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CLASSIFICATION OF GLOBAL ENVIRONMENTAL SYSTEMS ACCORDING TO THE LEVEL OF ANTHROPOGENIC TRANSFORMATION

Klasifikace globálních environmentálních systémů dle stupně antropogenní transformace

Doctoral thesis

Supervisor: RNDr. Dušan Romportl, Ph.D.

Prague, 2024

Prohlašuji, že jsem předloženou disertační práci zpracoval sám a že jsem uvedl všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyly předloženy k získání jiného nebo stejného akademického titulu.

V Praze dne 29. 8. 2023 ....……...........................

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Abstract

The topic of the doctoral thesis is the development of a comprehensive classification of global environmental systems based on a geographical synthesis of abiotic, biotic and anthropogenic factors. The dramatic changes in the Earth's natural environment, the noticeable loss of biodiversity and the increasing impact of human activity in many different aspects raise the need for a comprehensive classification that provides an appropriate spatial framework for assessing the impacts of these changes.

Several global classifications have been developed in the past, but most of them only work with various natural environmental gradients (especially climate or relief). However, most regions of the world have been so fundamentally affected or even completely transformed by human activity that the omission of anthropogenic factors in comprehensive environmental classifications may lead to erroneous conclusions. For this reason, new global environmental classifications have recently begun to emerge abroad that attempt to deal with anthropogenic changes to the natural environment and include them in a comprehensive assessment. The proposal of a methodology and the actual creation of the classification of global environmental systems based on abiotic gradients, biodiversity distribution and spatial differentiation of human influence is the main objective of the presented thesis. The classification is based on 22 datasets characterising abiotic, biotic, and anthropogenic factors. These factors include climatic conditions, relief characteristics, species richness of fauna and flora, land cover, population density, intensity of agricultural use, etc.

The input abiotic rasters underwent a principal component analysis (PCA) as a first step. The resulting multiband raster was subsequently subjected to a segmentation process which, after further modifications, resulted in a layer of 18,554 segments. The values of all abiotic, biotic and anthropogenic indicators were calculated for each segment, as well as the land cover was analysed for each segment. The next step was to perform a cluster analysis resulting in three classifications of abiotic, biotic and anthropogenic conditions, each with ten classes. The abiotic and biotic classifications were synthesised to form the classification of natural conditions, and its subsequent combination with the anthropogenic classification resulted in the final global environmental systems classification, comprising a total of 169 global environmental systems classes.

The distribution of biodiversity is significantly affected by global anthropogenic environmental transformation. The concept of biodiversity hotspots captures biodiversity gradients, as well as the degree of threat and the urgency of conservation. Biodiversity hotspots are regions where large numbers of often endemic species face enormous losses of their original habitat due to intensive human activities. The different sub-classifications – abiotic, biotic and anthropogenic – as well as the final classification of global environmental systems were analysed for each of the 36 biodiversity hotspots and for the hotspots as a whole. The results indicate that globally important hotspot areas are more threatened by various types of human activity than the rest of the world. Additionally, the most valuable biodiversity hotspots are currently experiencing significant anthropogenic impacts.

Key words: classification, anthropogenic transformation, global environmental systems, biodiversity hotspots

Abstrakt

Tématem disertační práce je vytvoření komplexní klasifikace globálních environmentálních systémů založených na geografické syntéze abiotických, biotických i antropogenních faktorů. Zásadní změny přírodního prostředí Země, znatelný úbytek biodiverzity a v mnoha různých ohledech stále rostoucí vliv člověka vyvolávají potřebu vytvořit komplexní klasifikaci, která bude vhodným prostorovým rámcem pro vyhodnocování dopadů těchto změn.

V minulosti vznikla celá řada globálních klasifikací, které však většinou pracují jen s různými přírodními gradienty prostředí (zejména klima či reliéf). Většina regionů světa je však natolik zásadně ovlivněna nebo dokonce zcela přeměněna činností člověka, že opomenutí antropogenních faktorů v komplexních klasifikacích prostředí může vést k mylným závěrům. Z tohoto důvodu v nedávné době začaly v zahraničí vznikat nové globální environmentální klasifikace, které se snaží s antropogenními změnami přírodního prostředí pracovat a zahrnout je do komplexního hodnocení. Návrh metodiky a vlastní vytvoření klasifikace globálních environmentálních systémů, která je založena na abiotických gradientech, distribuci biodiverzity a prostorové diferenciaci vlivu člověka, je hlavním cílem předložené práce. Klasifikace vychází z 22 datasetů charakterizujících abiotické, biotické a antropogenní faktory, jako například klimatické poměry, charakteristiky reliéfu, druhového bohatství fauny i flory, krajinného pokryvu, hustoty zalidnění, intenzity zemědělského využívání prostředí atd.

Nejprve byla na základě vstupních abiotických rastrů provedena analýza hlavních komponent (PCA). Vzniklý vícepásmový rastr prošel následně procesem segmentace, jejímž výsledkem byla po dalších úpravách vrstva čítající 18 554 segmentů. Hodnoty všech abiotických, biotických a antropogenních ukazatelů byly stanoveny pro každý jednotlivý segment, stejně tak byl pro každý segment analyzován krajinný pokryv. Dalším krokem bylo provedení clusterové analýzy, jejímž výsledkem byly tři klasifikace abiotických, biotických a antropogenních poměrů, každá o deseti třídách. Syntézou abiotické a biotické klasifikace vznikla klasifikace přírodních podmínek, její následnou kombinací s antropogenní klasifikací pak finální klasifikace globálních environmentálních systémů čítající celkem 169 tříd globálních environmentálních systémů.

Důležitou sférou, které se globální antropogenní transformace prostředí významně dotýká, je rozložení biodiverzity. Její gradienty, ale i míru ohrožení a naléhavost ochrany dobře vystihuje koncept tzv. horkých skvrn biodiverzity. Horké skvrny biodiverzity jsou oblastmi, kde velká množství často endemických druhů čelí enormním ztrátám rozlohy původního habitatu vlivem intenzivní lidské činnosti. Jednotlivé dílčí klasifikace - abiotická, biotická a antropogenní, stejně jako finální klasifikace globálních environmentálních systémů byly analyzovány pro každou z 36 horkých skvrn biodiverzity i pro horké skvrny jako celek. Z výsledků vyplývá, že celosvětově významné oblasti hotspotů jsou více ohroženy různými druhy lidské činnosti než zbytek světa a taktéž, že nejcennější horké skvrny biodiverzity čelí zásadnímu antropogennímu vlivu.

Klíčová slova: klasifikace, antropogenní transformace, globální environmentální systémy, horké skvrny biodiverzity

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1. Introduction

The Earth’s natural environment is naturally divided into specific zones. These have been classified in many different ways in the past. In 1949, Allee presented biome types (Allee et al., 1949), in 1961, Kendeigh came up with different terrestrial and marine biomes (Kendeigh, 1961), later Whittaker presented a classification of biome types (Whittaker, 1975), and Goodall edited a book on ecosystem types or biomes: terrestrial, aquatic and underground (Goodall, 1977). In the not so distant past, Schultz created the classification of eco-zones (Schultz, 1988) and Bailey developed a biogeographical classification system of ecoregions (Bailey, 1989). In 1998, Olson and Dinnerstein presented biogeographic realms and biomes (Olson and Dinnerstein, 1998; Olson et al., 2001). All of these classifications have been primarily driven by key abiotic environmental gradients, such as climate, topography, or productivity. They have not taken into account the increasing human domination of Earth's systems.

People have been changing ecosystems and their processes for a very long time (Goudie, 2013), the first evidence of such activity is over 3 million years old (Gosden, 2003). The Technological-Scientific Revolution was an important milestone, the development of modern industrial and urban civilizations enabled global ecosystem changes (Takács-Sánta, 2004; Goudie, 2013). Environmental issues that used to be local are becoming issues of regional or global importance (Hoekstra et al., 2010; Goudie, 2013; Ruddiman, 2013). Currently, nature and the natural environment are undergoing a major crisis on a global scale and the number of ways in which humans are affecting the environment is multiplying (Vitousek et al., 1997). Landscape fragmentation, climate change, pollution, natural resource use, invasive species, intensification of land use and significantly increasing anthropogenic pressure are eroding biodiversity, causing loss of ecosystems and species, and changing nature on a global scale (Newbold et al., 2015; Díaz et al., 2019; Di Minin et al., 2022). The 20th century was an epoch of very exceptional change (McNeill, 2003) and the current period is called by some scientists as the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002; Steffen et al., 2011; Waters et al., 2016). At least 75% of the Earth’s land surface is experiencing measurable human pressures (Venter et al., 2016; Williams et al., 2020; Ellis et al., 2021). Human interventions are increasingly complex and extensive. According to WWF, the ecological footprint has doubled in just under 50 years at the turn of the 20th century (Sanderson et al., 2006; WWF, 2010; Goudie, 2013). Therefore, several global classifications were presented in recent years to reflect the intensity of human influence covering a wide range of aspects of anthropogenic transformation of the natural environment.

Ellis and Ramankutty presented a global classification of anthropogenic biomes based on an empirical analysis of direct human-nature interaction in 2008. Just two years later, Ellis et al. presented a slightly different classification of anthromes. Letourneau et al. proposed a new classification based on land-use systems, which express specific combinations of interactions between the natural environment and humans. In the same year Van Asselen and Verburg came up with the classification of land systems. In 2013, Václavík et al. proposed a new approach for representing human-environment interactions and created a classification of land system archetypes. In 2020, Sayre et al. described a new map of terrestrial world ecosystems, where no socioeconomic data were used in the classification, and Keith et al. created a hierarchical classification: The IUCN Global Ecosystem Typology (Ellis and Ramankutty, 2008; Ellis et al., 2010; Letourneau et al., 2012; van Asselen and Verburg, 2012; Václavík et al., 2013; Sayre et al., 2020; Keith et al., 2020).

The main objective of this thesis is to develop a new classification of global environmental systems (GES) based on a range of abiotic, biotic, and anthropogenic factors. This dataset is intended to be freely accessible. The results are presented in detail in journal articles, tables and maps. A secondary aim is to analyse the individual sub-classifications and the classification of global environmental systems within biodiversity hotspots as an important concept of nature protection.

2. Scientific background

Anthropogenic transformation of the natural systems is of such great importance in the contemporary world that it is difficult not to include human influence in modern global classifications. Human impact on the natural environment used to be simplified or ignored (Alessa and Chapin, 2008; Ellis et al., 2010), but in recent years new classifications have begun to emerge abroad that include anthropogenic influences, either directly or indirectly. This includes global classifications of anthropogenic biomes, anthromes, land-use systems, land systems, land system archetypes, world ecosystems or global ecosystems (Ellis and Ramankutty, 2008; Ellis et al., 2010; Letourneau et al., 2012; van Asselen and Verburg, 2012; Václavík et al., 2013; Sayre et al., 2020; Keith et al., 2020). The individual classifications differ in their structure, approach, quantity and types of datasets used, resolution, possibilities of use, etc., but all provide a useful tool for exploring a changing world.

