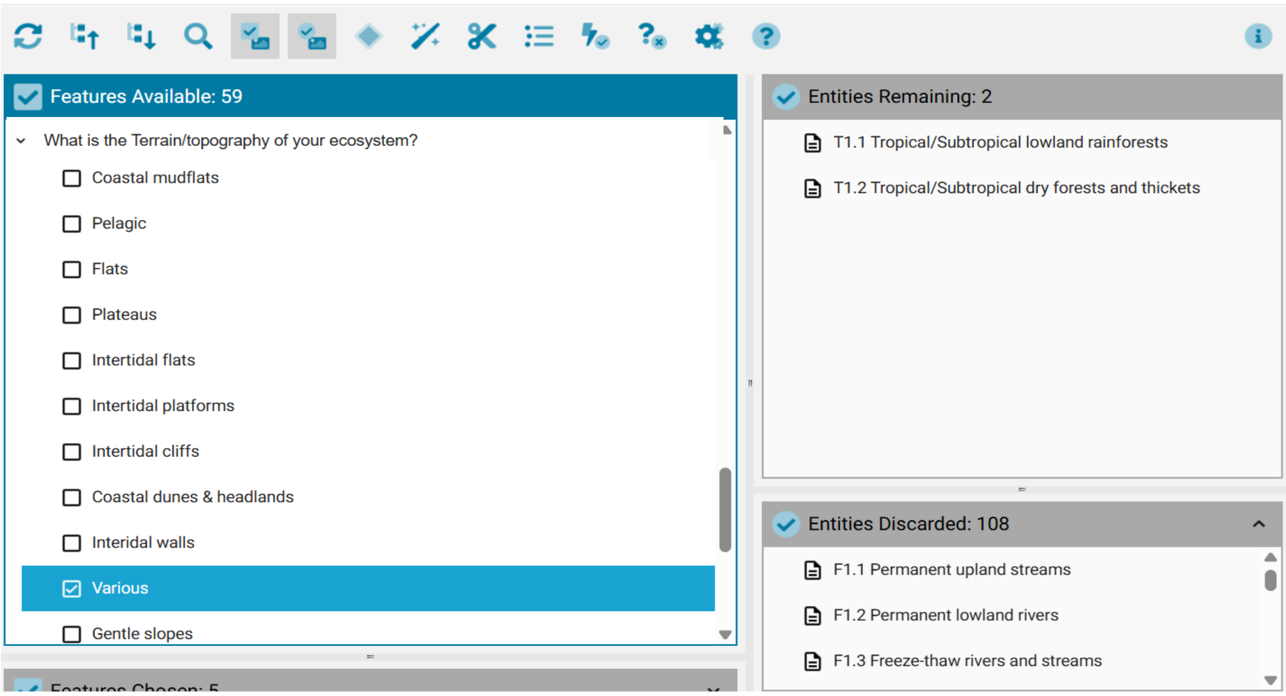
Source: D. A. Keith, J. R. Ferrer-Paris, S. Hay & M. G. Tozer. Image credit: David Keith.

