

SYNTHESIS & INTEGRATION

Vegetation Ecology

Advancing the EcoVeg approach as a terrestrial ecosystem typology: From global biomes to local plant communities

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Abstract

The goal of the EcoVeg approach is to fully describe and classify the diversity of the Earth's terrestrial ecosystems based on vegetation and ecological processes. The EcoVeg approach was used to develop the International Vegetation Classification (IVC) and various national classifications, which integrate patterns of vegetation growth form, structure, and floristics with ecological and biogeographic drivers at multiple spatial scales, from global formations to local plant communities. The approach remains unique among terrestrial ecological classifications in providing types at these scales. However, as a terrestrial typology, lack of context with respect to freshwater, marine and subterranean realms limited its clarity. Further, growth forms and structure were limited to readily observable features, which excluded important functional traits. The release by the International Union for Conservation of Nature (IUCN) of the Global Ecosystem Typology (GET) presented an opportunity to revisit the EcoVeg approach because GET has a conceptually robust, scalable, and spatially explicit functional approach for all of earth's ecosystems (terrestrial, freshwater, marine, subterranean). Here, we briefly introduce the EcoVeg

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approach and the GET, and then outline a biome-based revision to EcoVeg and the IVC that builds on the strengths of GET for global terrestrial types and the IVC for continental to local terrestrial types. The outcome is a revised IVC that we rename the ecosystem-based International Vegetation Classification (eIVC). As with GET, the eIVC has a conceptual foundation based on realms and transitional realms, but it focuses on the terrestrial and transitional terrestrial (wetland) realms. It then fully implements terrestrial biome concepts across all the upper levels based on the integration of vegetation with global ecosystem processes and properties. Interoperable compatibility with GET is reflected in the fact that 84% of the global ecosystem types are largely equivalent, which facilitates the linkage of GET with the continental to local ecosystem types of the eIVC. The revisions that now form the eIVC will enhance collaborative development of ecosystem types across the globe and provide more robust opportunities for co-application of the eIVC and GET in the terrestrial realm for management, conservation, and restoration.

KEYWORDS

alliance, biogeography, biome, division, formation, functional traits, Global Ecosystem Typology, International Vegetation Classification, macrogroup, realm, vegetation

INTRODUCTION

The goal of the Ecological Vegetation classification approach, termed EcoVeg, is to classify terrestrial ecosystems based on vegetation and ecological processes (Faber-Langendoen et al., 2014). Vegetation is a critical component of terrestrial ecosystems, given its role in energy capture, biomass production, nutrient and water cycling, trophic webs, and its contribution to niche diversity (Daubenmire, 1976). Vegetation types are defined based on the integration of vegetation growth form, structure, biogeography, and floristics with ecological drivers. The International Vegetation Classification (IVC) uses the EcoVeg approach to fully classify and describe Earth's diverse ecosystems from global formations to local plant communities. It partners with various national vegetation classifications that also use the EcoVeg approach (Faber-Langendoen et al., 2014, 2018). Global formation levels are comprehensive and based on synthetic interpretations of ecological and vegetation patterns (Faber-Langendoen et al., 2016), whereas types at mid and local scales are more often based on field surveys, plots, and mapping. Still, much remains to be done to provide a systematic global set of types across all levels.

The IVC relies strongly on vegetation properties organized by ecological gradients to characterize terrestrial ecosystem types. For the upper levels, it uses the physiognomic-ecological formation concept to define

types. This approach has long been a primary basis for terrestrial ecosystem typologies (Box & Fujiwara, 2005; Moncrieff, Bond, et al., 2016; Mucina, 2018; Sayre et al., 2020; Whittaker, 1975). However, there are limitations to the use of formation concepts as the basis for fully characterizing terrestrial ecosystems. First, as a terrestrial typology, it lacks context with respect to freshwater, marine, and subterranean realms, particularly for the transition from wetlands to freshwater and marine realms. Second, non-vegetated (or extremely sparsely vegetated) ecosystems, such as desert bedrock, rocky shores, and even glaciers, are not fully assessed, leaving the terrestrial typology incomplete. Finally, and more fundamental to the conceptual basis of the IVC, growth forms and structure are typically limited to macro-physiognomic features, which exclude important functional traits, such as wetland hydrophytic traits in water-logged soils, or C3/C4 photosynthetic pathways.

Recently the International Union for Conservation and Nature (IUCN) published the Global Ecosystem Typology (GET) (Keith et al., 2022). It has a conceptually robust, scalable, and spatially explicit functional approach for all of Earth's ecosystems, including the terrestrial, freshwater, marine, and subterranean realms and their transitions. Several developers and users of the IVC participated in the development of the terrestrial component of the GET. Its publication presents an opportunity to revisit the criteria for the typology of the EcoVeg approach and guide revisions to the IVC and partnering

national classifications. For that reason, we explore here how the ecological vegetation approach of the IVC could be improved in light of GET, and in turn how it might inform the GET.

The goal of our revision, along with other approaches, such as that of Braun-Blanquet (Braun-Blanquet, 1932; Guarino et al., 2018), is not to develop a single authoritative system. Rather, as Willner and Faber-Langendoen (2021) state, following Sterner et al. (2020), it is to recognize the existing “taxonomic pluralism” among vegetation and ecosystem ecologists and nonetheless to assist in bringing the full spectrum of global vegetation in view using a few global backbone classifications. Other perspectives, such as gradient analysis methods (Austin, 2013), provide alternative approaches, but here, our focus is on improving a global, hierarchical approach to ecosystem classification. The goal in collaborating with the GET is to build reliable (interoperable) relationships between global classifications (so far as their differing purposes and conceptual frameworks permit) and these with local classifications such that we facilitate information exchanges, whether about types, plot data, or conservation information.

First, we briefly summarize the principles of the EcoVeg approach/IVC typology and the GET. We used a structured international team-based peer review process to propose the revisions. We then identified key features of the upper levels of the IVC that could be revised in light of the GET, guided by the goal of providing a comprehensive treatment of world terrestrial vegetation (ecosystems) on the basis of biome concepts (Box & Fujiwara, 2005). A previous publication had already indicated the merit of this goal (Faber-Langendoen et al., 2020). In turn, we highlighted features of the EcoVeg approach and the IVC that can enhance the terrestrial component of GET. The revisions are substantial enough that we propose renaming the IVC as the ecosystem-based International Vegetation Classification (eIVC). Our goal is to enhance the ability of both typologies to classify terrestrial ecosystems at multiple scales across the globe and lead to greater consistency and complementarity in defining ecosystem types used in global to local assessments.

BACKGROUND

EcoVeg approach and the IVC typology

Guiding principles and general model of the IVC

The IVC is a terrestrial ecological vegetation classification based on the EcoVeg approach described in detail by

Faber-Langendoen et al. (2014). Nine key principles were identified (see Appendix S1: Core Principles of the EcoVeg Approach); briefly, these are that it

1. describes existing vegetation patterns, including cultural types (planted and dominated by human processes), natural types (spontaneously formed or dominated by nonhuman ecological processes), and ruderal (novel) ecosystem types (spontaneous formed but derived from strongly altered natural processes);
2. describes vegetation types at multiple thematic scales, from thematically coarse formations (biomes) to fine-scale plant communities (e.g., alliances and associations);
3. documents types using field-based data, especially vegetation plots, where differentiating criteria of species composition, site factors, and setting are used to interpret vegetation patterns along ecological and biogeographic gradients;
4. organizes types hierarchically with criteria for levels that are inter-related, with types within and among levels developed using a coordinated peer review process.

In the original EcoVeg approach and the IVC, upper level types are based largely on vegetation and ecological properties that reflect global natural and human drivers. The middle levels integrate continental biogeographic, ecological, and human drivers that shape large-scale patterns of species assemblages. Lower levels are driven by more local ecological site factors that structure local species diversity and composition (Table 1, Figure 1). See Appendix S1 (History of Development of the IVC) for a brief summary of the development of the IVC and the EcoVeg approach from 1992 to the present.

A full account of the EcoVeg and IVC typology is provided in Faber-Langendoen et al. (2014, 2018). Comparison of the natural hierarchy with the cultural vegetation hierarchy is provided in Appendix S1: Table S1, as are the definitions for Levels 1, 2, and 3 (L1–L3) for natural vegetation (Appendix S1: Table S2). Descriptions for each L1 formation class to L3 formation type were published in Faber-Langendoen et al. (2016). All mid-level type divisions and macrogroup types for North and South America were listed in Faber-Langendoen et al. (2018). Full descriptions for the Americas are available on NatureServe Explorer (<https://explorer.natureserve.org/>). National perspectives on these units are available for the U.S. National Vegetation Classification (USNVC) on usnvc.org and for the Canadian National Vegetation Classification (CNVC) on

TABLE 1 International Vegetation Classification (IVC) hierarchy and example for natural vegetation.

IVC hierarchy	Example (Faber-Langendoen et al., 2014)
Upper	
L1—Formation Class	Shrub & Herb Vegetation
L2—Formation Subclass	Temperate & Boreal Grassland & Shrubland
L3—Formation	Temperate Grassland & Shrubland
Mid	
L4—Division	Central North American Grassland & Shrubland
L5—Macrogroup	Central Lowlands Tallgrass Prairie
L6—Group	Central Tallgrass Prairie
Lower	
L7—Alliance	Central Mesic Tallgrass Prairie
L8—Association	Mesic Loam Tallgrass Prairie

cnvc-cnvc.org, both of which are key partners to the IVC (Faber-Langendoen et al., 2018).

Applications of the IVC

Several practical conservation and management applications influenced the development of the IVC; namely, a desire that it provide an effective basis for meeting the following needs:

1. guide field surveys and vegetation mapping;
2. support assessment of status and trends of vegetation and ecosystems, including identifying at-risk ecosystems;
3. facilitate interpretation of both long-term and short-term vegetation change;
4. provide a dynamic framework to track real-time ecosystem responses to invasive species, land use, and climate change;
5. guide restoration by providing reference conditions on structure, composition, and ecological processes.

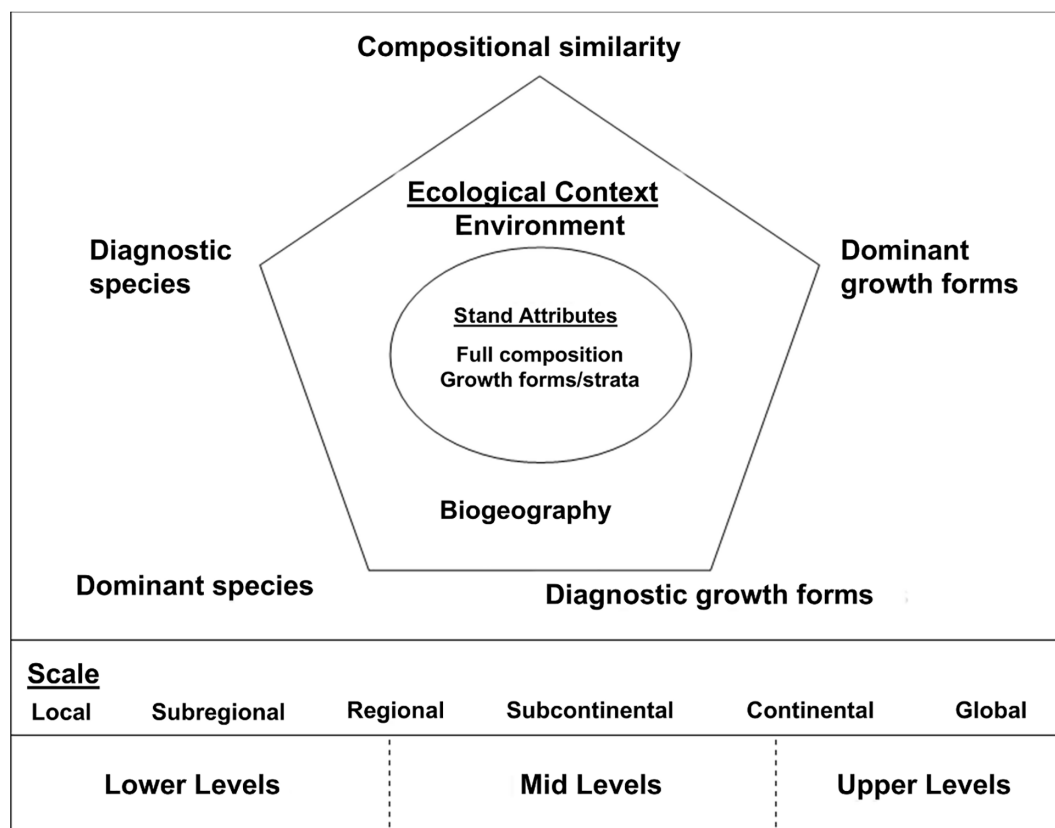


FIGURE 1 Original EcoVeg model for vegetation and ecological classification criteria. The diagram (from FGDC, 2008) portrays the five criteria, shown as five vertices of the pentagon, that are used to classify vegetation at all levels of the EcoVeg hierarchy and the ecological context. See Figure 7 for the revised International Vegetation Classification (IVC) model.