2.1. Anthropogenic biomes

Ellis and Ramankutty (2008) presented a classification and a global map of anthropogenic biomes. They used a multi-stage empirical procedure for the identification and mapping of anthropogenic biomes. Global datasets of land use: area of pastures, area of crops (Ramankutty et al., 2008), irrigated area (Siebert et al., 2007) and rice area (Monfreda et al., 2008); land cover: area of trees and bare earth (Hansen et al., 2003); and population (Dobson et al., 2000), which played a primary role in the classification, were used. The resolution of the data is 5 arc minutes. The classification consists of 18 anthropogenic biome classes in five categories (dense settlements, villages, croplands, rangelands and forested) and 3 wild biome classes in one category (wildlands).

2.2. Anthromes

Ellis et al. (2010) used a new anthrome classification algorithm for classifying these variables: population density; urban area, cropland area, pasture area (Klein Goldewijk, 2006) and irrigated area (Siebert et al., 2007); rice cover (Monfreda et al., 2008) and land cover (Ramankutty and Foley, 1999). The new classification has the same resolution, uses the same basic classification levels but the system is slightly simplified. Anthrome levels are aggregated into three categories: used anthromes (dense settlements, villages, croplands, rangelands), semi natural anthromes and wildlands.

2.3. Land-use systems

Specific combinations of interactions between the natural environment and humans resulted in a new classification based on land-use systems by Letourneau et al. (2012). Land-use systems work with the heterogeneity of land cover and land use intensity. The resolution is the same, 5 arc minutes. The input data characterises land cover / land use (bare soil area, tree cover area (Hansen et al., 2003), build-up area (Elvidge et al., 2007), croplands area, pastures area (Ramankutty et al., 2008); crop areas (Monfreda et al., 2008) and irrigated areas (Siebert et al., 2005)), accessibility (Verburg et al., 2011), population density (Dobson et al., 2000) and livestock density (sheep, goats, chicken, pigs, buffaloes, and bovines (FAO, 2007)). A two-step cluster analysis was employed to identify land-use systems, the classification has 24 classes grouped into six categories (densely populated systems, cropland systems, pastoral systems, mosaic systems, forested systems, and bare soil systems).

2.4. Land systems

In the classification of land systems by van Asselen and Verburg (2012) the land-use intensity plays a crucial role. Land cover (tree cover and bare soil cover (Hansen et al., 2003), cropland cover (Ramankutty et al., 2008), built-up area (Schneider et al., 2009)), livestock (FAO, 2007) and agricultural intensity data (Neumann et al., 2010) were used for classification, population was not used at all. All the input datasets were transformed into a spatial resolution of 5 arc-minutes. Van Asselen and Verburg used a hierarchical procedure for the classification and delineation of land systems, which comprise a total of 30 different classes in eight categories (cropland systems, mosaic cropland and grassland systems, mosaic cropland and forest systems, forest systems, mosaic (semi-)natural systems, grassland systems, bare systems, and settlement systems).

2.5. Land system archetypes

Václavík et al. (2013) proposed a different approach for representing human-environment interactions. They used a bottom-up approach driven by the data, which is a difference from previous classifications. Global land system archetypes are defined as unique combinations of land-use intensity (cropland and pasture data (Klein Goldewijk et al., 2011) and their trends, irrigation (Siebert et al., 2007), soil erosion (van Oost et al., 2007), use of N fertiliser (Potter et al., 2010), yields and yield gaps for wheat, maize and rice (IIASA/FAO, 2012), total production index and the human appropriation of net primary production (Haberl et al., 2007)), environmental conditions (5 bioclimatic variables (Kriticos et al., 2012), climate anomalies (Menne et al., 2009), NDVI (Tucker et al., 2005), soil organic carbon (Batjes, 2006) and species richness from the IUCN database), and also socioeconomic factors (population density and its trend (CIESIN, 2005), GDP, GDP from agriculture, the capital stock in agriculture (FAO), political stability (Kaufmann et al., 2010) and accessibility (Uchida and Nelson, 2009)). Václavík et al. (2013) have chosen a higher number of 32 indicators, spatial resolution was the same – 5 arc-minutes. A self-organising map algorithm in R software was used – an unsupervised neural network. The classification of Land system archetypes differs a lot in its structure; there are only 12 classes, which are neither subdivided nor grouped: forest systems in the tropics, degraded forest/cropland systems in the tropics, boreal systems of the western world, boreal systems of the eastern world, high-density urban agglomerations, irrigated cropping systems with rice yield gap, extensive cropping systems, pastoral systems, irrigated cropping systems, intensive cropping systems, marginal lands in the developed world, and barren lands in the developing world.

2.6. World ecosystems

The map of terrestrial world ecosystems (Sayre et al., 2020) was derived from the objective development and integration of global landforms (Karagulle et al., 2017), global temperature domains (Fick and Hijmans, 2017), global moisture domains (Trabucco and Zomer, 2009), and global vegetation and land use (ESA, 2017) at a spatial resolution of 8 arc-seconds. Global temperature domains (tropical, subtropical, warm temperate, cold temperate, boreal, and polar class) and global moisture domains (moist, dry, and desert class) were combined to derive a world climate regions layer of a total of 18 classes. The climate regions data were then combined with a world landforms data layer (mountains, hills, plains, and tablelands), resulting in 72 world climate and terrain settings. Sayre et al. (2020) combined this layer with the world vegetation and land cover data layer (forest, shrubland, grassland, cropland, sparsely or non-vegetated (bare) area, settlements, snow and ice, and water classes) and identified 431 world ecosystems.

2.7. IUCN Global ecosystem typology

(Keith et al., 2020) created this typology as a hierarchical classification with 6 levels. The upper three levels are based on functional variation among ecosystems that are defined by their convergent ecological functions and they are developed from the top-down approach. The lower three levels are based on compositional variation, ecosystems with differing groups of species influencing those ecological functions are defined. The fourth level is developed top-down by division of ecosystem functional groups, the fifth and sixth level facilitate integration of established local classifications into the global framework and use the bottom-up approach. The first level consists of five global realms (terrestrial, subterranean, freshwater, marine, and atmospheric). At the second level, there are 25 biomes ranging from anthropogenic biomes to tropical forests. At the third level, the classification splits into 108 ecosystem functional groups. The fourth level units are called biogeographic ecotypes, level five units global ecosystem types and level six units are known as sub-global ecosystem types.

2.8. Biodiversity hotspots

Biodiversity hotspots are areas with the highest concentrations of endemic species and at the same time they are facing huge loss of natural habitat. The concept of biodiversity hotspots was introduced by the British ecologist Norman Myers in 1988 (Myers, 1988). A year later, the concept was adopted by Conservation International (Mittermeier et al., 1998). To qualify as a biodiversity hotspot, two strict criteria must be met. Firstly, each biodiversity hotspot must contain at least 1500 endemic vascular plant species and secondly, must have lost at least 70 percent of its primary natural habitat. Currently, there are 36 biodiversity hotspots, with the newest one established in 2016 in North America. Biodiversity hotspots cover 2.4% of the Earth's land area and harbour approximately 42% of endemic terrestrial vertebrate species and 50% of endemic plant species (CEPF, 2024).

Among the biodiversity hotspots, there are significant and even more significant hotspots. Myers et al. (2000) analysed the importance of biodiversity hotspots based on two criteria: species endemism and degree of threat. They considered five different factors. Hrdina and Romportl (2017) considered thirteen factors: numbers of endemics and endemic/species ratios for different groups of animals and for plants, and habitat loss. Of these two analyses, the following six biodiversity hotspots emerged as the most significant: Madagascar and the Indian Ocean Islands, Sundaland, the Philippines, the Caribbean Islands, Indo-Burma, and Atlantic Forest. The most important biodiversity hotspots face a great anthropogenic impact.

3. Applied methods and data

The methodological procedure of creating a complex classification of global environmental systems consists of several sequential steps. There is a need to classify both the distribution of biodiversity and the environmental conditions as well as the degree of anthropogenic impact. The classification of GES is based on abiotic, biotic, and anthropogenic factors.

The initial stage of the preparations involved searching for and acquiring appropriate abiotic data that characterises the Earth's landmass. Datasets characterising climatic conditions come from the WorldClim database (Hijmans et al., 2005). This database provides 19 different temperature and precipitation indicators that characterise seasonality, annual trends, and extreme or limiting environmental factors. The spatial resolution of all these data layers is 30 seconds ($0.93 \times 0.93 = 0.86$ km^2 at the equator). Seven of them were eventually selected for further use, four representing temperature conditions: annual mean temperature, mean temperature of the warmest quarter, mean temperature of the coldest quarter, and temperature annual range. The remaining three represent precipitation conditions: annual precipitation, precipitation of the wettest quarter, and precipitation of the driest quarter. Among the unused variables were, for example, isothermality, mean diurnal range or monthly precipitation and temperature values. From the same source (Hijmans et al., 2005) an altitude data layer was obtained too. The analysis also considered topographic position index (TPI) and vertical heterogeneity as the last two abiotic factors. These variables were derived in ArcGIS.

Once these ten input abiotic rasters were prepared, they needed to be standardised. Their values were reclassified to a range of 0-100. With the standardised datasets, a principal component analysis (PCA) was performed. PCA is a procedure that allows the identification of a smaller number of uncorrelated variables, known as principal components, from a large set of data. The goal of the analysis is to explain the maximum possible amount of variance with the fewest number of the above-mentioned principal components. The result of the principal component analysis was a multiband raster with four principal components. That was the most suitable number of principal components.

With the multiband raster ready, I could proceed to the segmentation process. The multiresolution segmentation was carried out in eCognition software. This process was iterated several times with fixed settings of image layer weights based on the principal component analysis (L1: 77.4, L2: 12.8, L3: 6.3, L4: 3.4) and different parameters of scale, compactness and shape. To ensure that the shapes are neither too regular nor too irregular, and the number of segments is not too large, the settings were as follows: scale 100, compactness 0.5, and shape 0.1. The result of the multiresolution segmentation was a layer that consisted of 44,418 segments. This initial segmentation layer contained numerous water body segments and very small segments of less than 5 km^2, which were subsequently removed. The final layer consisted of 18,554 segments that were appropriate for further analyses.