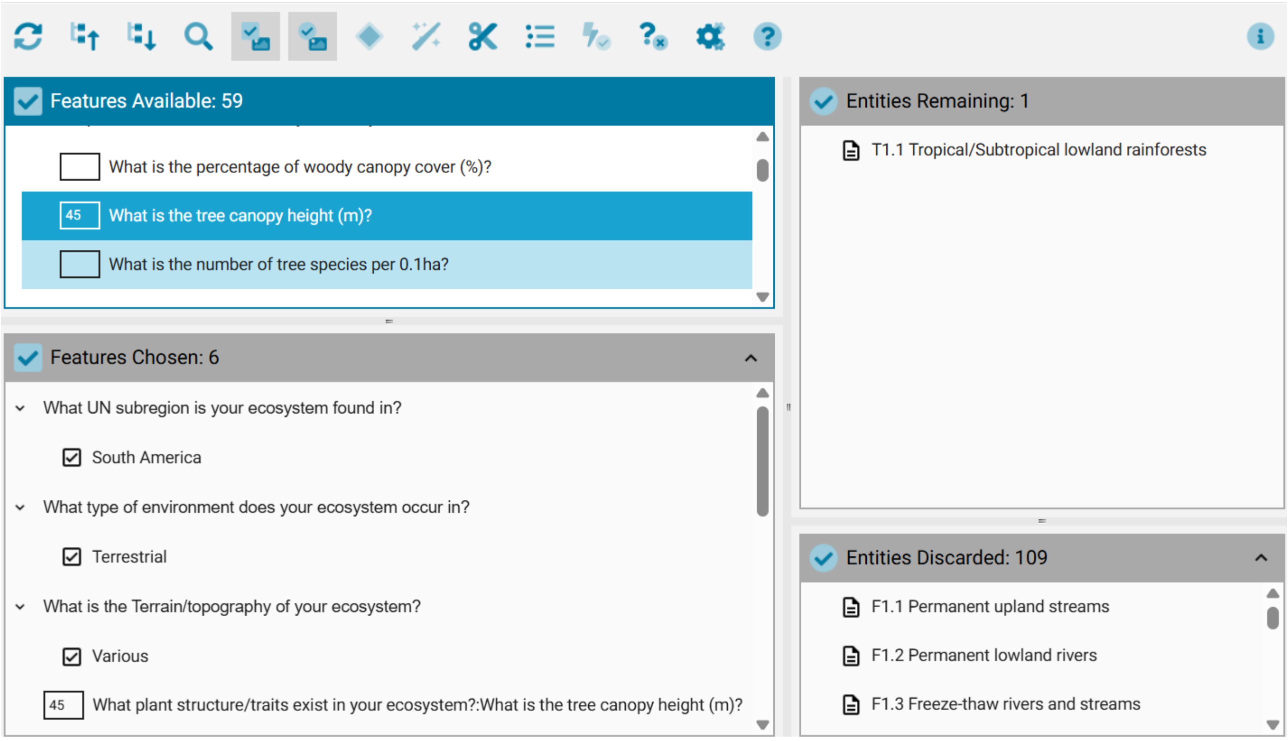



Features Available: 59
What type of environment does your ecosystem occur in?
Aquatic
Freshwater
Brackish water
Marine
Terrestrial
Coastal
Features Chosen: 2
What UN subregion is your ecosystem found in?
South America
What type of environment does your ecosystem occur in?
Entities Remaining: 44
MFT1.1 Coastal river deltas
MFT1.2 Intertidal forests and shrublands
MFT1.3 Coastal saltmarshes and reedbeds
MT1.1 Rocky Shorelines
MT1.2 Muddy Shorelines
MT1.3 Sandy Shorelines
MT1.4 Boulder and cobble shores
MT2.1 Coastal shrublands and grasslands
Entities Discarded: 66
F1.1 Permanent upland streams
F1.2 Permanent lowland rivers
F1.3 Freeze-thaw rivers and streams


Features Available: 59
What is the Dominant plant growth form?
None
Aquatic macrophytes
Freshwater algae
Marine benthic algae
Marine planktonic algae
Seagrass
Giant kelp
seagrass
Tree
Features Chosen: 3
What UN subregion is your ecosystem found in?
Entities Remaining: 17
MFT1.1 Coastal river deltas
MFT1.2 Intertidal forests and shrublands
MT2.1 Coastal shrublands and grasslands
T1.1 Tropical/Subtropical lowland rainforests
T1.2 Tropical/Subtropical dry forests and thickets
T1.3 Tropical/Subtropical montane rainforests
T1.4 Tropical heath forests
T2.3 Oceanic cool temperate rainforests
Entities Discarded: 93
F1.1 Permanent upland streams
F1.2 Permanent lowland rivers
F1.3 Freeze-thaw rivers and streams


Features Available: 59
What is the Leaf phenology?
What leaf sizes are present?
What plant groups are present in your ecosystem?
What is the abundance plants with of buttress roots?
Common
Rare
Absent
Features Chosen: 4
What UN subregion is your ecosystem found in?
South America
What type of environment does your ecosystem occur in?
Terrestrial
Entities Remaining: 5
T1.1 Tropical/Subtropical lowland rainforests
TF1.1 Tropical flooded forests and peat forests
T1.2 Tropical/Subtropical dry forests and thickets
T1.3 Tropical/Subtropical montane rainforests
TF1.2 Subtropical/temperate forested wetlands
Entities Discarded: 105
F1.1 Permanent upland streams
F1.2 Permanent lowland rivers
F1.3 Freeze-thaw rivers and streams