The IUCN GET

Conceptual basis of GET

The IUCN GET emerged from a need for a systematic typology that encompasses all of Earth's ecosystems and represents both ecosystem functional and biotic diversity (Keith et al., 2022). Ecosystem functions are the outcomes of ecological processes that depend on and regulate ecosystem structure and the stocks and fluxes of resources, energy, and biota and underpin biomass production. Together with species traits, these functions—collectively referred to as “ecosystem properties”—define and sustain ecosystem identity and shape ecosystem responses to environmental change, including anthropogenic changes (Keith et al., 2022). Ecosystems with different species composition may show functional convergence and thus are grouped together at upper levels of the typology if their biota share similar traits and contribute to similar ecological processes. Together with other ecosystem properties, the identity of constituent biota, recognized at lower levels of the typology, is central to biodiversity concepts, conservation goals, and human values (Keith et al., 2022).

GET structure

The GET, adopted by the International Union for the Conservation of Nature (IUCN) at the 2020 World Conservation Congress (Keith et al., 2022), has six hierarchical levels, enabling applications at different thematic scales. Three upper levels differentiate functional groupings, and three lower levels accommodate differences in biotic composition among functionally convergent ecosystems (Table 2). The scalable hierarchical structure and the explicit description of properties and related drivers and processes enable types to be mapped at any thematic level, which may depend on spatial scale. L4 types are derived by subdivision of L3 types to recognize regional expressions of functionally similar ecosystems that differ in species composition. In contrast, L5 is aggregated from L6 types (the most localized species assemblages) and may be attributed directly to L3 types based on functional properties. Thus, L4 and L5 provide alternative pathways (depending on available data) to define global-scale units with distinctive functional, structural, and compositional properties. L4 provides something of a proxy where data are limited at fine thematic scales (L5 and L6). Currently, the GET does not officially recognize any specific L5 and L6 types, while a first pilot set of L4 types are described in Tóth et al. (2025).

Level 1 of the GET divides the biosphere into five global realms: (1) terrestrial; (2) subterranean; (3)

freshwater (including saline water bodies on land); (4) marine; and (5) the atmosphere (this realm is not classified further) (Keith et al., 2022). The interfaces between these core realms are treated as transitional realms, accommodating ecosystems, such as mangroves, that depend on unique conditions and fluxes between contrasting environments. Most notably, from an IVC perspective, is that palustrine wetlands, deltas/brackish wetlands, and seashores are treated as transitional realms. The use of transitional realms is introduced because the ecological processes and species traits of these transitional realms differ substantially from the main terrestrial realm.

At Level 2, the typology defines 25 biomes (Keith et al., 2022): 7 within the terrestrial realm; 5 in freshwater, brackish, and marine wetland transitional realms; and the remaining 13 in subterranean, freshwater, and marine realms and their transitions. These biomes include familiar terrestrial types, such as tropical/subtropical forests and deserts, as well as functionally distinctive groupings that fall outside the traditional scope of the biome concept, including lentic and lotic freshwater biomes, pelagic and deep-sea benthic marine biomes, subterranean freshwater biomes, and several anthropogenic biomes. Ecosystems in this latter group are created by human activity, which continues to drive and maintain their composition, structure, and function.

Level 3 of the typology currently includes 110 Ecosystem Functional Groups (EFGs) across all realms, including 36 terrestrial realm EFGs (and 7 biomes), 7 terrestrial-freshwater EFGs (1 biome), 7 terrestrial-marine EFGs (3 biomes), and 3 marine-freshwater-terrestrial EFGs (1 biome). The EFGs are grouped into biomes based on shared common ecological drivers and dependencies, and thus exhibit convergent biotic traits. All global types were fully described in Keith et al. (2022) and are available at <https://global-ecosystems.org/>.

Because the IVC is essentially a terrestrial classification, we focus our comparison with GET on the 12 terrestrial /transitional biomes and the 53 terrestrial transitional EFGs.

REVISIONS PROCESS

IVC Revisions Work Group

After the release of the GET (Keith et al., 2022), an international team of terrestrial ecologists (i.e., the authors of this paper) agreed to participate in the IVC Revisions Work Group to consider revisions to the IVC based on what was learned by developing GET. Three members of

TABLE 2 Proposed structure of the ecosystem-based International Vegetation Classification (eIVC) in relation to the Global Ecosystem Typology (GET), showing slight modifications in italics to the definitions of the top three levels of the eIVC to indicate the shift to a biome perspective.

e-International Vegetation Classification (EcoVeg approach) [terrestrial realm] (Faber-Langendoen et al., 2014)	IUCN Global Ecosystem Typology (GET) [all realms] (Keith et al. (2022))
Upper levels	
Realm and Transitional Realm [new to eIVC]: One of four core components of the biosphere that differ fundamentally in ecosystem organization and function: terrestrial, freshwater, marine, subterranean. Transitional Realms describe overlap between the realms.	L1. Realm: One of five core components of the biosphere that differ fundamentally in ecosystem organization and function: terrestrial, freshwater, marine, subterranean, atmospheric.
L1. Biome [Formation Class]: A broad combination of dominant general growth forms and structure <i>regulated by common major ecological drivers</i> , including basic moisture, temperature, substrate, and/or disturbance regimes.	L2. 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).
L2. Subbiome [Formation Subclass]: A combination of general dominant and diagnostic growth forms <i>and structure that are regulated by global ecological drivers</i> , such as mega- or macroclimatic factors driven primarily by latitude and continental position, or that reflect overriding substrate and disturbance regimes.	
L3. Ecobiome [Formation]: A combination of <i>ecosystem properties</i> (especially dominant and diagnostic growth forms and structure) <i>that share common ecological drivers</i> , such as global macroclimatic conditions (modified by altitude and seasonality of precipitation), substrates, hydrologic, and disturbance regimes.	L3. Ecosystem Functional Group: A group of related ecosystems within a biome that share common ecological drivers promoting convergence of ecosystem properties that characterize the group. Derived from the top-down subdivision of biomes.
Mid-levels	
L4. Division: A combination of dominant and diagnostic growth forms and a broad set of diagnostic plant species that reflect biogeographic differences in composition and continental differences in mesoclimate, geology, substrates, hydrology, and disturbance regimes.	L4. Regional ecosystem subgroups: An ecoregional expression of an Ecosystem Functional Group derived from the top-down by subdivision of Ecosystem Functional Groups (level 3). They are proxies for compositionally distinctive geographic variants that occupy different areas within the distribution of a functional group.
L5. Macrogroup: A moderate set of diagnostic plant species and diagnostic growth forms that reflect biogeographic differences in composition and subcontinental to regional differences in mesoclimate, geology, substrates, hydrology, and disturbance regimes.	L5. Global ecosystem types: A complex of organisms and their associated physical environment within an area occupied by an Ecosystem Functional Group. Global ecosystem types grouped into the same Ecosystem Functional Group share similar ecological processes, but exhibit substantial differences in biotic composition. They are derived from the bottom-up, either directly from ground observations or by aggregation of Subglobal types (level 6).
L6. Group: A relatively narrow set of diagnostic plant species (including dominants and codominants), broadly similar composition, and diagnostic growth forms that reflect regional mesoclimate, geology, substrates, hydrology, and disturbance regimes.	L6. Subglobal ecosystem types: A subunit or nested group of subunits within a global ecosystem type, which therefore exhibit a greater degree of compositional homogeneity and resemblance to one another than Global ecosystem types (level 5). 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.
Lower levels	
L7. Alliance: A characteristic range of species composition, habitat conditions, physiognomy, and diagnostic species, typically at least one of which is found in the uppermost or dominant stratum of	L6. Subglobal ecosystem types: subtypes. See above.

TABLE 2 (Continued)

e-International Vegetation Classification (EcoVeg approach) [terrestrial realm] (Faber-Langendoen et al., 2014)	IUCN Global Ecosystem Typology (GET) [all realms] (Keith et al. (2022)
the vegetation. Alliances reflect regional to subregional climate, substrates, hydrology, moisture/nutrient factors, and disturbance regimes. L8. Association: A characteristic range of species composition, diagnostic species occurrence, habitat conditions and physiognomy. Associations reflect topo-edaphic climate, substrates, hydrology, and disturbance regimes.	L6. Subglobal ecosystem types: subtypes. See above.

the IVC Work Group (Faber-Langendoen, Keith, Plischoff) were part of the GET publication, and a fourth (Loidi) helped write descriptions for various GET types. Members of the Working Group are based in Australia, Austria, Bolivia, Chile, China, Ghana, Spain, and the United States. A summary of the Work Group process is provided in Appendix S1 (IVC Revisions Work Group Process).

The rationale for an IVC-GET Collaboration

The Work Group examined the structure of the IVC and GET to understand how to best leverage existing synergies between the IVC and the GET (e.g., similar hierarchical structure and comparable Level 3 types) and explored future opportunities for development (e.g., populating lower levels of the GET, fostering collaboration). Several key points were identified to strengthen the IVC’s connection to the GET and further its goal of classifying and describing the diversity of terrestrial ecosystems. These include:

Enhance the existing hierarchical connections between the IVC and GET typologies

As is apparent from Tables 1 and 2 above, there are fundamental similarities in the hierarchical structure of the two typologies. That said, the IVC structure for Levels 1 and 2 would require considerable adjustments if the goal is to incorporate the realms and transitional realms of GET. The work group explored ways in which those adjustments could be made.

Strengthen representation of existing ecosystem properties

Both the IVC and GET are based on describing the current processes and properties that identify the ecosystem

and drive ecosystem change. These properties, including characteristic biota at mid and lower levels, define and sustain ecosystem identity and shape ecosystem responses to environmental change, including anthropogenic changes. Champreux et al. (2024) refer to this as the functional biome approach, in which the focus of classification and mapping is to summarize the distribution and structural and functional attributes of existing, rather than potential, biomes based on their currently expressed vegetation patterns and ecological processes.

Emphasize the terrestrial scope of the IVC, including transitional terrestrial-wetland realms of the GET

We propose to tighten the terrestrial focus of the IVC by both excluding aquatic vegetation from the IVC and ensuring that all terrestrial ecosystems, including very sparsely vegetated ecosystems, are included.