In the next step, biotic and anthropogenic datasets entered the analysis. Four biotic factors were selected: species richness of mammals, species richness of birds, and species richness of amphibians derived from the Biodiversity Mapping website (Jenkins et al., 2013; Pimm et al., 2014), and diversity of plants coming from the work of Kier et al. (2005). These biotic factors portray long-term evolution in specific natural conditions and human impact and management. Anthropogenic factors are represented by these eight datasets: density of cattle, pigs, sheep, goats, and chickens (Robinson et al., 2014) used as one index – livestock density; population density (CIESIN, 2005), accessibility (Nelson, 2008) and global land cover (ESA Land Cover global raster data, 2017). Number of patches, total area, and percentage of all land cover classes in each segment were calculated using a Python script. The land cover data were originally classified in 37 classes, which were later generalised into 17 categories. These categories are presented in Table 1. Within each of 18,554 segments, the mean, minimum, and maximum values of every continuous abiotic, biotic, and anthropogenic variable were calculated in ArcGIS using zonal statistics and raster algebra and then they were standardised (except global land cover) to enable cluster analysis in IBM SPSS software. Abiotic and biotic data required a different type of analysis than anthropogenic data. The K-Means clustering method with a setting of a maximum of 100 iterations was used for biotic and abiotic data, the TwoStep cluster analysis was performed on anthropogenic data, because the dataset contained both continuous (livestock density, population density and accessibility) and categorical variables (land cover). Several different settings for the number of clusters were tested, in the end the number of ten clusters seemed to be the most convenient. This setting was used for all three classifications – abiotic, biotic and anthropogenic.

Table 1: Land cover categories

GLC category	**Land cover classes**
GLC1	Cropland, rainfed Herbaceous cover Tree or shrub cover Cropland, irrigated or post-flooding
GLC2	Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%) Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)
GLC3	Tree cover, broadleaved, evergreen, closed to open (>15%)
GLC4	Tree cover, broadleaved, deciduous, closed to open (>15%) Tree cover, broadleaved, deciduous, closed (>40%) Tree cover, broadleaved, deciduous, open (15-40%)
GLC5	Tree cover, needleleaved, evergreen, closed to open (>15%) Tree cover, needleleaved, evergreen, closed (>40%) Tree cover, needleleaved, evergreen, open (15-40%)
GLC6	Tree cover, needleleaved, deciduous, closed to open (>15%) Tree cover, needleleaved, deciduous, closed (>40%) Tree cover, needleleaved, deciduous, open (15-40%)
GLC7	Tree cover, mixed leaf type (broadleaved and needleleaved)
GLC8	Mosaic tree and shrub (>50%) / herbaceous cover (<50%) Mosaic herbaceous cover (>50%) / tree and shrub (<50%)
GLC9	Shrubland Evergreen shrubland Deciduous shrubland
GLC10	Grassland
GLC11	Lichens and mosses
GLC12	Sparse vegetation (tree, shrub, herbaceous cover) (<15%) Sparse tree (<15%) Sparse shrub (<15%) Sparse herbaceous cover (<15%)
GLC13	Tree cover, flooded, fresh or brakish water Tree cover, flooded, saline water Shrub or herbaceous cover, flooded, fresh/saline/brakish water
GLC14	Urban areas
GLC15	Bare areas Consolidated bare areas Unconsolidated bare areas
GLC16	Water bodies
GLC17	Permanent snow and ice

When the results of the cluster analyses were ready, their subsequent synthesis could take place in ArcGIS. First, the abiotic and biotic classifications were merged using the union function. The combined 10 classes of abiotic classification and 10 classes of biotic classification could create up to 100 classes of natural conditions. However, 59 natural classes were created and this number was further reduced when classes with distinctly similar biotic characteristics that belonged to the same abiotic class were merged. This process led to a reduction in the number of classes to a total of 30 natural classes. The classification of natural conditions was then combined with the anthropogenic classification, up to 300 classes could have been created by this synthesis. In fact, 169 types of global environmental systems (GES) were created (Figure 1). This is the main outcome of this complex classification process and this doctoral thesis.

Each GES is identified by a unique code consisting of one or two letters ('A' to 'J' and 'a' to 'e') and a number (1 to 10). For example, A8, Hc2 or Cc10. Affiliation with one of the ten abiotic classes is indicated by the letters 'A' to 'J'. These classes are further subdivided into one to five classes, and individual biotic classes or groups of classes are distinguished by the letters 'a' to 'e'. The number indicates affiliation to the anthropogenic class. Abiotic, biotic and anthropogenic classifications, as well as the classification of natural conditions and especially the classification of global environmental systems, were presented in maps.

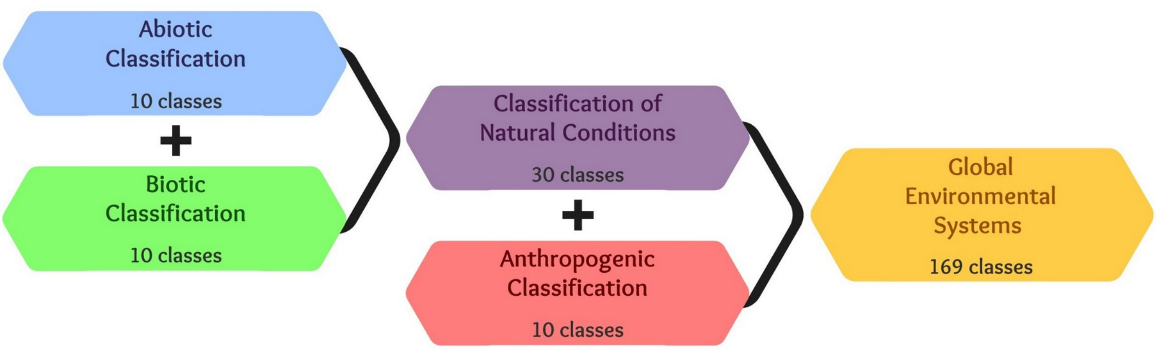

Figure 1: GES classification scheme

Global environmental systems and all sub-classifications were analysed for biodiversity hotspot areas to determine the current status of nature, landscape and human impact in these globally important areas. The proportion of each abiotic, biotic, anthropogenic, natural class and each global environmental system was calculated using zonal statistics in ArcGIS for all 36 hotspots. The data thus obtained were then further processed in Excel. The importance of each biodiversity hotspot was determined based on the works of Myers et al. (2000) and Hrdina and Romportl (2017).

4. Author's contribution statement

1. Evaluating Global Biodiversity Hotspots – Very Rich and Even More Endangered
   - Hrdina, A. & Romportl, D., 2017, Journal of Landscape Ecology, SCOPUS 90 %

2. Current Global Land Systems Classifications: Comparison of Methods and Outputs
   - Hrdina, A. & Romportl, D., 2022, AUC Geographica, WoS IF 0.6 95 %

3. Global Environmental Systems – Multivariate Anthropoecological Classification
   - Hrdina, A. & Romportl, D., 2023, Journal of Maps, WoS IF 2.2 85 %

4. Global Environmental Systems – A Spatial Framework for Better Understanding the Changing World
   - Hrdina, A. & Romportl, D., 2024, Environments, WoS IF 3.7 90 %

I confirm the contribution of Aleš Hrdina in the above-mentioned publications.

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RNDr. Dušan Romportl, Ph.D.

5. Publications

5.1. Evaluating Global Biodiversity Hotspots – Very Rich and Even More Endangered

Hrdina, A., Romportl, D. (2017). Evaluating Global Biodiversity Hotspots – Very Rich and Even More Endangered. Journal of Landscape Ecology, 10(1), 108-115. https://doi.org/10.1515/jlecol-2017-0013.

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10.1515/jlecol-2017-0013 Journal of Landscape Ecology (2017), Vol: 10 / No. 1.

EVALUATING GLOBAL BIODIVERSITY HOTSPOTS – VERY RICH AND EVEN MORE ENDANGERED

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ABSTRACT

Species on the Earth are under increasing human pressure, according to some authors, the current rate of extinction occurred only a few times in the past, for the last time in the Cretaceous Period in the Mesozoic Era. The main goal of current nature conservation is to maintain the highest native biological diversity and to preserve and enhance life-supporting ecosystem processes, functions and services with the best possible use of financial resources. The areas where can be found the highest concentrations of endemic species and that also face the highest loss of natural habitats are called biodiversity hotspots. Globally, now there are 36 hotspots, covering 2.4 % of the Earth's land area and harbouring about 50 % of endemic plant species and 42 % of endemic terrestrial vertebrate species in the world. The areas can be compared in terms of species richness, endemism, natural habitat loss or territorial protection and nature conservation can be carried out in the most efficient way. The most important hotspots are Madagascar and the Indian Ocean Islands and Sundaland.

Keywords: biodiversity, hotspots, endemism, threats, conservation

INTRODUCTION

British ecologist Norman Myers first introduced the concept of terrestrial biodiversity hotspots, very important areas for biological conservation, in 1988 he identified ten hotspots in the tropical forest biome (Myers, 1988). At that time, there were no quantitative criteria to define areas of biodiversity hotspots (Mittermeier *et al*., 2004). Two years later, in 1990, he added eight hotspots, including four areas of Mediterranean type ecosystems (Myers, 1990). Conservation International adopted Myers' concept of hotspots in 1989 (Mittermeier *et al*., 1998) and in 1999 were introduced quantitative biodiversity hotspots identification criteria (Conservation International, 2014). Generally, such areas must meet two criteria: a hotspot must harbour 1,500 or more vascular plant species being endemics there and has to have lost at least 70 % of its original primary habitat. The number of hotspots increased to 25, covering 1.4 % of the Earth's land area and maintaining 44 % of the world's plant species and 35 % of terrestrial vertebrate species, and then again to 34. This number of hotspots lasted until 2011, comprising 2.3 % of the land surface and supporting more than 50% of endemic plant species and 42 % of the world's endemic terrestrial vertebrate species (CEPF, 2014). Now there are 36 hotspots, covering 2.4 % of the land surface. Forests of East Australia were identified in

2011 and North American Coastal Plain in 2016 (Williams *et al.*, 2011; Noss *et al.*, 2015; CEPF, 2016).

The boundaries of biodiversity hotspots were determined by common biological features. Each of the areas is a unique biogeographic unit. This is evident in the case of islands or archipelagos and the same is true for continental ecological islands in clearly defined units. Typical examples are the Philippines, Japan, the East Melanesian Islands, New Caledonia, Polynesia-Micronesia, New Zealand, the Caribbean Islands, Madagascar and the Indian Ocean Islands or Southwest Australia, the Caucasus and the Cape Floristic Province, respectively. In some other areas are the boundaries defined by the lines of recognized divisions such as Wallace's line between Wallacea and Sundaland, or according to the expert judgement (Myers *et al.*, 2000).