Features Available: 59
What is the Terrain/topography of your ecosystem?
Coastal mudflats
Pelagic
Flats
Plateaus
Intertidal flats
Intertidal platforms
Intertidal cliffs
Coastal dunes & headlands
Interidal walls
Various
Gentle slopes
Entities Remaining: 2
T1.1 Tropical/Subtropical lowland rainforests
T1.2 Tropical/Subtropical dry forests and thickets
Entities Discarded: 108
F1.1 Permanent upland streams
F1.2 Permanent lowland rivers
F1.3 Freeze-thaw rivers and streams



Source: D. A. Keith, J. R. Ferrer-Paris, S. Hay & M. G. Tozer

Tree height varies from 35 to 45 m at the sites observed, and does not conclusively eliminate either T1.1 Tropical-subtropical lowland rainforest or T1.2 Tropical-subtropical lowland rainforest, although trees in the latter rarely exceed 40 m. Refer to EFG descriptions to verify that abundant ferns and mosses (visible in the image) are consistent with T1.1. The ecosystem type occurs in a climatic region with a dry season of several months (consistent with T1.2), but occurs in topographically sheltered locations where a moist microclimate persists through most of the dry season. The ecosystem type is likely or very likely a member of T1.1 (thus, membership estimate = 0.85), but there remains a possibility that it could belong to T1.2 (membership estimate = 0.15, summing to a value of ‘1’ for the two plausible outcomes).

Artificial intelligence (text-only) diagnostic tool

This section shows example input and output dialogue of the text-only Large Language Model for GET EFGs, following the procedure outlined in the section on Artificial intellegence diagnostic tools. The model is currently available for testing at https://www.chatpdf.com/share/nlWIjvieG9n0nXhC459WT. The example uses a published description of a forested wetland ecosystem type in northwestern Australia. The AI responses are in *italics*. Note that queries should be as direct and concise as possible, to minimise energy consumption and carbon footprint.

PDF: *Hello and Welcome!*

[introductory text]

Me: The ecological community in Western Australia called "Assemblages of Big Springs organic mound springs" is described as: "a complex system of freshwater seepages and peaty springs with internal moats with broad tidal flats on the seaward margin and cracking clay flats on the landward margin. It occurs in the West Kimberley. A further feature is the scattered clusters of small outlying, densely vegetated mound springs. The main seepage area supports well developed rainforest vegetation dominated by forests of Terminalia microcarpa (damson plum). Several mistletoe species (Loranthaceae) have been recorded in the Terminalia canopy, which reaches 20 m in places. Other trees present include Ficus racemosa (cluster fig), Ficus virens (banyan fig), Melaleuca leucadendra (weeping paperbark), Pandanus sp. (screwpines), Sesbania formosa (white dragon tree) and Timonius timon. Much less common species noted were Antidesma ghaesembilla (yangu), Diospyros maritima and Nauclea orientalis (Leichhardt tree). The understorey varies from central open glades with turf of Cyperaceae to pure leaf litter under the Terminalia canopies. Internal moats support Acrostichum speciosum (mangrove fern). The outer perimeter of the large seepage feature is relatively dry in most places with this ring generally dominated by dense thickets of Melaleuca alsophila or Acacia ampliceps (or both) with scattered Lysiphyllum cunninghamii, Dichrostachys spicata (Chinese lantern) and occasional Adansonia gregorii (boab) of small stature. Outlying mound spring islands on tidal flats vary markedly in size and in the diversity of vegetation. Some of the smallest islands consist solely of Typha domingensis (bulrush). Larger examples often feature Pandanus spiralis, Sesbania formosa, Acacia neurocarpa and occasionally Terminalia microcarpa and Ficus sp. (fig), with a range of Cyperaceae. Several islands were noted with unusual associations such as Typha sp. growing with the mangrove Lumnitzera sp. The permanent groundwater discharge from the springs provides aquatic habitats (pools and seepages, plus the saturated peat itself) that support distinct assemblages of aquatic invertebrates, often with stygal and restricted elements. The mesic environment in these springs probably also support distinct terrestrial invertebrate fauna assemblages."