Explore how a revised IVC could add depth to the GET

Many biome classifications, including GET, provide well-developed global concepts but do not provide units that scale down to continental, regional, and local types (but see Navarro & Molina, 2021; Navarro et al., 2023). Conversely, the IVC has already developed a multi-scaled approach across large parts of the globe, including across the Americas (Faber-Langendoen et al., 2018), parts of Australia (Muldavin et al., 2021), Africa (Sayre et al., 2013), and for Europe in partnership with the European Vegetation Survey (Willner & Faber-Langendoen, 2021). The Work Group examined how, if the IVC upper levels were better aligned with the GET, then the IVC mid-level units (IVC L4–L6) could provide a comprehensive guide to the lower levels of the GET. Such linkages could foster standard mid-level types for many national and continental assessments

(e.g., Ferrer- Paris et al., 2019). The IVC also contains a formal set of criteria for types at IVC L7 and L8, whereas the GET simply lists these as subtypes of GET L6. IVC L7 (alliance level) is particularly important, as it forms the basis for defining major plant communities around the globe (Willner, 2020).

Better alignment between a revised IVC and GET could foster collaboration among the International Community of Ecologists and Resource Managers

An improved alignment at upper levels of the IVC and GET, in combination with mid-levels of the IVC that are comparable to GET L5 and L6, also establishes guidance for dialogue with many national and local classifications that are developed at the lower levels of the IVC (L6–L8). This collaboration is critical for describing the full range of ecosystems, for guiding mid- and fine-scaled conservation and resource management assessments, and for fostering collaborations between those classifications and various continental (Willner & Faber-Langendoen, 2021), national (Faber-Langendoen et al., 2018; Murray et al., 2020), and subnational classifications.

Nomenclature of ecosystem types

Because the GET has only developed types down to GET L3 Ecosystem Functional Group, the question of standardizing nomenclatural conventions for all levels of the hierarchy is still in development. Given that the GET encompasses all realms, further collaborations are needed to develop nomenclatural standards that meet the needs of diverse traditions across the realms. Conversely, as part of the EcoVeg approach, the IVC has relatively formal nomenclatural standards based on terrestrial vegetation naming conventions, and these standards are shared by other users of the EcoVeg approach, including national and subnational partners (Faber-Langendoen et al., 2014). Given the open peer-review process, especially at lower and mid-levels, these nomenclatural standards guide consistency in submissions of names when revising or proposing new types. For that reason, even when revisions to the IVC led to equivalence with GET types, we applied the nomenclatural standards of the EcoVeg approach to those names (e.g., IVC using singular capitalized terms for all types; i.e., GET L3 *T2.5 Temperate pyric humid forests* = IVC L3 *TT2.a2 Temperate Pyric Humid Forest*).

SYNOPSIS OF REVISIONS TO THE ECOVEG APPROACH: THE eIVC

Introducing the eIVC

Given the key conceptual changes to the EcoVeg Approach, the IVC required substantial modification of both the upper level definitions and the units in those levels. For that reason, we rename the IVC to the eIVC and we use that term through the rest of the publication.

Revising the EcoVeg principles

Several basic ecological principles from the GET are brought into the eIVC:

Explicit Terrestrial and Wetland Transitional Realms

The EcoVeg approach and the IVC encompassed terrestrial vegetation. Wetlands were included but were dispersed among various terrestrial formation types based on shared physiognomy. We now follow the GET in explicitly recognizing the Terrestrial Realm and Wetland Transitional Realms as distinct from Freshwater, Marine, and Subterranean realms (Figure 2). We exclude aquatic vegetation in permanent open water bodies with no emergent vegetation; that is, ecosystems with only floating and submerged macrophytes (e.g., seagrass beds and freshwater submerged vegetation). See the full set of GET realms and biomes for the placement of freshwater, marine, and subterranean ecosystems.

Extension of eIVC across the Entire Terrestrial Realm

We reworked the EcoVeg approach to include types where vegetation biomass or cover is minimal and may not be detectable with remote sensing. Virtually all such ecosystems have plants that contribute primary production, but they are either nonvascular (bryophytes, lichens, algae) or transient on annual or long interannual time scales. The ecological properties that are shared with closely related vegetation types guide the eIVC classification and placement of these types. For example, alpine or polar montane rock vegetation, such as alpine cliffs and talus, are placed in the same biome with more vegetated alpine-polar counterparts and then treated separately at lower levels. Even glaciers and ice sheets can be classified as ecosystems with microbial biota and placed with

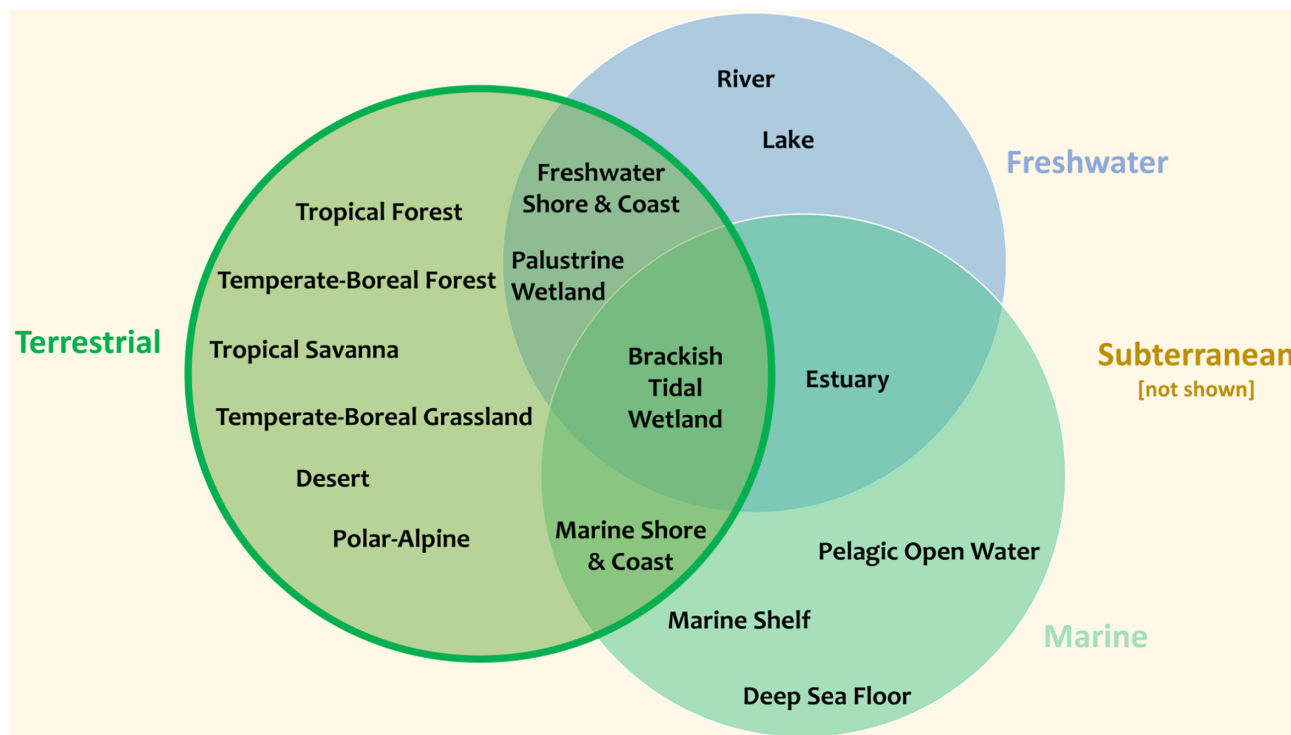


FIGURE 2 The scope of the ecosystem-based International Vegetation Classification (eIVC) across the Terrestrial Realm. The full scope of the Terrestrial Realm (dark green circle) includes both the core “upland/dryland” biomes and the transitional wetland biomes (names abbreviated from Table 4). Figure adapted from Keith et al. (2022), including names of Biomes in the Freshwater and Marine realms. Subterranean realm not shown for clarity.

cryogenic vegetation to ensure comprehensive coverage of the eIVC on land (Anesio & Laybourn-Parry, 2012). Similarly, sand dunes and hyperarid deserts with minimal or no vegetation can be placed with their vegetated counterparts (see example in Appendix S2).

Emphasize ecological properties alongside vegetation

The EcoVeg approach emphasizes vegetation characteristics such as growth forms, composition, and structure, alongside climate, soils, geology, disturbances, and humans. But growth form and structural criteria sometimes combine types that were otherwise ecological and functionally distinct; for example, the IVC placed mangroves, tropical rain forests and boreal forests together under a “Forest & Woodland” class. Here, we rely on a biome approach, where the combination of vegetation and ecological drivers guide the overall structure. In line with GET, the eIVC balances climatic drivers with other drivers and includes a broader set of functional properties.

Nonetheless, because most terrestrial ecosystems are dominated by or include some vegetation, the

classification of ecosystems based on vegetation often captures key ecological properties. Physiognomic and structural traits of vegetation may directly gauge some terrestrial ecosystem properties, like net primary production, and be useful proxies for others (e.g., climate patterns and historic fire regimes).

Structural changes to upper levels of the eIVC

Here we detail the results of the changes made to the upper levels of the eIVC and how these changes lead to a congruent hierarchical structure with that of GET. The overall congruence is summarized in Figure 3.

eIVC realms and level 1 biomes

First, we adopt the GET Realms as the overarching structure, which then focuses the eIVC on the core terrestrial realm and terrestrial-transitional realms, such as freshwater and marine wetlands (Figure 2, Table 3). The essential change is that the eIVC now excludes permanent water bodies with sub aquatic vegetation. We can