Along with the development of the terrestrial hotspots biodiversity concept were also identified the least endangered areas with high biodiversity. Wilderness areas are quantitatively defined as areas still harbouring more than 70 % of the original habitat area and with population density lower than 5 people per km^2. These criteria are met by 44 % of the land surface, but high biodiversity wilderness areas, which must also meet the criterion of more than 1,500 endemic plant species, cover only 6.1 % of the total area in 5 regions: Amazonia, the North American Deserts, the Congo Forests of Central Africa, the Miombo-Mopane Woodlands and Grasslands of Southern Africa and New Guinea. In the five areas is found 17 % of endemic plant species and 8 % of the world's endemic terrestrial vertebrate species (Mittermeier *et al.*, 2004). Besides terrestrial biodiversity hotspots there were also identified ten marine biodiversity hotspots: South Japan, the Gulf of Guinea, the North Indian Ocean, Eastern South Africa, the Cape Verde Islands, the West Caribbean, the Philippines, the Red Sea and the Gulf of Aden, the South Mascarene Islands, the Sunda Islands (Roberts *et al.*, 2002). There are many approaches, based on the ecological criteria of vulnerability and irreplaceability, and their combinations, how to identify global conservation priorities. Conservation International uses a two-pronged strategy for prioritizing global conservation. At the same time is focusing on the threatened and irreplaceable terrestrial biodiversity hotspots and on the high biodiversity wilderness areas, which are also irreplaceable but still largely intact and providing significant conservation opportunities (Conservation International, 2014).

The hotspot concept has also many critics. Peter Kareiva and Michelle Marvier (2003) argued that the hotspot idea attracted too many financial resources and other areas playing a significant ecological role are downplayed. By investing exclusively in hotspots we risk to lose important areas that contribute to many ecosystem services. Similarly Jepson and Canney (2001) think that biodiversity hotspots concept provides only a partial response. From another point of view, Cañadas *et al.* (2014) claim that hotspots are to large for effective conservation and they detect smaller hotspots within larger hotspots. Stork and Habel (2014) criticize identifying biodiversity hotspots without considering invertebrates. Marine biodiversity hotspots have also been the subject of controversy (Marchese, 2015).

Biodiversity within Hotspots

Natural environment and geographical conditions of biodiversity hotspots have been attracting over a long period a large number of fauna and flora species. There are, based on the CEPF (2014) data, more than 150,000 endemic plant species, half of all species of the world. The highest number of species, about 30,000 vascular plant species, grows in the Tropical Andes. The next hotspots ranked include Sundaland, the Mediterranean Basin and

Atlantic Forest with more than 20,000 species. Special attention should be paid to Madagascar and the Indian Ocean Islands, where 9 of 10 species are endemic.

The highest mammal species richness – 570 species – can be found in the Tropical Andes, similarly in Indo-Burma, Mesoamerica and the Eastern Afromontane hotspot. The largest proportion of endemic species can be found within all the island hotspots; in the foreground is as usual Madagascar with 92.9 %. The top positions in bird diversity belong to the same four hotspots, complemented by species-rich hotspots Himalaya or South American Atlantic Forest or Tumbes-Chocó-Magdalena. Especially three regions are important with respect to amphibian diversity: American hotspots the Tropical Andes, Mesoamerica and Atlantic Forest; Southeast Asian hotspots Indo-Burma and Sundaland; East African hotspots Madagascar and the Indian Ocean Islands and the Eastern Afromontane. On the other hand New Caledonia has no amphibian species. Most reptile species are located in the same three regions, the most important region being Central America and the Caribbean. The Mekong, Chao Phraya, Salween and Irrawaddy river basins are extremely rich in freshwater fish species, Indo-Burma is inhabited by 1,262 and Sundaland 950 species. Species-rich are also rivers and lakes of the East African Rift, the Eastern Afromontane hotspot harbouring 893 species. The Cerrado gets ranking number four with 800 freshwater fish species.

Threats for biodiversity

Threats in biodiversity hotspots are the same as those that threaten biodiversity worldwide, having been only more intensive there. Habitat fragmentation, degradation, destruction and loss are a pervasive threat affecting hotspots (Brooks *et al.*, 2002). Anthropogenic acceleration of climate change magnifies the effects of habitat fragmentation, degradation and loss (Thomas *et al.*, 2004). The average proportion of land area per hotspot with novel climate was modelled to be about 16 %. The distribution of novel and disappearing climate are principally concentrated at low latitudes (Bellard *et al.*, 2014). Predatory invasive alien species have already had a devastating impact on the island hotspots, where species evolved in the absence of predators. Introduction of invasive alien plant species, particularly those of Mediterranean-type vegetation, is also having massive ecosystem effects. Direct wildlife exploitation for food, pet trade, or medicine is a serious threat to all hotspots (CEPF, 2014). In biodiversity hotspots live about 2 billion people. However, the relationship between people and biodiversity is not simply one where presence of more people results in greater impacts on biodiversity. For human-biodiversity interactions is more important human activity than human density (Mittermeier *et al.*, 2004). Biodiversity hotspots are also notable centres of violent conflict (Dudley *et al.*, 2002).

Evaluation of hotspots' importance

The analysis by Myers *et al.* (2000) was driven by two criteria: species endemism and degree of threat, and considered five key factors: numbers of endemics and endemic/species ratios for plants and vertebrates, and habitat loss. Hotspots, which appeared most often in the top ten listings for each factor, were the leaders. Scientific knowledge has deepened, the number of hotspots has increased. These are the main reasons for the new analysis. In this analysis was used modified Myers' method for mutual comparison of the quality of biodiversity hotspots, which considered thirteen factors (instead of five): numbers of endemics and endemic/species ratios for plants, mammals, birds, amphibians, reptiles and freshwater fishes, and habitat loss. These factors do not carry equal weight, so they cannot be combined into a single quantitative ranking. For the purposes of qualitative comparison were compiled the rankings of each factor. Due to the higher number of hotspots, 36 instead of 25 were considered top twelve listings for each factor. As a proxy indicator was used the sum of all factors rankings. For assessing the distribution of national parks in hotspots, was used a database (based on the WDPA dataset), analysed in GIS.

Biodiversity hotspots, appearing for all thirteen factors in the top twelve listings, are the most important on the world´s terrestrial surface. These are Madagascar and the Indian Ocean Islands and Sundaland followed by the Philippines appearing twelve times and the Caribbean Islands appearing eleven times. All the areas are island hotspots, most of them being small areas, making them even more important. Next ranking numbers get to the Atlantic Forest, scoring also eleven times, Indo-Burma nine times, the Tropical Andes eight times and Mesoamerica and the Eastern Afromontane seven times. The six richest hotspots in terms of biodiversity are those with the lowest proportion of the remaining natural vegetation, reaching in Madagascar and the Indian Ocean Islands and the Caribbean Islands hotspots 10 %, others displaying even smaller proportion.

Some other hotspots are hot conservation candidates because they greatly excel in one of the factors. The Mediterranean Basin has exceptional totals of endemic plants: 13,000, while the proportion of remaining natural vegetation is the smallest among all the hotspots. The Cape Floristic Region displays the second highest endemic species/area ratio for plants, just after the first New Caledonia. Although some of the biodiversity hotspots do not appear in the top twelve listings in any factor, they still must meet the criteria to qualify themselves as a hotspot and in comparison with the rest of the world have extraordinarily high species richness and endemism rate. The nine hotspots are Forests of East Australia, Himalaya, the California Floristic Province, the Chilean Winter Rainfall Valdivian Forests, Southwest Australia, Irano-Anatolian, Maputaland-Pondoland-Albany, the Caucasus and the Mountains of Central Asia.

Formerly 36 biodiversity hotspots covered an area of almost 24.9 million square kilometres, i.e. 16.7 % of the Earth's land surface (CEPF, 2014; CEPF, 2016). The area of the original primary habitat has been gradually decreasing there over the years, nowadays reaching 3.6 million square kilometres, i.e. 2.4 % of the Earth's land surface. The area of the original biodiversity hotspots' habitat was reduced by 85.5 %, only 14.5 % still remains. The average area of remaining vegetation is now only 100,224 km^2, which is almost seven times less than the original area. Generally, hotspots located outside the highly productive tropics in temperate or subtropical zone, have a larger proportion of the remaining natural vegetation. The northern hemisphere situated hotspots: the California Floristic Province, the Caucasus, the Mountains of Central Asia and Japan; and in the southern hemisphere: the Chilean Winter Rainfall-Valdivian Forests, the Succulent Karoo, the Cape Floristic Region, Maputaland-Pondoland-Albany, Southwest Australia and New Zealand, still having had 20 % or more of the original habitat area remaining. The only exception is the Mediterranean Basin, showing the lowest proportion due to the long-term and continuing human exposure. They are also located in developed countries (the United States, Japan, Australia, New Zealand), or in Chile and South Africa, known for their traditional and quite developed nature conservation.

The distribution of hotspots across biomes is very unequal. Of the total 36 biodiversity hotspots, 22 are located in the tropics, from very humid areas to sparsely wooded areas of savannas and grasslands. Seven hotspots are situated in the temperate forests biome: the Caucasus, the Irano-Anatolian hotspot, the Mountains of Central Asia, the Mountains of Southwest China, Japan, New Zealand and North American Coastal Plain; six can be characterised by the Mediterranean vegetation: the California Floristic Province, the Chilean

Winter Rainfall-Valdivian Forests, the Cape Floristic Region, Southwest Australia, the Mediterranean Basin and the Horn of Africa; and one – the Succulent Karoo – is desert.

Nature conservation

Approximately 2.7 million square kilometres, i.e. 10.9 % of the total area of hotspots has already been at least officially protected. The proportion of protected areas varies between individual hotspots in a wide range from 3.2 % to 37 %. Two of the five most important hotspots, Madagascar and the Indian Ocean Islands, and Atlantic Forest, have the lowest proportion of area under some types of territorial protection, only 3.2 % and 4.1 %, respectively. Protected areas in IUCN categories I-IV provide higher levels of protection, because they control to various extent resource use and human presence. The average coverage of protected areas in categories I-IV is 5.0 % within the hotspots' original area, in total reaching 1,248,258 km^2. Generally, hotspots situated outside the tropics have above-average proportion of protected areas in IUCN categories I-IV, from New Zealand with 22.1 % to Japan with 5.9 %. The exception is again the Mediterranean Basin and then also a specific desert hotspot, namely the Succulent Karoo. National parks (as defined in national legislations) cover an area of 1,043,308.52 km^2, the proportion of the total hotspots' area is 4.2 %. In all 36 biodiversity hotspots has been established 1,858 national parks of the total number of 3,375 so far. Thus, in the hotspots is situated more than every second of the world's national parks, but only 24 % of their total area is there. It is caused by the low average size of national parks in the highly fragmented landscape of hotspots.

Biodiversity hotspots are irreplaceable areas at high risk, with significant species richness, diversity and endemism. They deserve the most attention in the process of conservation, together with high biodiversity wilderness areas, also irreplaceable but still largely intact. In 2000 was established the Critical Ecosystem Partnership Fund focusing exclusively on the funding of conservation activities in the areas of biodiversity hotspots, particularly from U.S. private foundations (Dalton, 2000). The concept has attracted over $1 billion in conservation investments (Mittermeier *et al.*, 2011). Almost thirty of the 50 countries with the most underfunded biodiversity conservation programmes and projects host the global biodiversity hotspots: therefore, much more funding is required there (Waldron *et al.*, 2013).