Provide a list of three to five candidate Ecosystem Functional Groups that this ecological community could belong to and a brief summary of the matching features for each candidate.

PDF: *Based on the description of the "Assemblages of Big Springs organic mound springs" in Western Australia, here are three to five candidate ecosystem functional groups that may match the features of this ecological community:*

1. TF1.1 Tropical Flooded Forests and Peat Forests

- *Summary: This group includes ecosystems characterized by closed forest canopies in tropical swamps and riparian zones. The presence of well-developed rainforest vegetation dominated by species like Terminalia microcarpa aligns with the features of this functional group. The high biodiversity and complex trophic networks, including various tree species and mistletoe, further support this classification.*

2. TF1.3 Permanent Marshes

- *Summary: Permanent marshes are shallow, permanently inundated freshwater wetlands dominated by herbaceous macrophytes. The description mentions aquatic habitats, pools, and seepages, which are indicative of marsh-like conditions. The presence of Typha domingensis and other wetland plants suggests a strong connection to this functional group, which supports high primary productivity and complex food webs.*

3. MFT1.3 Coastal Saltmarshes and Reedbeds

- *Summary: This group includes ecosystems characterized by salt-tolerant grasses and low shrubs, structured by gradients of salinity and tidal influence. The mention of tidal flats and the presence of mangrove species like Lumnitzera sp. indicates a coastal influence, making this functional group a potential match, especially considering the diverse vegetation on the tidal flats.*

4. TF1.4 Seasonal Tropics and Subhumid Temperate Regions

- *Summary: This group encompasses wetlands with strongly seasonal water regimes, supporting diverse mosaics of aquatic plants and variable trophic networks. The description of the complex system of freshwater seepages and the seasonal dynamics of the ecosystem may align with this functional group, particularly in terms of the adaptations of flora and fauna to varying water availability.*

5. MFT1.2 Intertidal Forests and Shrublands

- *Summary: This group includes mangrove-dominated ecosystems in the intertidal zone. The presence of mangrove ferns and the description of the outer perimeter dominated by dense thickets of Melaleuca and Acacia suggest a transition zone between terrestrial and aquatic environments, which is characteristic of intertidal forests and shrublands.*

These candidate groups reflect the unique features of the "Assemblages of Big Springs organic mound springs," highlighting the complex interactions between freshwater, terrestrial, and coastal influences in this ecological community.

Me: Of these candidates, which one is the closest match to the description?

PDF: *The closest match to the description of the "Assemblages of Big Springs organic mound springs" is TF1.1 Tropical Flooded Forests and Peat Forests.*

Reasons for this Match:

- *Closed Canopy Rainforest Vegetation: The description highlights well-developed rainforest vegetation dominated by species such as Terminalia microcarpa, which is characteristic of tropical flooded forests.*
- *Aquatic Habitats: The presence of permanent groundwater discharge, pools, and seepages supports the aquatic habitats typical of flooded forest ecosystems.*
- *Diverse Flora: The variety of tree species, including Ficus and Melaleuca, along with the presence of understory plants and ferns, aligns well with the biodiversity found in tropical flooded forests.*
- *Moisture and Nutrient Dynamics: The mesic environment and the presence of peat suggest a nutrient-rich habitat that supports complex trophic networks, which is a hallmark of this ecosystem functional group.*

Overall, the combination of rainforest characteristics, aquatic habitats, and the specific plant species mentioned strongly supports the classification of this ecological community within the TF1.1 Tropical Flooded Forests and Peat Forests functional group.

Me: Please tell me source of your answer and where can I find more information

PDF: *The source of the information regarding the ecosystem functional groups and their characteristics comes from the provided PDF document, specifically the sections detailing the various ecosystem functional groups, including TF1.1 Tropical Flooded Forests and Peat Forests.*

For more information, you can refer to the specific sections in the PDF:

- *TF1.1 Tropical Flooded Forests and Peat Forests: This section provides details about the characteristics, ecological traits, and distribution of this ecosystem functional group. You can find it on Page 205 of the document.*

Additionally, you can explore the following link for the version of the profile related to this ecosystem functional group: TF1.1 Tropical Flooded Forests and Peat Forests Profile.

This link will provide you with more comprehensive information about the ecosystem, including its ecological significance, features, and examples.

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