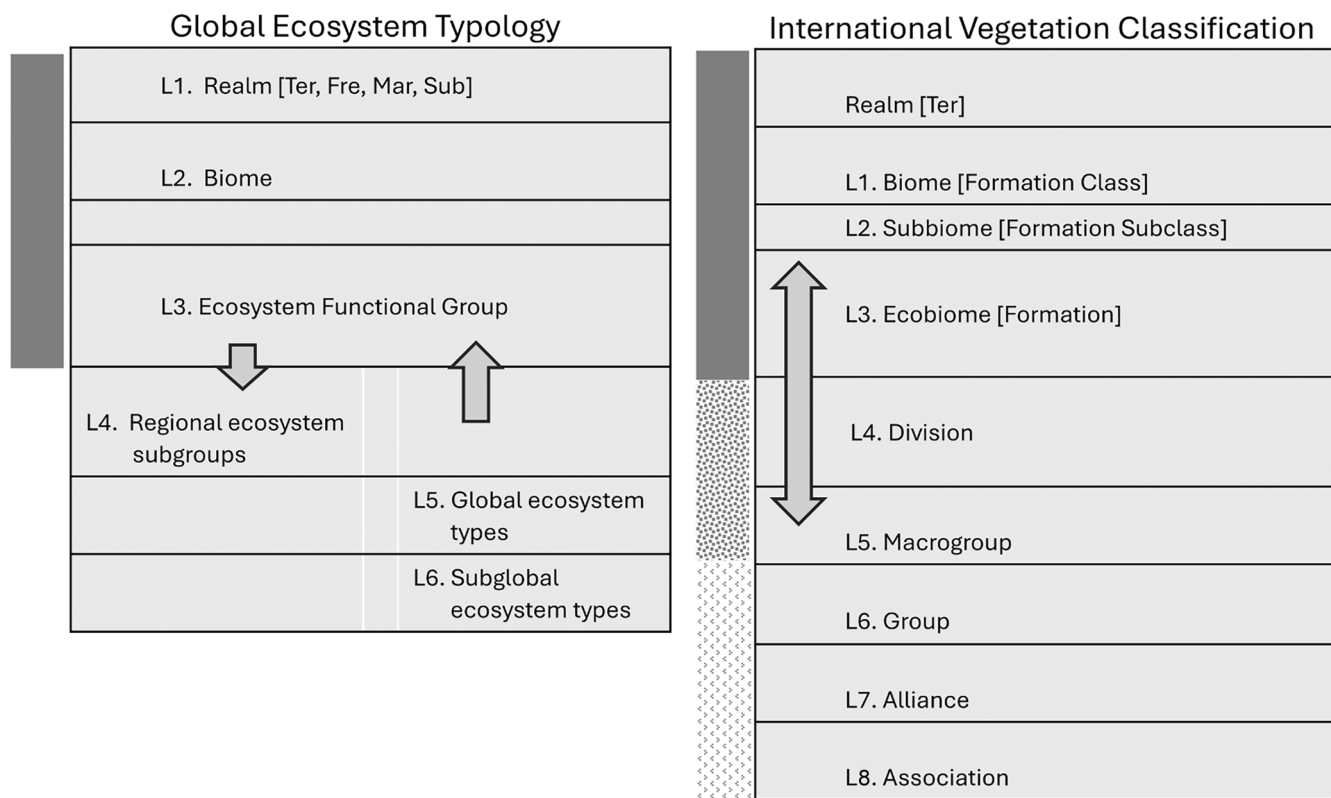


FIGURE 3 Comparison of Hierarchical Structure of Global Ecosystem Typology (GET) and the revised International Vegetation Classification (eIVC). The GET has six hierarchical levels (Keith et al., 2022), with Level 1 being Realms (Terr, Terrestrial; Fre, Freshwater; Mar, Marine; and Sub, Subterranean). Level 4 types derived by subdivision of Level 3 types to recognize regional expressions of functionally similar ecosystems that differ in species composition. In contrast, Level 5 is aggregated from Level 6 types (the more localized species assemblages) and may be directly attributed to Level 3 types based on functional equivalence. The eIVC has eight levels; realms are a categorical set of units above L1, L1–L3 are renamed as various biome levels (old formation names in square brackets); L2 is a subbiome level not used in GET, and L7 and L8 are fine-scaled plant community types treated as possible subtypes within GET L6. All levels are integrated. GET L1–L3 are fully developed (solid gray bar), but L4–L6 are not yet developed except in pilot form; IVC L1–L3 are fully developed (solid gray bar), L4 to L5 are widely developed (dense stippling) and L6–L8 are partially developed (light stippling).

use the GET to address subtidal marine, submerged, or floating aquatic vegetation in the freshwater or marine realms. Having adopted the Realm structure, we moved IVC emergent wetland formations that had been separated from each other based on physiognomic differences into a shared eIVC L1 biome, guided by the combination of biota and wetland processes. For example, freshwater forested wetlands and freshwater marshes, formerly separated into IVC Forest & Woodland Formation Class and a Shrub & Herb Vegetation Formation Class, were moved together into an eIVC Palustrine Wetland biome (Table 3). Moreover, freshwater/inland wetlands (terrestrial-freshwater transitional realm) are separated from tidal brackish/estuarine wetlands in the terrestrial-freshwater-marine transitional realm (mangrove, salt marsh).

Second, we consistently adopt the biome concept for L1 of the eIVC. Thus, the eIVC separates *TT1 Tropical Forest* from *TT2 Temperate-Boreal Forest &*

Woodland at L1 (in the IVC they had been placed together under a Forest & Woodland formation class). We make the same distinction for grassland and shrublands, separating *TT3 Tropical Savanna & Shrubland* from *TT4 Temperate Grassland & Shrubland* (the GET assembly model results in a somewhat different treatment of grasslands and shrublands; see Appendix S3 for details). This revision produces a more uniform treatment of the role of climate drivers for all eIVC L1 types because the IVC had already treated *TT5 Desert & Semi-desert* and *TT6 Polar & High Montane Scrub & Grassland* as biome-scale types.

To complete the shift to biomes, we then follow the GET in distributing the lithomorphic types that were in the IVC Formation Class 6, Open Rock Vegetation, to the next lower level within the eIVC Biomes *TT3* and *TT4* (Table 3). This treatment addresses all open rock vegetation more equitably within all eIVC L1 Biome types because desert rock vegetation had

TABLE 3 Revision process of International Vegetation Classification (IVC) Formation Class to ecosystem-based International Vegetation Classification (eIVC) Biome, showing adoption of the Realm level and separation of wetland formations from upland formations into new biomes.

Category 1	IVC level 1—Class	eIVC revision	Realm	eIVC biome
Natural	1. Forest & Woodland	Terrestrial Tropical vs. Temperate (TT1, TT2), Freshwater Swamps (TP1), Mangroves (MB1)	TT	TT1. Tropical Forest TT2. Temperate-Boreal Forest & Woodland
	2. Shrub & Herb Vegetation	Terrestrial Tropical vs. Temperate (TT3, TT4), freshwater marshes (TP1), Salt marshes (MB1)		TT3. Tropical Savanna & Shrubland TT4. Temperate-Boreal Grassland & Shrubland
	3. Desert & Semi-desert	Expand to non-vegetated deserts		TT5. Desert & Semi-Desert
	4. Polar & High Montane Scrub & Grassland	Expand to non-vegetated ecosystems		TT6. Polar & Alpine
	5. Aquatic Vegetation	Excluded and treated as part of either Freshwater or Marine realms		
	6. Open Rock Vegetation	Move to Subbiome types within TT3 and TT4 Biomes		See TT3 and TT4 (above)
Cultural	7. Agricultural & Developed Vegetation	Largely unchanged		TT7. Intensive Land Use
		New	TP	TP1. Palustrine Wetland TP2. Freshwater Coast TP3. Anthropogenic Freshwater Coast
		New	MB	MB1. Brackish Tidal Wetland (Estuarine)
		New	MS	MS1. Marine Shoreline MS2. Supralittoral Marine Coast MS3. Anthropogenic Marine Shoreline

Note: TT, Terrestrial; TP, Terrestrial-Freshwater; MB, Marine-Freshwater-Terrestrial; MS, Marine-Terrestrial.

already been placed in IVC Formation Class 3 Desert & Semi-desert and polar and alpine rock vegetation had already been placed in Formation Class 4 Polar & High Montane Scrub & Herb Vegetation. Essentially, the emphasis here is that at the global scale, the ecological drivers and the biodiversity of open rock ecosystems, such as cliff, talus, and rocky outcrops, share many of the same biome properties as non-rocky ecosystems when found in similar climates and ecological settings.

Completing these changes leads to a strong congruence between the IVC L1 Biome and the GET L2 Biome (Table 4). We add two biomes to the eIVC that are not provided in GET; namely, the eIVC *TP2 Freshwater Coast* and the *TP3 Anthropogenic Freshwater Coast*. The GET *MT2 Supralittoral coastal biome* only encompasses marine coastlines. For that reason, we also added “marine” to the name of eIVC *MS2* (i.e., *MS2 Supralittoral Marine Coast*). Although the supralittoral freshwater coast biome is much more restricted than that of marine, there are dramatic examples found in the great lakes of the world, where this biome is best expressed (see Appendix S3).

Level 2 subbiome revisions

Following from the L1 revisions, we largely retained the original L2 types of the IVC in the eIVC but reworked them based on eIVC L1 Biome concepts (Box 1). The GET does not contain an equivalent level (see Figure 2, Table 2), but this level adds greater depth to our understanding of the ecological drivers of global biomes, including climate and its interaction with non-climate drivers, such as fires (Bond, 2019). For example, the eIVC L2 *TT1.a Tropical Rainforest* aggregates the three rainforest formations/Ecosystem Functional Groups at L3 that share similar structures and ecological processes as compared with the eIVC L2 *TT1.b Tropical Dry Forest* subbiome (Whitmore, 1998). Similarly, *TT5.b Warm Desert & Semi-desert* is often recognized separately from *TT5.a Cool Semi-desert* (Barbour & Billings, 2000).

To assess whether our climatic drivers represented current understandings of climate-biome relationships, we compared the eIVC L2 types with the subbiome types of Loidi et al. (2022) (see Appendix S4). Because many of our L2 types are strongly related to those of Loidi et al., we adopt the term “subbiome” for this level, but we

TABLE 4 Summary of the relationship between the ecosystem-based International Vegetation Classification (eIVC) Typology and the Global Ecosystem Typology, showing that, of the 14 eIVC Biomes, 10 are equivalent to the GET Biomes, two are modified (TT3 and TT3 marked with *) and two are new (TP2 and TP3 marked with \$).

Global ecosystem typology	eIVC typology
Terrestrial Realm (T)	Terrestrial Realm (TT)
T1 Tropical-subtropical forests	TT1 Tropical Forest
T2 Temperate-boreal forests and woodlands	TT2 Temperate-Boreal Forest & Woodland
T3 Shrublands and shrubby woodlands	TT3 Tropical Savanna & Shrubland*
T4 Savannas and grasslands	TT4 Temperate-Boreal Grassland & Shrubland*
T5 Deserts and semi-deserts	TT5 Desert & Semi-desert
T6 Polar/alpine	TT6 Polar & Alpine
T7 Intensive land use	TT7 Intensive Land Use
Terrestrial-Freshwater (TF)	Terrestrial-Freshwater (TP)
TF1 Palustrine wetlands	TP1 Palustrine Wetland
	TP2 Freshwater Coast\$
	TP3 Anthropogenic Freshwater Coast\$
Marine-Freshwater-Terrestrial (MFT)	Marine-Freshwater-Terrestrial (MB)
MFT1 Brackish tidal	MB1 Brackish Tidal Wetland
Marine-Terrestrial (MT)	Marine-Terrestrial (MS)
MT1 Shorelines	MS1 Marine Shoreline
MT2 Supralittoral coastal biome	MS2 Supralittoral Marine Coast
MT3 Anthropogenic shorelines	MS3 Anthropogenic Marine Shoreline

caution that we do not limit the bases for our biome or subbiome concepts to those controlled by climate (i.e., zonal types) (cf. Loidi et al., 2022; Navarro & Molina, 2021), nor to strictly natural and potential biomes (cf. Hunter et al., 2021). Nonetheless, as shown in Figure 4, many of our eIVC L2 subbiome and L3 types do have strong climatic drivers and this is also evident for comparable GET types, as shown in Figure 5 for GET *T2.4 Warm temperate laurophyll forests* (= to eIVC *TT2a1 Warm Temperate Evergreen Forest & Woodland*). Separate biome maps will be needed for the “azonal” biome and subbiome types, as documented in Keith et al. (2022).

Thus, the maps of Figure 4 should be seen as indicative of the distribution of subbiome types where climate is a major factor.

The eIVC L2 *TT7.a Agricultural Land* and *TT7.b Developed Land* subbiomes are, in line with GET, simplified from the more detailed IVC approach based on growth form and structure. The L2 cultural type distinctions developed in IVC, which relied strongly on vegetation characteristics, are rarely used in classifying and mapping types included in these subbiomes.

Level 3 ecobiome (formation) revisions

With the realignment of L1 and L2, it was then possible to compare the IVC L3 formation types with the GET L3 Ecosystem Functional Groups (EFGs) and revise the formations as needed for the eIVC. Given the overall shift to the biome approach for the upper levels, we adopt the term “ecobiome” for L3, a term introduced by Polunin (1984) and Bailey and Hogg (1986). The term “formation” often conveys the sense that only plants are considered, and the eIVC now includes units where plants may be minor, such as, for example, open dunes and oceanic rock outcrops with seabirds. Ecobiome is consistent with the L1 Biome and L2 Subbiome names, and concise, which is helpful when adding the level of the hierarchy to the name of a type. The name also highlights the increasing diversity of ecological drivers that shape biomes at L3. It shares a similar role as GET L3 (Ecosystem Functional Group) in uniting ecosystems with distinct species composition that share similar growth forms, functional traits, and ecological processes.