Conclusion

Every day biodiversity is being lost at up to 1,000 times the natural rate. The extinction of species, habitat destruction, land conversion, climate change, pollution or the spread of invasive species are only some of the threats responsible for today's crisis (IUCN, 2010). For the first time in human history, the rate of species extinction may exceed that of species discovery (Wheeler *et al.*, 2012). Traditionally among the main responses to the current biodiversity crisis, there also is the establishment and effective management of protected areas to ensure the persistence of biodiversity not only in the hotspots (Bruner *et al.*, 2001). Surprisingly high number of currently existing protected areas are no more than "paper parks", it means they have official designation, but lack management plans, funding, capacity or enforcement and in some cases, even borders. Mismanagement also includes biodiversity conservation (CEPF, 2014). The main objectives of the current global conservation should be, *inter alia*, ensuring long-term stability in the already declared protected areas, reducing fragmentation and then also establishing new protected areas in places with intact habitat with the highest conservation priority (Mittermeier *et al.,* 2004). Climate change is likely to have a large impact on biodiversity. Establishing protected areas that remain resistant and resilient to climate change as well as new ones in novel ecosystems is a further challenge (Araújo *et al*., 2004; Hannah *et al*., 2007; Bellard *et al*., 2014). Species movement including dispersal may be very difficult or impossible in heavily fragmented habitat (Thomas, 2011). Therefore, it is necessary to protect also the areas that will host target species in the near future and to establish, manage and protect the corridors, both linear ones and stepping stones (Mittermeier *et al*., 2004). The long-term goal is to attempt to restore degraded habitats to provide increased connectivity and to decrease fragmentation (CEPF, 2014).

Biodiversity hotspots and high biodiversity wilderness areas are inhabited by two-thirds of endemic plant species and half of the world's endemic species of terrestrial vertebrates in only 8.5 % of the Earth's land surface. Hotspots provide us with the real measure of the conservation challenge. Unless we succeed in conserving this small fraction of the planet's land area, we will lose more than half of our natural heritage (CEPF, 2014).

To conclude, the analysis evaluates 36 instead of 25 hotspots that existed in 2000. The current available species data are more complete and accurate, so they allow consideration of 13 factors instead of 5 and more precise results of biodiversity hotspots' importance. Hotspots with the highest conservation priority are Madagascar and the Indian Ocean Islands, Sundaland, the Philippines and the Caribbean Islands, all island hotspots, with the lowest proportion of the remaining natural vegetation, located in the tropics. Effective conservation in the areas of biodiversity hotspots must be among the tasks of high priority at present and in the near future.

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5.2. Current Global Land Systems Classifications: Comparison of Methods and Outputs

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Current global land systems classifications: comparison of methods and outputs

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ABSTRACT
The anthropogenic impact on the functioning of natural systems and the concept of Anthropocene as a period of the human domination of the Earth has been widely discussed in literature in the past few decades. Consequently, several land systems classifications have been developed on a global scale to capture the diversity, intensity, and spatial distribution of the human suppression of natural stratification. This review presents the comparison of the most widely used complex global classifications, incorporating both natural conditions and the human influence on nature. Methods, input data, the number and type of output categories as well as their geographical extent and distribution are described and compared. The review will help potential users to find differences between available classifications and choose the right one for a particular use.

KEYWORDS
anthropogenic transformation; environmental stratification; global land use; human impact; land systems

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1. Introduction

The Earth is naturally stratified into specific zones, which have been classified in different ways by humans from ancient times. Humans have substantially changed this natural distribution by their actions, in the case of some regions so significantly that the original natural conditions have been completely suppressed in favour of anthropogenic factors (Vitousek et al. 1997). Therefore, several global classifications were presented to reflect the intensity of human influence covering a wide range of aspects of anthropogenic transformation. Most of the classifications are used as a spatial framework for assessing ecosystem or landscape processes (e.g. land cover / land use change, ecosystem services evaluation, ecosystem degradation etc.) and biodiversity monitoring (e.g. Ellis and Ramankutty 2008; Václavík et al. 2013). Some classifications were presented in order to describe the diversity and geographical differentiation of human pressure on the Earth (e.g. Letourneau et al. 2012).

In recent times of global climate and environmental change, understanding the different trends and impacts in specific land systems will be crucial in finding appropriate adaptation and mitigation measures. Existing global classifications may provide a useful spatial framework for such evaluation.

The aim of this review is to present selected global classifications, which are widely used and compare their methodology and results. Such an overview will help potential users in orientation and decision making, that is; which classification would fit a particular purpose of use.

2. Human domination of the Earth – development and geographical demonstration

People have been changing ecosystems, their processes and forms, for several million years (Goudie 2013). The oldest records (more than 3 million years ago) of human activity and technology have been found in various parts of Africa (Gosden 2003). The tools have become more sophisticated during the Stone Age (3.4 million years – ca. 4,000 BCE) and have enabled greater exploitation of natural resources. Other important factors were the development of communicative skills such as speech, and the discovery of the use of fire. Fire was one of the most powerful tools of environmental transformation. The Neolithic revolution (starting 10,000 to 8,000 BCE) has brought about many changes: the transition from a lifestyle of hunting and gathering to agriculture and settlement, the domestication of plants and animals, population growth, deforestation, irrigation etc. In the Holocene humans also began to mine ores and smelt metals (Goudie 2013). The Technological-Scientific Revolution and the development of modern industrial and urban civilizations have led to immense changes in the reshaping of ecosystems globally (Takács-Sánta 2004; Goudie 2013). The impact of human activities on the global environment rapidly increased (Crutzen 2002) and the number of ways in which humans are affecting the environment is multiplying (Vitousek et al. 1997). The 20th century was especially an epoch of very exceptional change (McNeill 2003).

The current period is called by some scientists, the Anthropocene (Crutzen 2002, Waters et al. 2016). The Earth is now more influenced by human activities than the forces of nature, according to a number of authors, anthropogenic transformation of the biosphere prevails (Vitousek et al. 1997; Crutzen 2002; Steffen et al. 2007; Ellis et al. 2010; Steffen 2010). Human impact is mainly reflected in land cover changes, therefore this information is often included in global classifications. However, the range of anthropogenic activities is much wider – e.g. geographical differentiation of population density, varied intensity of natural resource use, diverse intensities of domestic livestock, degradation of natural processes, etc. play important role as well in terms of natural systems alternation. Human activities are causing global biodiversity declines (Newbold et al. 2015), both inside and outside protected areas (Schulze et al. 2018), 75% of the planet's land surface is experiencing measurable human pressures (Venter et al. 2016; Williams et al. 2020; Ellis et al. 2021). Therefore, anthropogenic transformation of the natural systems cannot be simply ignored in modern global classifications. Human influence used to be simplified or ignored (Alessa and Chapin 2008; Ellis et al. 2010) and biomes were identified chiefly as a result of a combination of abiotic and biotic factors (Udvardy 1975; Olson et al. 2001; Bailey 2004, Higgins et al. 2016, Dinerstein et al. 2017). Several studies on environmental stratifications involving human influence have recently been published resulting in different spatially explicit classifications. The classifications result in the creation of global maps of anthropogenic biomes, anthromes, land-use systems, land systems, land system archetypes or world ecosystems (Ellis and Ramankutty 2008; Letourneau et al. 2012; van Asselen and Verburg 2012; Václavík et al. 2013; Sayre et al. 2020).

3. Global environmental classifications

3.1 Anthropogenic biomes

Ellis and Ramankutty (2008) presented the first global classification of terrestrial biomes based on an empirical analysis of direct human-nature interaction. The result of the analysis is a global map of anthropogenic biomes. A multi-stage empirical procedure was used for the identification and mapping of anthropogenic biomes, based on global data of land use (percent area of pastures, crops, irrigated and rice), land cover (percent area of trees and bare earth) and population (Table 1). The analysis was executed at 5 arc minute resolution (5′ grid cells cover, i.e. 86 km² at the equator). The procedure first separated wild cells from anthropogenic cells based on the presence of human populations, pastures, and crops. The authors then categorized human-ecosystem interactions in anthropogenic cells into four classes according to population density. Dense class with high population intensity (more than 100 persons km^{-2}), residential class with substantial population intensity (10 to 100 persons km^{-2}), populated class with minor population (1 to 10 persons km^{-2}) and remote class with inconsequential population (less than 1 person km^{-2}). During the next step of cluster analysis using SPSS, natural groupings within the cells of each class were identified based on non-urban population density, percentage of urban areas, crops, pastures, irrigated lands, rice fields, tree cover and bare land. As the last step, the derived strata were organised into groupings based on their populations, land-cover and land-use characteristics; resulting in the 18 anthropogenic biome classes and 3 wild biome classes (Ellis and Ramankutty 2008).

Anthropogenic biome classes were classified into five basic groups: dense settlements, villages, croplands, rangelands and forested; wild biome classes belong to wildlands (Table 3). Dense settlements contain two biomes, 40% of people live here, the majority is urban population. This category covers 1.5 million km² and can be found especially in South and Southeast Asia, North America or in Western Europe. Villages include six biomes which also host 40% of people in the world but only 38% is urban. Village biomes cover 7.7 million km², and are most commonly found in Asia, where they cover more than a quarter of all land. They are also typical for regions of Europe or Africa. Croplands cover more than 27 million km² and host 15% of people (7% urban) in five biomes. In Europe croplands occupy almost half of all land; the residential irrigated cropland biome covers about 35%. Croplands are often also located in South and Southeast Asia, Latin America and Africa, covering about 25% of land in these areas. Rangeland biomes are the most extensive, covering nearly 40 million km², almost 30% of North and Latin America, Australia, New Zealand and Asia, but they are most common in Africa; (> 40%) especially in the Near East region (> 45%). Rangelands are divided into three different biomes, they account for less than 5 % of the global population. Forested biomes contain two classes: populated and remote forests, and cover 25 million km² of which more than 45% is covered with trees. Forested biomes contain only 0.6% of the global population and are typical for Latin America (40%) and Eurasia (25%). Wildlands occupy nearly 30 million km² (i.e. only 22% of Earth's ice-free land) and are located mainly in the Near East region (50%), North America, Australia and New Zealand (40%) and North Asia (30%) (Ellis and Ramankutty 2008).

Tab. 1 Datasets used for the classification of anthropogenic biomes.

Classification factor	Reference
Population	Dobson et al. (2000)
Pastures area	Ramankutty et al. (2008)
Crops area	Ramankutty et al. (2008)
Irrigated area	Siebert et al. (2007)
Rice area	Monfreda et al. (2008)
Tree cover	Hansen et al. (2003)
Bare earth	Hansen et al. (2003)

Tab. 2 Datasets used for the classification of anthromes.