Our rigorous assessment of each Ecosystem Functional Group of GET provided guidance on both revising formations into ecobiome concepts or adding new ecobiomes. After completing this review, we assessed the degree of similarity between the eIVC and GET L3 units using the available descriptions and distribution information from the IVC that were still relevant to the eIVC formations (Faber-Langendoen et al., 2016). We then formally compared our ecobiome concepts and distributions with the concepts and distribution maps available in the GET from Keith et al. (2022). Because our concepts are not always the same as that of GET, we chose a coding structure distinct from but parallel to that of GET. As noted in the Nomenclature section above, we also maintain an EcoVeg naming standard that is applied to all eight levels. By adopting a comparable coding structure to the GET, it is relatively straightforward to follow the relationships between the two classifications. For example, eIVC *TT1.a1 Tropical Lowland Rainforest* is largely equivalent to GET *T1.1 Tropical/Subtropical lowland rainforests*, and eIVC

BOX 1 Ecosystem-based International Vegetation Classification (eIVC) Level 2 Subbiome types nested within Level 1 Biome types

eIVC Biome

eIVC Subbiome

Terrestrial (TT)

TT1 Tropical Forest

TT1.a Tropical Rainforest

TT1.b Tropical Dry Forest

TT2 Temperate-Boreal Forest & Woodland

TT2.a Warm Temperate Forest & Woodland

TT2.b Cool Temperate Forest & Woodland

TT2.c Boreal Forest & Woodland

TT3 Tropical Savanna & Shrubland

TT3.a Tropical Savanna

TT3.b Tropical Shrubland

TT3.c Tropical Open Rock

TT4 Temperate-Boreal Grassland & Shrubland

TT4.a Mediterranean Scrub & Grassland

TT4.b Temperate Grassland & Shrubland

TT4.c Continental Boreal Shrubland & Grassland

TT4.d Temperate-Boreal Open Rock

TT5 Desert & Semi-desert

TT5.a Cool Semi-desert

TT5.b Warm Desert & Semi-desert

TT6 Polar & Alpine

TT6.a Polar & Alpine Snow & Ice

TT6.b Temperate-Polar Alpine & Tundra

TT6.c Tropical High Montane

TT7 Intensive Land Use

TT7.a Agricultural Land

TT7.b Developed Land

TT7.c Ruderal Land

Terrestrial-Freshwater (TP)

TP1 Palustrine Wetland

TP1.a Forested Wetland

TP1.b Emergent Open Wetland

TP1.c Bog & Fen

TP2 Freshwater Coast

TP2.a Freshwater Coast

TP3 Anthropogenic Freshwater Coast

TP3.a Developed Freshwater Coast

Marine-Freshwater-Terrestrial (MB)

MB1 Brackish Tidal Wetland

MB1.a Brackish Tidal Wetland

Marine-Terrestrial (MS)

MS1 Marine Shoreline

MS1.a Marine-Intertidal Shoreline

MS2 Supralittoral Marine Coast

MS2.a Supralittoral Marine Coast

MS3 Anthropogenic Marine Shoreline

MS3.a Developed Marine Shoreline

TT1.a2 Tropical Montane Forest is largely equivalent to GET *T1.3 Tropical/Subtropical montane rainforests*. A few notable differences between the eIVC and GET are summarized in Table 5. Full details of the comparison are provided in Appendix S5.

By restructuring the eIVC based on consistently applied ecobiome concepts, we have developed types that are substantially congruent with the Ecosystem Functional Groups of GET (Table 6). Now, 71% of the types in GET and the eIVC are the same, 8% of the eIVC types are finer, 5% are broader, and 8% intersect in somewhat complex ways. There are 4 eIVC types (8%) recognized in the eIVC that are not tracked by GET. In summary, 84% of the eIVC types are either equivalent or have minimal lumping or splitting of GET types.

eIVC mid-levels add depth to GET

To test our proposed revisions of the upper levels, we took all existing units at the eIVC L4–L8 (division to association) and reaggregated them from their current L3 formations to the new ecobiomes. The units included the 140 divisions and 375 macrogroups in the Americas (Faber-Langendoen et al., 2018), the 163 macrogroups in Africa (Sayre et al., 2013) and the 30 divisions and 109 Braun-Blanquet classes in Europe (Willner & Faber-Langendoen, 2021). In a few cases, we had to develop new divisions to account for new ecobiomes, but most (>95%) of the divisions and lower level units were already sufficiently informed by distinctions based on ecological processes, structure, and species composition that they could readily be placed under the ecobiomes. At this time, all division and macrogroup units in the Americas and Africa, along with European divisions and Braun-Blanquet classes, have been placed under the new ecobiomes. The new upper levels and divisions and macrogroup units for North and South America are available on NatureServe

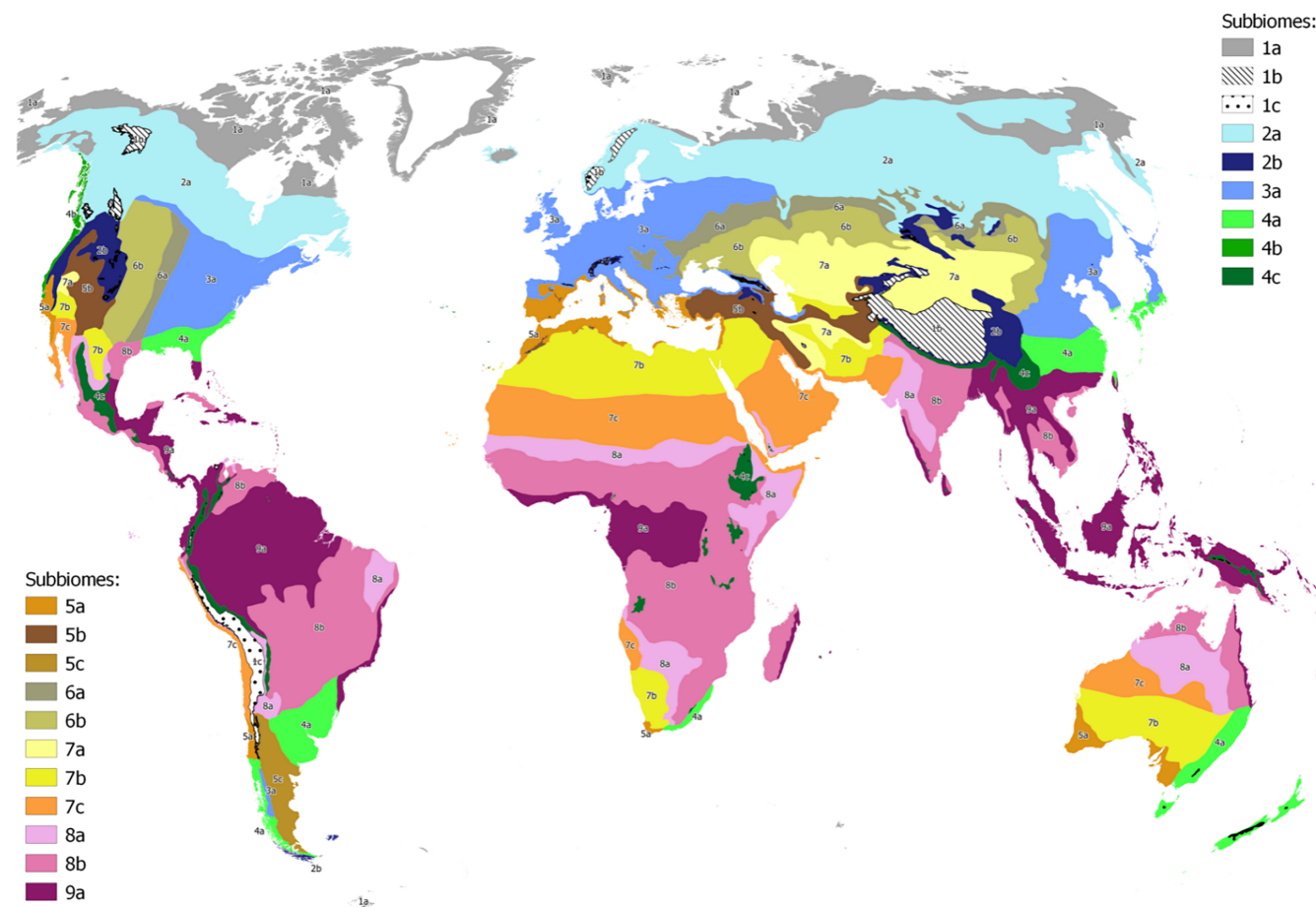


FIGURE 4 Map of various subbiome and ecobiome types based on climate (from Loidi et al., 2022); see Appendix S4 for details. Compare 4a and 4c with the map in Figure 5.

Explorer (<https://explorer.natureserve.org>). Units in Africa will be made available on NatureServe Explorer, pending further peer review. For units in Europe, see Appendix S6, where we update the integration of EcoVeg and Braun-Blanquet units published in Willner and Faber-Langendoen (2021).

We demonstrate the realignment process using the eIVC L3 *TT2.a5 Oceanic Cool Temperate Rainforest* ecobiome (equivalent to GET L3 T2.3). The divisions to association units now placed in this ecobiome were previously treated in the IVC under the very broad formation 1.B.2. Cool Temperate Forest & Woodland. In North America, that formation is now split into multiple cool temperate ecobiomes (eIVC *TT2.a4 Temperate Deciduous-Mixed Forest & Woodland*, *TT2.a5 Oceanic Cool Temperate Rainforest*, and *TT2.a6 Temperate Continental Conifer Forest & Woodland*). The map in Figure 5 makes evident how the revised temperate forest concepts better track major drivers of temperate forest vegetation pattern across North America. The new ecobiomes also required some new divisions because the previous division types only separated eastern North

American cool temperate forests from western North American cool temperate forests. Because of the new rainforest ecobiome, we created a new eIVC division *D338 Pacific Coast Temperate Rainforest*, under which we placed the existing macrogroup *M024 North Pacific Coastal Rainforest* and its component groups, alliances, and associations. The rainforest ecobiome and mid-level types are shown in Table 7; rainforest groups are mapped in Figure 6.

DISCUSSION

Fundamental improvements to EcoVeg and the eIVC typology

A terrestrial biome approach to vegetation classification

Our revisions to the EcoVeg approach and the IVC fully implement the concept of biomes (a process already initiated in Faber-Langendoen et al., 2020), informed by the

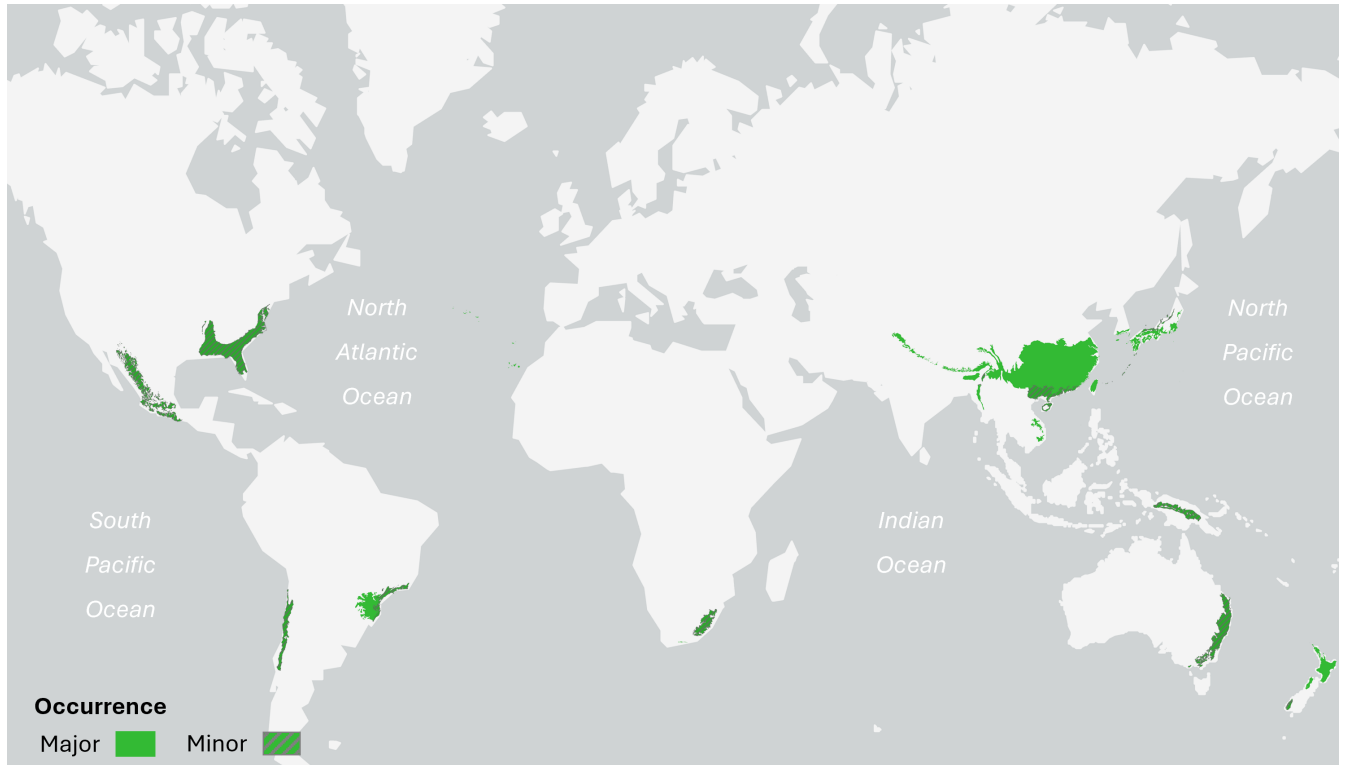


FIGURE 5 Distribution map of Global Ecosystem Typology (GET) T2.4 Warm temperate laurophyll forests map/eIVC TT2.a1 *Warm Temperate Evergreen Forest & Woodland*. Figure is adapted from available map data on the Global Ecosystem Typology website (<https://global-ecosystems.org/explore/groups/T2.4>). See also Keith et al. (2022).

TABLE 5 Summary of key differences between the ecosystem-based International Vegetation Classification (eIVC) L3 ecobiome types and Global Ecosystem Typology (GET) L3 Ecosystem Functional Group types, showing eight types that do not have clear correspondence between the two typologies (details in Appendix S5).

eIVC L3 Ecobiome	GET L3 Ecosystem Functional Group
TT1.b2 <i>Tropical Thorn Woodland</i>	No direct equivalent in GET; but overlaps with T5.2 and T1.2
TT2.b3 <i>Temperate Continental Conifer Forest & Woodland</i>	GET largely combines eIVC TT2.b3 <i>Temperate Conifer Forest & Woodland</i> and TT2.c1 (<i>Boreal Forest & Woodland</i> in GET T2.1 <i>Boreal and temperate high montane forests and woodlands</i> . But temperate high montane is rather expansive and, apart from temperate subalpine forests, differs in ecosystem functions and traits from boreal forest. But in Europe, the Central European subalpine conifer forests with <i>Picea abies</i> are often treated as part of Boreal Forest Some lower montane expressions of eIVC TT2.b3 may also be tracked as GET T4.4 Temperate woodlands
No direct equivalent. eIVC treats temperate woodlands in the context of closely related forests, for example, in TTa2, TT2.a3, TT2.a4, TT2.a6. Relationship needs further review.	T4.4 <i>Temperate woodlands</i>
TT4.c1 <i>Boreal Shrubland & Grassland</i>	No equivalent in GET but see T6.3, and maybe T3.3 in warmer parts of boreal
TT7.c1 <i>Derived Field</i> . The eIVC treats this narrowly as fallow lands, whereas old fields are treated as ruderal (novel) ecosystems and placed in ecobiomes with related native grassland and shrubland.	T7.5 Derived seminatural pastures and oldfields
TP1.b3 <i>Inland Salt Marsh</i>	No equivalent but associated with F2.7
TP2.a1 <i>Coastal Freshwater Shore & Dune</i>	No equivalent
TP3.a1 <i>Developed Freshwater Shoreline</i>	No equivalent

structure of the GET. This revision aligns the eIVC with biome concepts that are perhaps the most widely agreed units of ecosystem classification among ecologists who apply large-scale ecosystem concepts. A perusal of college Ecology textbooks will invariably include a section on Biome types (e.g., Bowman & Hacker, 2021), and there is now an Encyclopedia of World Biomes (Goldstein & DellaSala, 2020). Biome concepts provide insights into some of the most basic global relationships between vegetation, climate, and other physical factors and disturbances. As Bowman and Hacker (2021) put it “...we will use the biome concept to introduce the amazing diversity of terrestrial life.” Documenting the patterns of this amazing diversity has long attracted interest in biome-related concepts, from von Humboldt (1806) to the present (Mucina, 2018). Our revisions enhance the ability of the EcoVeg approach that underlies the eIVC to

provide a comprehensive global accounting of the world's terrestrial ecosystems, from global biomes to local plant communities. Our multi-scaled approach to defining terrestrial biomes (Table 2) is in line with widely used definitions of terrestrial biomes, such as those of Garnier et al. (2016) (“A grouping of terrestrial ecosystems that are similar in vegetation structure and physiognomy, in the major features of the environment to which this structure is a response, and in some characteristics of the animal communities”) and Mucina et al. (2024) (“A large-scale ecosystem sharing a similar climate and large-scale natural disturbance regime (at finer biome scales also some geologic-pedological and hydrological conditions) resulting in a high similarity of vegetation physiognomy”). The GET definition of biome is more general, as it encompasses biome concepts for terrestrial, freshwater, marine, and subterranean realms.

The eIVC now includes all terrestrial areas, with uplands (terrestrial) separated from freshwater and coastal saline wetlands. Our biome-based approach is widely shared with other ecologically based vegetation classifications (e.g., Barbour et al., 2007; Barbour & Billings, 2000; Brown et al., 1998; Edinger et al., 2014; Keith, 2017; Minnesota Department of Natural Resources, 2005; Mucina et al., 2016; Thompson et al., 2019).

The eIVC and the GET incorporate the role of humans in affecting and creating ecosystem types. This is in line with most approaches to ecosystem concepts, where human processes have the potential to create new ecosystem types, including agricultural, urban,

TABLE 6 Relationship between Ecobiomes of the ecosystem-based International Vegetation Classification (eIVC) to the Ecosystem Functional Groups of the Global Ecosystem Typology (GET).

Relationship	Number (%)
E (eIVC and GET equivalent)	37 (71%)
F (eIVC finer)	4 (8%)
B (eIVC broader)	3 (5%)
I (intersects or uncertain)	4 (8%)
New	4 (8%)
Total	52

TABLE 7 Illustration of the linkage between upper and mid-levels of the ecosystem-based International Vegetation Classification (eIVC) types (codes and names) and the equivalent types (in brackets) of the Global Ecosystem Typology (GET) (GET units not available for L2, L4–L6).

L1	L2	L3	L4	L5	L6	G-rank	RLE
TT2 Temperate-Boreal Forest & Woodland [GET T2 Temperate-boreal forests and woodlands]							
TT2.b Temperate Forest & Woodland [GET no equivalent]							
TT2.b2 Oceanic Cool Temperate Rainforest [GET T2.3 Oceanic cool temperate rainforests]							
D338 Pacific Coast Temperate Rainforest							
M024 North Pacific Coastal Rainforest							
					G235 Coastal Redwood Forest	G3?	VU
					G240 Coastal Douglas fir—Western Hemlock Rainforest	G3?	VU
					G241 Coastal Silver fir—Western Hemlock Rainforest	G4G5	NT
					G751 Coastal Western Hemlock—Sitka Spruce Rainforest	G3?	VU
					G237 Coastal Red Alder—Bigleaf Maple—Douglas fir Rainforest	G4G5	NT
					G750 Coastal Alaskan Western Hemlock—Sitka Spruce Rainforest	G4G5	NT

Note: L1, Biome; L2, Subbiome; L3, Ecobiome; L4, Division; L5, Macrogroup; L6, Group. G-rank is the Global Rank status of ecosystems from NatureServe's Conservation Status Assessment, where G3 is Vulnerable and G4G5 is Apparently Secure to Secure (Master et al., 2012). RLE is the Red List of Ecosystems (RLE) status (adapted from Comer, Hak, & Seddon, 2022), where VU is Vulnerable and NT is Near Threatened.

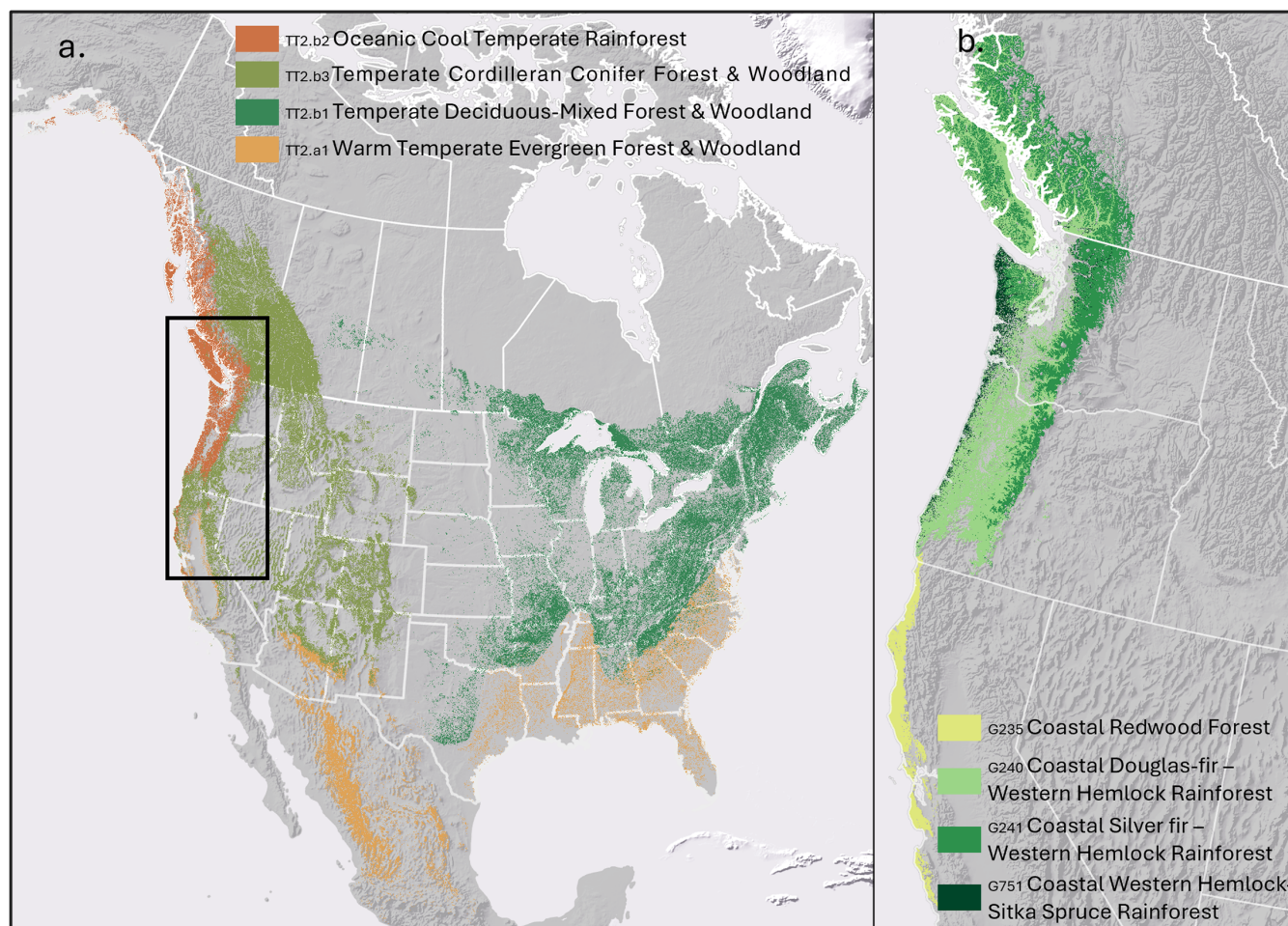


FIGURE 6 Mapping the ecosystem-based International Vegetation Classification (eIVC). (a) Mapping of the four eIVC temperate forest ecobiome units in North America, with an inset box for location enlarged in panel b. (b) Mapping of eIVC group types within the *TT2.b2 Oceanic Cool Temperate Rainforest* ecobiome. Maps produced by Hannah Ceaser, building on map products in the US from the LANDFIRE program and in Canada from forest cover maps of the Canadian Space Agency, guided by the vegetation zones of Baldwin et al. (2021).