Classification factor	Reference
Population density	Klein Goldewijk (2007)
Urban area	Klein Goldewijk (2007)
Cropland area	Klein Goldewijk (2007)
Pasture area	Klein Goldewijk (2007)
Irrigated area	Siebert et al. (2007)
Rice cover	Monfreda et al. (2008)
Land cover	Ramankutty and Foley (1999)

3.2 Anthromes

Ellis et al. (2010) used a new *a priori* anthrome classification algorithm built on standardized thresholds for classifying the same variables (Table 2) instead of the *a posteriori* anthrome classification used by Ellis and Ramankutty (2008). The new classification used the same basic classification levels but the system was simplified. Village classes were collapsed from six to four, croplands from five to four and wildlands from three to two. The forested level was broadened from two to four classes and named seminatural (Table 3). Ellis et al. (2010) also simplified the system interpretation by aggregating anthrome levels into three categories: used anthromes (dense settlements, villages, croplands, rangelands), semi natural anthromes and wildlands.

3.3 Land-use systems

Letourneau et al. (2012) proposed a new classification based on land-use systems, which represent specific combinations of interactions between humans and the natural environment. Land-use systems try to describe the heterogeneity of land cover and also land-use intensity; they are characterized by land cover, land use, population pressure and accessibility (Table 4). The spatial units of the analysis cover an area of less than 100 km² each (5 arc-minutes resolution). Multiple datasets were used in the classification: population density, land use / land cover data,

Tab. 3 List of classes of all classifications.

Classification	Category	Classes
Anthropogenic biomes	Dense settlements	1) Urban; 2) Dense settlements
	Villages	1) Rice villages; 2) Irrigated villages; 3) Cropped and pastoral villages; 4) Pastoral villages; 5) Rainfed villages; 6) Rainfed mosaic villages
	Croplands	1) Residential irrigated cropland; 2) Residential rainfed mosaic; 3) Populated irrigated cropland; 4) Populated rainfed cropland; 5) Remote croplands
	Rangeland	1) Residential rangelands; 2) Populated rangelands; 3) Remote rangelands
	Forested	1) Populated forests; 2) Remote forests
	Wildlands	1) Wild forests; 2) Sparse trees; 3) Barren
Anthromes	Dense settlements	1) Urban; 2) Mixed settlements
	Villages	1) Rice villages; 2) Irrigated villages; 3) Rainfed villages; 4) Pastoral villages
	Croplands	1) Residential irrigated croplands; 2) Residential rainfed croplands; 3) Populated rainfed cropland; 4) Remote croplands
	Rangeland	1) Residential rangelands; 2) Populated rangelands; 3) Remote rangelands
	Seminatural lands	1) Residential woodlands; 2) Populated woodlands; 3) Remote woodlands; 4) Inhabited treeless and barren lands
	Wildlands	1) Wild woodlands; 2) Wild treeless and barren lands
Land-use systems	Bare soils	1) Remote bare soils; 2) Accessible bare soils; 3) Populated areas covered by bare soils
	Cropland system	1) Accessible rainfed croplands; 2) Rainfed croplands with intensive livestock breeding; 3) Remote rainfed croplands; 4) Rice croplands with intensive bovines breeding; 5) Rice croplands with intensive bovines and monogastrics breeding; 6) Partly irrigated croplands with intensive livestock breeding; 7) Partly irrigated croplands with extensive livestock breeding; 8) Irrigated croplands with intensive livestock breeding; 9) Irrigated croplands with intensive bovines breeding
	Densely populated systems	1) Urban areas; 2) Villages or peri-urban area; 3) Villages and rice croplands; 4) Villages and irrigated croplands
	Forested systems	1) Sparse trees; 2) Populated areas with forests; 3) Remote forests
	Mosaic systems	1) Mosaic landscape; 2) Populated areas mosaic landscape
	Pastoral systems	1) Extensive pastures; 2) Intensive pastures with bovines and small ruminants; 3) Intensive pastures with bovines
Land systems	Cropland systems	1) Cropland extensive with few livestock; 2) Cropland extensive with bovines, goats and sheep; 3) Cropland extensive with pigs and poultry; 4) Cropland medium intensive with few livestock; 5) Cropland medium intensive with bovines, goats and sheep; 6) Cropland medium intensive with pigs and poultry; 7) Cropland intensive with few livestock; 8) Cropland intensive with bovines, goats and sheep; 9) Cropland intensive with pigs and poultry
	Mosaic cropland and grassland systems	1) Mosaic cropland and grassland with bovines, goats and sheep; 2) Mosaic cropland and grassland with pigs and poultry; 3) Mosaic cropland (extensive) and grassland with few livestock; 4) Mosaic cropland (medium intensive) and grassland with few livestock; 5) Mosaic cropland (intensive) and grassland with few livestock
	Mosaic cropland and forest systems	1) Mosaic cropland and forest with pigs and poultry; 2) Mosaic cropland (extensive) and forest with few livestock; 3) Mosaic cropland (medium intensive) and forest with few livestock; 4) Mosaic cropland (intensive) and forest with few livestock
	Forest systems	1) Dense forest; 2) Open forest with few livestock; 3) Open forest with pigs and poultry
	Mosaic (semi-)natural systems	1) Mosaic grassland and forest; 2) Mosaic grassland and bare
	Grassland systems	1) Natural grassland; 2) Grassland with few livestock; 3) Grassland with bovines, goats and sheep
	Bare systems	1) Bare; 2) Bare with few livestock
	Settlement systems	1) Peri-urban and villages; 2) Urban
Land system archetypes	–	1) Forest systems in the tropics; 2) Degraded forest/cropland systems in the tropics; 3) Boreal systems of the western world; 4) Boreal systems of the eastern world; 5) High-density urban agglomerations; 6) Irrigated cropping systems with rice yield gap; 7) Extensive cropping systems; 8) Pastoral systems; 9) Irrigated cropping systems; 10) Intensive cropping systems; 11) Marginal lands in the developed world; 12) Barren lands in the developing world
World ecosystems	–	431 classes; see Sayre et al. (2020)
IUCN Global ecosystem typology	Terrestrial	25 biomes and 108 ecosystem functional groups; see Keith et al. (2020)
	Subterranean	
	Freshwater	
	Marine	
	Atmospheric	

Tab. 4 Datasets used for the classification of land-use systems.

Classification factor	Reference
Bare soil area	Hansen et al. (2003)
Tree cover area	Hansen et al. (2003)
Build-up area	Elvidge et al. (2007)
Croplands area	Ramankutty et al. (2008)
Pastures area	Ramankutty et al. (2008)
Crop areas	Monfreda et al. (2008)
Irrigated areas	Siebert et al. (2005)
Sheep density	FAO (2007)
Goats density	FAO (2007)
Chicken density	FAO (2007)
Pigs density	FAO (2007)
Buffaloes density	FAO (2007)
Bovines density	FAO (2007)
Population density	Dobson et al. (2000)
Accessibility	Verburg et al. (2011)

livestock density and accessibility. Cropland data was not divided into several types in contrast with Ramankutty et al. (2008); livestock density data was converted to livestock unit densities according to FAO, which enabled the comparison of the densities of different types of livestock. Letourneau et al. used a two-step cluster analysis to identify particular land-use systems. Firstly, all the grid-cells were pre-grouped into many sub-clusters; secondly an algorithm grouped the sub-clusters into the optimal number of clusters according to the algorithm used. During the first stage of the clustering; wild areas, croplands or pastures were identified, then major categories of landscapes were determined. Each major category was further classified; the classification had 32 land-use systems, subsequently reduced to 24 classes (Letourneau et al. 2012).

Land-use system classes are grouped into six categories: densely populated systems (4 classes), cropland systems (9), pastoral systems (3), mosaic systems (2), forested systems (3) and bare soil systems (3). South America, Africa and Australia are dominantly covered by extensive pastoral land-use systems; in Europe, South America and New Zealand we can find intensive grazing systems; croplands are mainly found in Europe, SE Asia and North America. Densely populated systems are characterized by population densities above ca. 1000 inhabitants/km^2 (Letourneau et al. 2012). This classification is comparable with anthropogenic biomes (Ellis and Ramankutty 2008; Ellis et al. 2010).

3.4 Land systems

Van Asselen and Verburg (2012) claim that land use and land management were not represented adequately until the classification by Ellis and Ramankutty (2008). Relatively small, but important types of land use were not represented and mosaic landscapes were inaccurately characterized by a single homogeneous land cover type. Van Asselen and Verburg (2012) consider land-use intensity as a crucial characteristic of land systems and a main cause of environmental damage (Foley et al. 2005). Land cover, livestock and agricultural intensity data was used for classification of land systems (Table 5), population wasn't used as a classification criterion. Land cover variables were tree cover and bare soil cover (Hansen et al. 2003), cropland cover (Ramankutty et al. 2008) and built-up area (Schneider et al. 2009). Livestock data comes from FAO statistics (2007) and agricultural intensity is based on global data of Neumann et al. (2010). All data was transformed into spatial resolution of 5 arc-minutes in this study. For the classification and delineation of land systems, a hierarchical procedure was used (van Asselen and Verburg 2012).

The global land system classification map contains 8 categories. Cropland systems are divided into nine classes and cover about 8% of the world's land surface. They are characterized by an average cropland cover of ca. 70% and are distinguished based on agricultural intensity, and livestock type and intensity. 28% of the global population lives in this category. Extensive croplands can be found in Africa and India while intensive croplands are found in central-eastern US, Europe, SW Russia, in parts of China and India. The second category is called mosaic cropland and grassland systems, which contain five classes that all together cover 5% of the land surface and host 10% of the world's population. Extensive types occur mainly in Africa, whereas intensively managed systems are found in the United States, Europe or Argentina. Mosaic croplands and forest systems cover only 4% of the world's area, and 9% of the world's population lives in this area. These systems occur all over the world. Forest systems cover a much larger area of 21% of the world's land surface, but only 8% of the population can be found here. Dense forest systems have an average tree cover of about 80% and mostly include tropical forests or temperate forests at higher latitudes. Open forest systems (two different classes) have an average tree cover of about 55%. The next category, grassland systems cover 12% of the land surface and host 4.6% of the world's population. This category

Tab. 5 Datasets used for the classification of land systems.

Classification factor	Reference
Tree cover	Hansen et al. (2003)
Bare soil cover	Hansen et al. (2003)
Cropland cover	Ramankutty et al. (2008)
Build-up area	Schneider et al. (2009)
Livestock density	FAO (2007)
Efficiency of agricultural production	Neumann et al. (2010)

is divided into 3 classes, one natural; in tundra and two anthropogenic all over the world. Mosaic (semi-) natural systems are widely spread covering 24% of the world land surface, 8% of the population lives in the mosaic grassland and forest system, which occurs in Canada, Russia, South America, Central Africa and China, only 1.5% live in the second class – mosaic grassland and bare system. Settlement systems are subdivided into the urban, and peri-urban and village systems. They cover only 2% of the world's land surface, but 25% of people live here. Both classes can be found all over the world. The last category is named bare systems, and is subdivided into two classes; the average bare cover is 90%. Bare systems cover 1/4 of the land surface and host 5% of the world's population. These systems occur in the Sahara, Australia, western China, the Middle East, Mongolia, Kazakhstan etc. (van Asselen and Verburg 2012).