and novel ecosystems alongside forest, grassland and wetland ecosystems (Hobbs et al., 2013). Human influences on ecosystem processes and properties are pervasive. We navigate this issue by conceptualizing biome types on one hand that are largely created and sustained by human activity, and on the other those that retain characteristic processes and properties shaped primarily by nonhuman drivers, even as these may be altered to varying degrees by human activity (Ellis et al., 2021). Because humans may profoundly impact all critical processes that shape ecosystems, it is appropriate to develop distinct ecosystem concepts for them. This focus on existing ecosystems was articulated by Tansley's (1935) foundational paper on ecosystems, in which he stressed "We must have a system of ecological concepts which will allow for the inclusion of *all* forms of vegetation expression and activity. We cannot confine ourselves to the so-called 'natural' entities and ignore the processes and expressions of vegetation now so abundantly provided by the activities of

man. Such a course is not scientifically sound..." Indeed, one could hardly describe the biotic interactions occurring in an ecosystem without a focus on existing ecosystems. Thus, within the eIVC and GET approaches, ecosystem boundaries are dynamic at multiple levels; it is the interaction of humans with other ecological processes that often leads to potential ecosystem collapse or restoration, as documented by the IUCN Red List of Ecosystems assessment (Keith et al., 2013) and NatureServe's Conservation Status Assessments (Master et al., 2012; NatureServe, 2023). And ultimately, humans help create novel ecosystems (Hobbs et al., 2013). That said, linking these existing ecosystem concepts to the wide variety of potential or predictive models of ecological sites provides a means for placing current ecosystems in the context of historical and potential vegetation models at multiple scales, from biomes (Loidi et al., 2022) to ecological sites (Bestelmeyer & Brown, 2010). In addition, ecological land classifications and geo-ecosystem approaches help

place these ecosystem types in a spatial-ecological gradient perspective (e.g., Bailey, 1996; Navarro et al., 2023).

Conceptual model

Because of the shared biome approach of the eIVC and GET, we find the conceptual model used by GET to be very helpful (Keith et al., 2022). That model covers all realms; thus, with the terrestrial focus of the eIVC, we modify it to focus more directly on terrestrial vegetation and ecosystem processes and properties (Figure 7). The

model is a substantial shift in emphasis from the earlier IVC model (Figure 1) in that the ecological processes are more clearly identified, vegetation attributes relevant to ecosystem properties more fully described, and the role of human activity is explicit across all realms, including the impact on other ecological processes. Even though animals typically provide secondary properties for how terrestrial biomes are classified, they are often very important drivers (e.g., see GET T4.1 *Trophic savannas* and both GET MT2.2 and eIVC MS2.a2 *Large Seabird & Pinniped Colony*) (see also Brown, 1982; Kolstad et al., 2018).

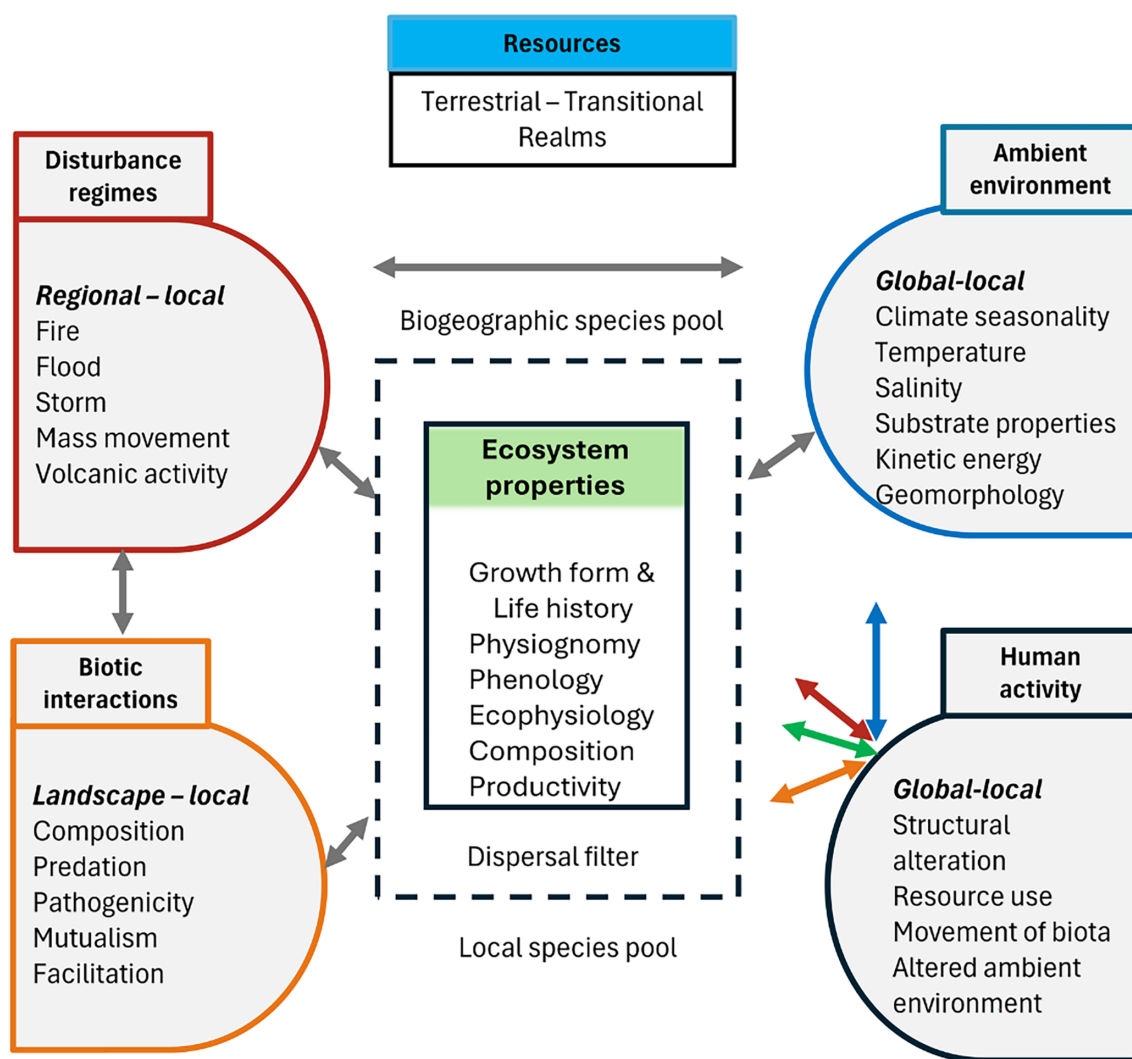


FIGURE 7 The general conceptual model for the ecosystem-based International Vegetation Classification (eIVC). The model is adapted for terrestrial ecosystems from the all-realms model of Keith et al. (2022). The outer boxes represent abiotic and biotic drivers that filter species assemblages and form evolutionary pressures that in turn shape ecosystem level properties. The range of scales at which the drivers operate is shown in each box. The species pool provides the available life history traits on which the processes operate over short (ecological) and long (biogeographical/evolutionary) time. The dashed box represents both the contemporary dispersal filter that mediates the biota affected by current processes and the long-term biogeographic filter, reflecting the interplay of ecology and biogeography on ecosystem patterns. Arrows show the interactions between biotic and abiotic drivers and the ecosystem properties, with the potential for human activity to override the other drivers.

L1–L3 biome levels

Our revisions to the IVC led to substantial congruence between the eIVC and GET (Figure 3). There are only minor differences between eIVC L1 Biome and GET (L2) Biome (Table 4). At the same time, the inclusion of IVC L2 Subbiome, not available in GET, provides a bridge to many other biome classifications (e.g., Whittaker, 1975), as illustrated by the comparison with the biomes and subbiomes of Loidi et al. (2022) in Appendix S4.

At Level 3, the eIVC ecobiome and GET Ecosystem Functional Group largely converge (Table 6). The revised eIVC L3 is now better organized in relation to both growth forms and functional traits. The incorporation of functional traits by the eIVC is typically implicit in the use of realms and biomes, for example, eIVC TP1.b3 *Inland Salt Marsh* is distinguished from both inland freshwater marshes (TP1.a2 Marsh, Wet Meadow & Shrub Wetland) and coastal salt marshes (MB1.a3 *Coastal Saltmarsh & Reedbed*) based on the different ecological drivers (tidal versus nontidal, desert drought conditions). Currently, the GET describes types more clearly based on the role of assembly rules, functional traits, and trophic structure, following its conceptual model, whereas the eIVC is more descriptive, focusing on the global and continental variation in patterns that are core to how the types are classified.

At L3, there is still much to learn about the role of functional traits in guiding terrestrial ecosystem classification. Functional traits are often expressed as growth forms such that the eIVC incorporates them into the classification process, but by no means includes all those that are relevant to community assembly (e.g., seed germination traits feature in the assembly models of some ecosystem functional groups at L3 of GET; Keith et al., 2022). Our knowledge of functional traits needs further surveys; we are still far from understanding their diversity across all ecosystems of the world (Loidi, 2018). In addition, functional traits of ecosystems can be expressed at multiple scales and can also be studied in relation to compositional patterns at GET and eIVC L5 and L6 (Garnier et al., 2016; Keddy & Laughlin, 2022; Standen & Baltzer, 2022); that is, functional groupings are intertwined with compositional ones at these lower levels.

L4 division and biogeography

The eIVC and GET differ most strongly at L4—the eIVC Division and the GET Regional ecosystem subgroups. This is because GET provides two alternative pathways

for defining compositionally based types (see Figure 3). On the one hand, it proposes to integrate nationally defined compositional types being developed at L6, scale them up to L5 types, which can then be aggregated directly into the L3 Ecosystem Functional Groups (see section below: eIVC macrogroup and Group and the Level 5 and 6 types of GET). Alternatively, recognizing that the development of national units is very uneven, GET provides a top-down solution to populate L4 with compositional variants of L3 Ecosystem Functional Groups based on appropriate biogeographic spatial units as compositional proxies (e.g., Leal & Spalding, 2024; Tóth et al., 2025). Both pathways implement a strongly deductive approach to defining units.

The eIVC takes a different approach to the development of L4 types by developing peer-review-based units iteratively between L4 and other levels, with formal nomenclature, description, publication, and integration into the hierarchy. The L4 division level was adapted from the Braun-Blanquet approach, and it defines units based on biogeographically shared species, growth forms, and ecological processes (Willner & Faber-Langendoen, 2021). Stepping down from L3, the division concept introduces the compositional criteria by which the upper level biome types can be subdivided by continental scale biogeographic species pools. In turn, shared growth forms and other functional traits among division types, which reflect a set of shared climatic and edaphic factors, lead to their placement within the same eIVC L3 formation. For example, we can step down from the L3 formation *TT2.a4 Temperate Deciduous-Mixed Forest & Woodland* by relying on both ecoregions and biogeography, which leads to three (long recognized and biogeographically separated) divisions of this formation in the northern hemisphere: the *Western Eurasian Cool Temperate Forest & Tall Scrub* division in Willner and Faber-Langendoen (2021), the *Eastern North American Forest & Woodland* division in Faber-Langendoen et al. (2018), and a comparable temperate forest division in Eastern Asia, each found in a cluster of ecoregions on those continents (Loidi & Marcenò, 2022). From there, the lower L5 and L6 units (Braun-Blanquet classes and orders and eIVC macrogroups and groups) are available. Similarly, the compositional analyses of DRYFLOR (2016) anchor the biogeographical L4 division concepts of neotropical dry forests that are aggregated into the L3 eIVC *TT1.b1 Seasonally Dry Tropical Forest & Thicket* (Faber-Langendoen et al., 2018).

Recent debates about the role of biogeography in defining biomes and ecosystems (Mucina, 2018, 2024; Proches, 2020) reflect some long-standing differences between approaches that emphasize the

“historical-floristic” perspective versus the “environmental constraints and ecological relations” perspective (Box & Fujiwara, 2005). As with Mucina (2024), we suggest that both perspectives are needed, with the eIVC L4 division level giving some additional weight to the historical-floristic/biogeographic perspective. In this way the knowledge gained from biogeographic patterns informs our understanding of how functional traits of a biome may be constrained by historic factors (Lehmann et al., 2014; Moncrieff, Scheiter, et al., 2016; Smith et al., 2018).

Past applications of the IVC have already shown the merits of the Division level as both a useful stepdown from global biomes/large-scale ecosystems to “continental scale biomes/mid-scale ecosystems” (Dixon et al., 2014; Faber-Langendoen et al., 2018; Willner & Faber-Langendoen, 2021). The eIVC incorporates over 20 years of developing IVC L4 types within which L5 and 6 types are nested (see Faber-Langendoen et al., 2018). Interpretation of eIVC L3 formation/ecobiome types is grounded in the details of the lower levels (see also Appendix S6). Thus, the eIVC emphasizes both a top-down and a bottom-up approach for L4, distinct from the top-down deductive approach of GET.

L5 Macrogroup, L6 Group, and GET

At L5 and L6, the eIVC and GET provide comparable approaches. But, whereas the GET has not yet populated L5 as a set of global assemblages based on locally/nationally derived types, the eIVC has already defined these regional ecosystems across the Americas, Africa, and in collaboration with the Braun-Blanquet types in Europe. Given that 375 terrestrial (including wetland) macrogroups have been described for the Americas, which represent 31.1% of the land area of the globe, Faber-Langendoen et al. (2020) estimated that close to 1200 macrogroups may exist. There is great potential for GET to leverage this work in populating L5 and L6 for the terrestrial realm. Doing so would greatly enhance national and international collaboration at both these mid-scales and finer scales (L7 alliance, L8 association), and thereby provide a shared set of finer resolution global units in eIVC and GET. These mid-level units can serve as standard types that guide conservation assessments, such as Key Biodiversity Areas (Dobrowski et al., 2021) and Red Lists of Ecosystems (Ferrer- Paris et al., 2019), as well as help set templates for ecological restoration, where knowledge of function, structure, and composition are needed (McDonald et al., 2016).

Biota and the eIVC

Animals are rarely used directly to classify terrestrial ecosystems because, as noted above, plants have a much stronger influence on terrestrial ecosystem properties. However, the ecological drivers that distinguish some of the biomes and formations at eIVC L3 often separate out important variation in animals, such as the marine coastal versus palustrine inland salt marshes. The division level further amplifies those distinct animal assemblages, for example, Great Basin inland salt marshes versus Sonoran or Asian inland salt marshes. Similarly, as noted above, the L3 *TT2.a4 Temperate Deciduous-Mixed Forest & Woodland* formation is subdivided at L4 into eastern North American, western European, and east Asian divisions, each of which has broadly distinct bird assemblages (Campbell et al., 2021). Currently, these relationships are largely implicit in the eIVC types at L4, but to express this relationship, the eIVC divisions are also organized by the biogeographic realms of Olson et al. (2001), a feature we retain from the IVC. At L5 and L6, relationships between eIVC types and animal species are increasingly documented, and the role of animals in shaping ecological processes is factored into NatureServe’s ecological integrity assessments of eIVC types (Faber-Langendoen et al., 2016). Indeed, modeling of ecosystems as habitats in relation to endangered plant and animal species is an important tool for effective conservation of multiple endangered species that depend on the same ecosystem (Noss et al., 2021).

International, national, and local collaboration

Collaboration with the international community of ecologists is a critical need if the description and classification of ecosystems are to have an impact, both scientifically (such as a better understanding of the assembly rules and ecological drivers that shape ecosystems) and operationally (i.e., seeking consensus on data collection and description that help refine and improve our ecosystem classification) and for conservation and resource management applications. Thus, working with active research communities in Europe (European Vegetation Survey), in North America (partners of the CNVC, USNVC), in Latin America (Vegetation of Bolivia, Chilean vegetation classification), Africa (South African National Biodiversity Institute), Australia (Australian National Vegetation Classification), among others, will lead to robust development and application of GET and eIVC in the terrestrial realm. In addition, as these partnerships grow, the

opportunity to compile data to explore the identity and dynamics of ecosystems at multiple scales can grow. In this regard, the development of s-PLOT by Bruelheide et al. (2019) and its ability to link plots to large-scale ecosystem concepts, such as biomes and formations, is an exciting step in that direction (Appendix S7).

Enhancing mapping at all scales

Both the eIVC and GET recognize that a classification of ecosystems is a distinct activity from mapping ecosystems. Maps need to be an expression of a classification because the spatial data available to construct maps often lacks the required complement of compositional, functional, and ecological properties needed to classify ecosystems. Both the eIVC and the GET provide a classification structure for mapping existing biomes (the “functional biomes” of Champreux et al., 2024) that can guide global to local mapping efforts, without constraining the classification by what is mappable from a given set of mapping technologies or map layers. Examples of such mapping products are now available, for example, the Global Ecosystems Atlas (<https://globalecosystemsatlas.org/>) is using the GET Biomes and Ecosystem Functional Groups to guide compilation of maps across the globe, and the IVC has effectively guided mapping of macrogroups and groups across tropical and temperate North America (Comer et al., 2020; Comer, Hak, Dockter et al., 2022; see also Figure 5). Decoupling classification and mapping into separate steps also enables maps to be updated without perturbing the classification structure. Mapping approaches and input data can thus be selected and revised at any time, where capability is defined by current technology and data availability, to maximize the ability to capture spatial patterns in the essential properties of the ecosystems described by the GET and the eIVC.

Hierarchies and ecological gradients

Finally, we highlight the limits of a hierarchical structure in describing ecosystem diversity along environmental gradients. The eIVC and GET seek to hierarchically organize ecological gradients and shared ecological properties. However, hierarchies only partially account for the relationships among types along underlying ecological gradients. An alternative or complement to a hierarchical approach is to explore relationships among ecosystems with gradient analyses. Whittaker (1975, fig. 4.10) famously portrayed climatic envelopes of terrestrial biome types with precipitation and temperature

gradients. A notable feature of his gradient analysis was that it recognized uncertainty in climate envelopes (Bond, 2019) such that more than one biome type could occur within the same climatic envelope. Closed forests, savannas, grasslands, and shrublands could occur as mosaics or be distributed along other unaccounted for finer scale gradients in the same region. We now know that these boundaries are fluid, being mediated by factors such as fire regimes, soil nutrients, or grazing. To account for continuous variation in ecosystems, the eIVC and GET consider biomes to be “biome gradient concepts.” Still, balancing the explanatory power of types arranged within a hierarchy as compared with using ecological gradients remains challenging.

Characterizing ecosystem diversity using gradient analyses has robust theoretical justification (Halvorsen et al., 2020). At local to regional/national scales, ecologists have shown relationships among types based on species composition using a variety of gradient analytic tools, including edatopic grids (MacKenzie & Meidinger, 2018), multivariate ordination, and various gradient analyses (Austin, 2013). But, as Halvorsen et al. (2020) also point out, a major obstacle to gradient analyses at continental to global scales arises when differences among species pools and their adaptations can cause sites with similar edaphic conditions to greatly differ from each other. A second major obstacle noted by Halvorsen et al. is that ecologists are challenged by the lack of systematic biodiversity data and our lack of understanding of ecological gradients across the globe. They further note that “ecological complexity increases in a nonlinear manner toward broader spatial and temporal scales.” To help overcome these two obstacles, the eIVC and GET hierarchies first account for ecosystem diversity using a variety of ecosystem properties that can reflect responses to environmental gradients, including species composition, functional traits/life histories and growth forms. Secondly, the eIVC and GET use available global data on ecosystem properties as reflected in biome concepts to characterize types.

That said, there are ways to continue exploring ecosystem diversity using both hierarchical and gradient approaches. Among the nine principles of the EcoVeg approach (Faber-Langendoen et al., 2014, see also Appendix S1), the first five take priority, including principle 5—differentiate types with specific criteria along gradients. Characterizing the ecological drivers that shape ecosystems along ecological gradients enhance the explanatory power of ecosystem classifications. Whittaker (1975), in addition to describing 36 biome types around the globe, used gradient analysis (“major ecoclines”) to relate these biomes to global geographic-climatic drivers (e.g., from South American

tropical lowland rainforests to high montane paramo). The challenge is to find a practical way to link hierarchies and gradients to repeatedly test the effectiveness of a typology. Locally and regionally, this can be done using edatopic grids, direct gradient analyses, and ordination graphs. Regional ecoclines can be developed by characterizing ecosystem gradients within and across ecoregions (Dixon et al., 2014). Navarro et al. (2023) demonstrate an achievement in this direction with a graphic zonation model characterizing ecosystem patterns across landscapes within biogeographic provinces of South America. Rather than focusing on the hierarchical arrangement of ecosystems, the method displays ecosystem relationships along transects (e.g., their “Lowland and montane evergreen guyanan forest & shrubland geocomplex”). Together, hierarchical and gradient approaches can enhance our understanding of the drivers of ecosystem diversity.

CONCLUSIONS

The reworking of the EcoVeg approach and the eIVC in line with the GET has improved the linkage between vegetation and ecological processes. On the one hand, narrowing the focus of the eIVC to the terrestrial realm (including the wetland terrestrial-transitional realms) is appropriate given that vegetation plays a primary role in structuring most terrestrial ecosystems. At the same time, expanding the eIVC to cover all terrestrial areas ensures that it provides a comprehensive classification structure conducive to assessing all terrestrial ecosystems (Faber-Langendoen et al., 2020; Rounce et al., 2023). A summary of the entire revision to the biome levels of the eIVC hierarchy is provided in Appendix S8.

Over time, we hope that both the GET and eIVC can be informed by and help inform both top-down deductive approaches that synthesize global ecosystem processes and properties and bottom-up inductive approaches that bring together data-rich information on composition, ecology and biogeography. As noted in the introduction, the goal of the eIVC and GET is not to develop a single authoritative system but to build reliable (interoperable) relationships between various global to local classifications such that we facilitate information exchanges at multiple scales. These approaches and expected outputs can strengthen efforts to implement a consistent approach to the calculation of status and trends in ecosystem extent, where nations that are Party to the UN Convention on Biological Diversity, are now responsible for tracking trends in extent of natural ecosystems (such as the 2022

“Monitoring framework for the Kunming-Montreal Global Biodiversity Framework”). While countries are free to use their own classifications, it is important that cross-referencing is feasible to ensure meaningful aggregations of ecosystem data for regional and global assessments.

AUTHOR CONTRIBUTIONS

All authors participated in the meetings of the IVC Formations Work Group, contributed to the revised IVC structure and draft manuscripts, and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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