3.5 Land system archetypes

Mapping land systems with the incorporation of land-use intensity and land management is useful for a better understanding of the interactions and feedbacks between nature and people, measuring impacts, addressing global trade-offs of land-use change and developing better policies adapted to regional conditions (Foley et al. 2011; Seppelt et al. 2011; Václavík et al. 2013). In previous studies top-down approaches were used based on expert's rules or *a priori* classification. In the study of Václavík et al. (2013) a new approach was proposed for representing human-environment interactions, a bottom-up approach driven only by the data. Global land system archetypes were defined as unique combinations of environmental conditions, socioeconomic factors and land-use intensity; they were identified based on 32 indicators (Table 6). All datasets were derived for the period around the year 2005; spatial resolution was the same as in all previous studies – 5 arc-minutes. Land-use intensity was characterized by data on cropland and pasture (Klein Goldewijk et al. 2011) and their trends, use of N fertilizer (Potter et al. 2010), irrigation (Siebert et al. 2007), soil erosion (van Oost et al. 2007), yields and yield gaps for wheat, maize and rice (IIASA/FAO 2012), total production index and the human appropriation of net primary production (Haberl et al. 2007). Environmental conditions were characterised by 35 bioclimatic variables, from which 5 were selected for the final analysis (Kriticos et al. 2012), climate anomalies (Menne et al. 2009), NDVI mean and seasonality (Tucker et al. 2005), soil organic carbon (Batjes 2006) and species diversity of terrestrial mammals, birds, amphibians and reptiles from the IUCN database. Finally GDP, GDP from agriculture, the capital stock in agriculture (FAO), population density and its trend (CIESIN 2005), political stability (Kaufmann et al. 2010) and accessibility (Uchida and Nelson 2009) were used as socioeconomic factors. For the classification of land system archetypes, a self-organizing map algorithm (SOM) was used; an unsupervised neural network. The SOM analysis was conducted in R version 2.14.0. A 3 by 4 hexagonal plane was chosen as the two-dimensional output space. The final result was a map of global land system archetypes (Václavík et al. 2013).

Forest systems in the tropics represent the first archetype of a total of 12 archetypes. They cover ca. 14% of terrestrial ecosystems and they are determined mainly by climate. This archetype can be found in Latin America and the Amazon basin, West and Central Africa and in SE Asia. Degraded forest/cropland systems in the tropics cover only 0.35% of the world's land surface area; are characterized by enormous soil erosion and occur in Southeast Asia and Latin America. Boreal systems of the western world cover 14% of the world's land surface, it's an area of scarcely populated boreal forests and tundra. This LSA occurs mainly in Canada, Northern Europe, and Patagonia; or in higher elevations. Boreal systems of the eastern world occupy 20% of terrestrial ecosystems and are typical for Russia and Northeast China. Extensive cropping systems (11%) are defined by a high density of cropland and its increasing trend and the population density exceeding the global average. Extensive cropping systems occur in Eastern Europe, Sub-Saharan Africa, South America, India and China. Intensive cropping systems (5%) are also characterized by a high density of cropland, but it has decreased in recent decades. This land system archetype occurs in Western Europe, Eastern United States of America and Western Australia. Only 2% of terrestrial ecosystems are covered by irrigated cropping systems. The intense land-use pressure can be illustrated by a very dense population that has increased in the last 50 years. This archetype is typical for India, China or Egypt. Irrigated cropping systems with rice yield gap (only 1%) occur in economically very poor and also politically unstable regions such as Bangladesh, India and Southeast Asia. Pastoral systems (13%) are characterized by high densities of pastures and grasslands and are still scarcely populated. They are located in Central Asia, South and North Africa and Sahel, and in Latin America. High-density urban agglomerations cover only 0.1% of the world's land surface and values of its indicators are predominantly extreme, the population density is 7138 persons per km^2 etc. Marginal lands in the developed world (9%) have low values for indicators of land-use intensity, and the population density is only 6 people per km^2 and decreasing. This archetype occurs in Western USA, Australia or Argentina. The last land system archetype is called barren lands in the developing world and covers 11% of terrestrial ecosystems. It consists of mainly barren and desert areas characterized by low densities of cropland and pastures, extremely low primary production and an extreme climate. The population density is only 12 people per km^2, the countries are

Tab. 6 Datasets used for the classification of land system archetypes.

Classification factor	Reference
Temperature	Kriticos et al. (2012)
Diurnal temperature range	Kriticos et al. (2012)
Precipitation	Kriticos et al. (2012)
Precipitation seasonality	Kriticos et al. (2012)
Solar radiation	Kriticos et al. (2012)
Climate anomalies	http://www.ncdc.noaa.gov/cmb-faq/anomalies.php#grid
NDVI – mean	Tucker et al. (2005)
NDVI – seasonality	Tucker et al. (2005)
Soil organic carbon	Batjes (2006)
Species richness	http://www.iucnredlist.org/technical-documents/spatial-data
Cropland area	Klein Goldewijk et al. (2011)
Cropland area trend	Klein Goldewijk et al. (2011)
Pasture area	Klein Goldewijk et al. (2011)
Pasture area trend	Klein Goldewijk et al. (2011)
N fertilizer	Potter et al. (2010)
Irrigation	Siebert et al. (2007)
Soil erosion	Van Oost et al. (2007)
Yield for wheat	http://www.gaez.iiasa.ac.at/
Yield for maize	http://www.gaez.iiasa.ac.at/
Yield for rice	http://www.gaez.iiasa.ac.at/
Yield gap for wheat	http://www.gaez.iiasa.ac.at/
Yield gap for maize	http://www.gaez.iiasa.ac.at/
Yield gap for rice	http://www.gaez.iiasa.ac.at/
Total production index	http://faostat.fao.org/
HANPP	Haberl et al. (2007)
Gross domestic product	http://faostat.fao.org/
Gross domestic product in agriculture	http://faostat.fao.org/
Capital stock in agriculture	http://faostat.fao.org/
Population density	CIESIN (2005)
Population density trend	CIESIN (2005)
Political stability	http://www.govindicators.org
Accessibility	http://bioval.jrc.ec.europa.eu/products/gam/index.htm

poor and very politically unstable. Barren lands exist in regions of the Middle East, Saharan Africa, the deserts of Namibia and the Gobi and Atacama deserts (Václavík et al. 2013).

3.6 World ecosystems

Sayre et al. (2020) described a new set of maps of global ecosystems at a spatial resolution of 250 m (8 arc-seconds resolution). The map of terrestrial world ecosystems was derived from the objective development and integration of global temperature domains, global moisture domains, global landforms, and global vegetation and land use (Table 7).

Tab. 7 Datasets used for the classification of world ecosystems.

Classification factor	Reference
Global temperature domains	Fick and Hijmans (2017)
Global moisture domains	Trabucco and Zomer (2009)
Global landforms	Karagulle et al. (2017)
Global vegetation and land use	ESA (2017)

Temperature data come from the WorldClim version 2 (Fick and Hijmans 2017) database. Global temperature domains consist of six temperature classes (tropical, subtropical, warm temperate, cold temperate, boreal, and polar). World moisture domains are based on the value of the aridity index (AI) (Trabucco and Zomer 2009), and there are three classes (moist, dry, desert) designed. The world temperature domains layer and the world moisture domains layer were then combined to derive a world climate regions layer. With six temperature domains and three moisture domains, a total of 18 climate regions is possible (Sayre et al. 2020). The climate regions data were then combined with a world landforms data layer that is an aggregation of the global Hammond landforms layer (Karagulle et al. 2017) into four classes (mountains, hills, plains, and tablelands), extending the 18 climate region classes to 72 possible climate region and landform combinations, called world climate and terrain settings. In the end Sayre et al. (2020) combined this layer with the world vegetation and land cover data layer. The world vegetation and land cover layer contains forest, shrubland, grassland, cropland, sparsely or non-vegetated (bare) area, settlements, snow and ice, and water classes, and was derived from the global land cover data produced by the European Space Agency (ESA 2017). A combination of the previous 72 settings with the eight vegetation classes yields 576 total possible combinations of world ecosystems. A total of 431 world ecosystems were identified, and of these a total of 278 units were natural or semi-natural vegetation/environment combinations. The biggest classes of the classification are Tropical moist forest on plains, Tropical desert sparsely or non-vegetated on plains, Boreal moist forest on mountains, and Subtropical moist forest on mountains, all having more than 3 million km² (Sayre et al. 2020).

3.7 IUCN Global ecosystem typology

This typology (version 2.0) is created as a hierarchical classification. In its upper three levels, functional variation among ecosystems is represented, ecosystems are defined by their convergent ecological functions. In its lower three levels, compositional variation is represented, ecosystems with differing groups of species influencing those ecological functions are defined (Keith et al. 2020).

The top level of the classification consists of five global realms: terrestrial, but also subterranean,

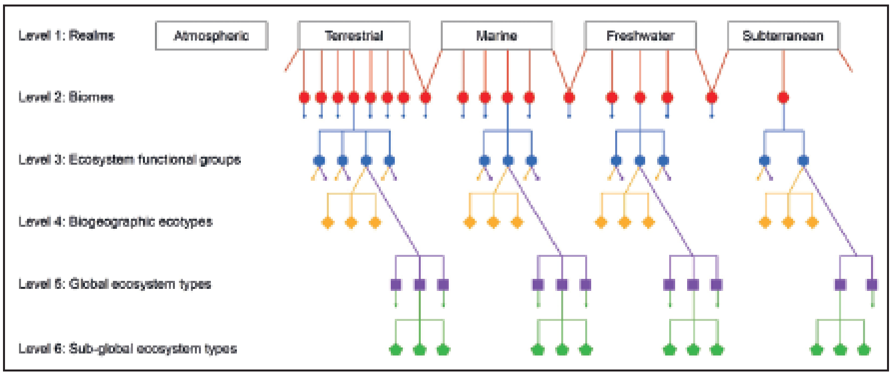

Fig. 1 Hierarchical structure of Global Ecosystem Typology.
Source: Keith et al. 2020

freshwater, marine, and atmospheric. Realms at the interface between contrasting environments are called transitional realms. At the second level, the classification defines 25 biomes ranging from tropical forests to several anthropogenic biomes. At the third level, the classification splits into 108 classes called Ecosystem Functional Groups (EFG). These three levels were developed from the top-down approach. The units of the fourth level are developed top-down by division of EFGs. In contrast, the fifth and sixth level facilitate integration of established local classifications into the global framework. Integration uses the bottom-up approach. The units at the fourth and fifth level are both nested with the third level units; they represent alternative pathways below the third level (Figure 1). Level four units are called Biogeographic ecotypes, they are ecoregional expressions of an EFG. Global ecosystem types create the fifth level of the classification, they are complexes of organisms, with similar ecological processes and their associated physical environment within an area occupied by an EFG, but with substantial difference in composition of organisms. And finally the sixth level – Sub-global ecosystem types are subunits or nested groups of subunits within a global ecosystem type, which exhibit more compositional homogeneity and resemblance to one another than global ecosystem types (Keith et al. 2020).

In the terrestrial realm can be found seven biomes: tropical-subtropical forests, temperate-boreal forests and woodlands, shrublands and shrubby woodlands, savannas and grasslands, deserts and semi-deserts, polar-alpine, and intensive land-use systems. These biomes are further divided into 34 EFGs. There are also transitional realms with terrestrial component: palustrine wetlands, shoreline systems, supralittoral coastal systems, anthropogenic shorelines, and brackish tidal systems comprising altogether a total of 16 EFGs (Keith et al. 2020).

4. Comparison and discussion of methods and outputs of global environmental classifications

Ellis and Ramankutty (2008), Ellis et al. (2010), Letourneau et al. (2012), Van Asselen and Verburg (2012) applied top-down approaches based on expert's rules or *a priori* classification, in contrast Václavík et al. (2013) used a bottom-up approach to reduce the level of subjectivity and also used a much

Tab. 8 Comparison of global environmental classifications.

Name	Authors	Number of categories	Number of classes	Resolution
Anthropogenic biomes	Ellis and Ramankutty (2008)	6	21	5 arc minutes
Anthromes	Ellis et al. (2010)	6	19	5 arc minutes
Land-use systems	Letourneau et al. (2012)	6	24	5 arc minutes
Land systems	Van Asselen and Verburg (2012)	8	30	5 arc minutes
Land system archetypes	Václavík et al. (2013)	–	12	5 arc minutes
World ecosystems	Sayre et al. (2020)	–	431	8 arc seconds
IUCN Global ecosystem typology	Keith et al. (2020)	5 25	108	30 arc seconds

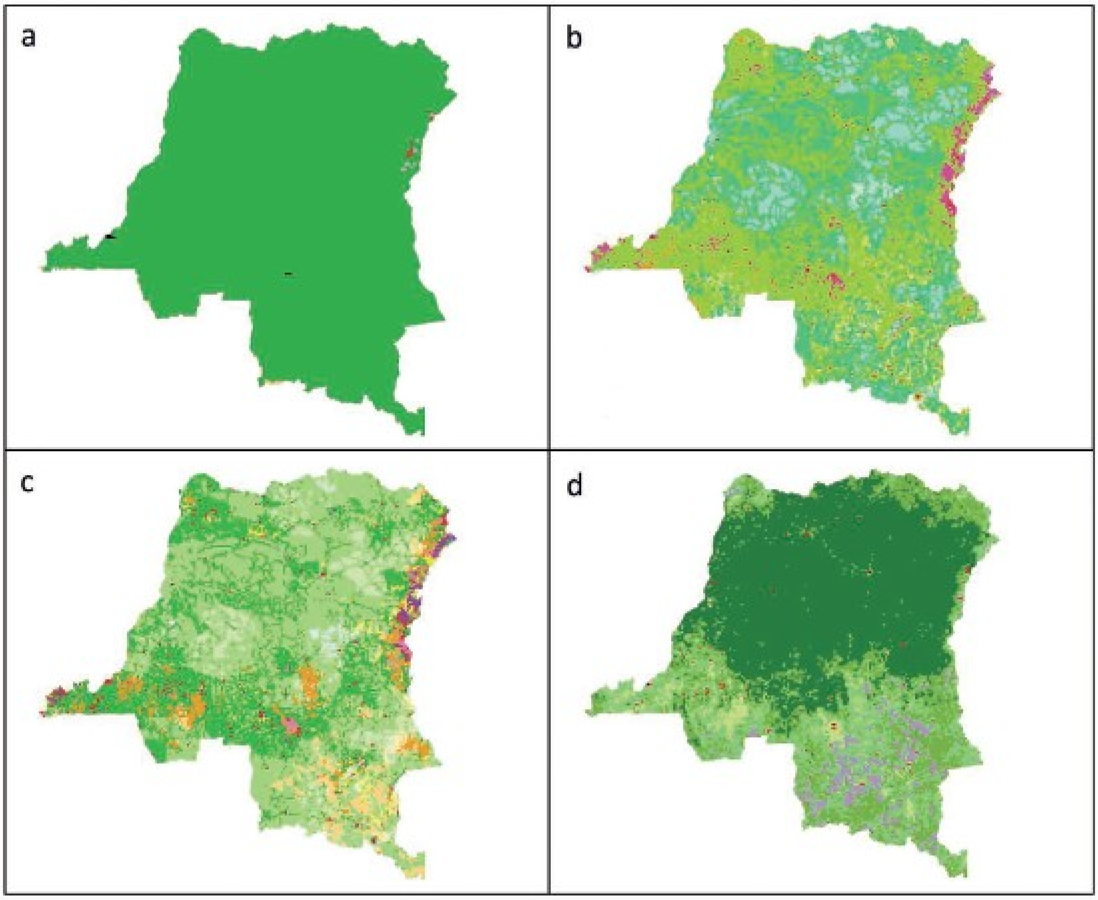

Fig. 2 Comparison of land system archetypes (a), anthropogenic biomes (b), anthromes (c) and land systems (d) on the example of The Democratic Republic of the Congo.

higher number of input classification factors (32) compared to the other studies (Tables 1–2, 4–6). All these classifications were executed at the same 5 arc minute resolution. Sayre et al. (2020) have taken the structural approach. They mapped and subsequently integrated different natural elements. World ecosystems were executed at the 8 arc seconds resolution. Keith et al. (2020) used the combination of top-down and bottom-up approaches, which serves to balance consistency with realism. The IUCN Global ecosystem typology was executed at the 30 arc seconds resolution. Anthropogenic biomes, anthromes, land-use systems and land systems all have a similar structure. They are grouped into six or eight categories respectively; each category is further divided into individual classes. Land system archetypes are completely different, there are 12 categories, which are not further divided. World ecosystems consist of 431 different classes. The IUCN Global ecosystem typology has five categories at the top level further divided into 25 classes and further into 108 units, etc. (Table 8).

Anthropogenic biomes, anthromes, land-use systems and land systems are suitable for further use on a wide range of scales, from global to regional; or a sub-regional scale. Land system archetypes are useful mainly on a global or continental scale (Figure 2).

On the other hand, land system archetypes present the most objective classification and they are based on much more different types of input data. World ecosystems and Global ecosystem typology are created at a much finer spatial resolution. They are useful especially for conservation management.

The availability of individual classifications including a link for download is shown in the following table (Table 9), classifications of Ellis and Ramankutty (2008), Ellis et al. (2010), Van Asselen and Verburg (2012), Václavík et al. (2013), Sayre et al. (2020) and Keith et al. (2020) are for those interested, freely available.

Tab. 9 Availability of global environmental classifications

Name	Authors	Data reference (link for download)
Anthropogenic biomes	Ellis and Ramankutty (2008)	Anthrome Data (https://ecotope.org/anthromes/data/)
Anthromes	Ellis et al. (2010)	Anthrome Data (https://ecotope.org/anthromes/data/)
Land-use systems	Letourneau et al. (2012)	N/A
Land systems	Van Asselen and Verburg (2012)	Global Land System classification data (https://www.environmentalgeography.nl/site/data-models/data/global-land-system-classification/)
Land system archetypes	Václavík et al. (2013)	Land system archetypes (https://www.ufz.de/index.php?en=37603)
World ecosystems	Sayre et al. (2020)	World ecosystems (https://rmgsc.cr.usgs.gov/outgoing/ecosystems/Global/)
IUCN Global ecosystem typology	Keith et al. (2020)	Global ecosystems (https://global-ecosystems.org/)

5. Summary

All the classifications show human-environment interactions, but each in a slightly different way. Interesting regional patterns, similarities on a global level and differences on a sub-national scale – can all be found here. Every classification provides a naturally generalized and simplified picture of a rather diverse reality. The best currently available datasets are used, but the quality and spatial resolution of all the input data are the limiting factors, moreover datasets often capture information for different periods. Many factors that could be very useful for classification aren't available or lack the necessary quality (Ellis and Ramankutty 2008; Letourneau et al. 2012; van Asselen and Verburg 2012; Václavík et al. 2013). Anthropogenic biomes, anthromes, land-use systems, land systems, land system archetypes, world ecosystems or whatever we want to call them, are useful in the better understanding of global human-environment interactions and land-use change impacts, identifying regions with similar policy demands, they can also help with the global change challenges and can be used as inputs for global land change models and other modelling.

Naturally, all classifications presented differ in the purpose of their development, complexity of input variables and range of use by both scientists, international institutions, government bodies and the general public. Anthropogenic biomes and anthromes (Ellis and Ramankutty 2008; Ellis et al. 2010), land-use systems (Letourneau et al. 2012), land systems (van Asselen and Verburg 2012) and land system archetypes (Václavík et al. 2013) have certainly had a significant impact, and each has been cited hundreds or thousands of times. Anthropogenic biomes and anthromes have become part of the Principles of Terrestrial Ecosystem Ecology and the National Geographic Atlas of the World, and have been incorporated into the IUCN Global ecosystem typology (Keith et al. 2020). These classifications have recently been used also in analysing long-term changes (Ellis et al. 2021). The most recent classifications with most likely future impact are, firstly, World ecosystems, the system devised by Sayre et al. (2020) for the Nature Conservancy and IPCC, a useful tool for the Convention on Biological Diversity's (CBD) Aichi Target 11, IUCN, FAO or IPBES. World ecosystems can be used in global conservation, global planning efforts. This system is data-derived with high spatial resolution. On the contrary, WWF Ecoregions (Olson et al. 2001, Dinnerstein et al. 2017) are expert-derived, coarse, and macroscale. And, secondly, the Global ecosystem typology (Keith et al. 2020) approved by the IUCN. Ecosystems of the new IUCN Red List of Ecosystems are classified according to the IUCN Global ecosystem typology, a framework based on ecosystem function and biodiversity.

All the classifications provide a complex global spatial framework incorporating both natural and human factors that influence the functioning of land systems. Therefore, they can be used for the monitoring of global change of land use, ecosystems and biodiversity dynamics, global conservation and much more.

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5.3. Global Environmental Systems – Multivariate Anthropoecological Classification

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Global environmental systems – multivariate anthropoecological classification

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ABSTRACT

Changes to the Earth's environment, increasing anthropogenic pressure, and the global decline of biodiversity bring the need to establish spatial frameworks for the monitoring and assessment of such dynamic processes. Several environmental stratifications have been developed at the global level; however, most of them only include natural conditions in the classification process. Incorporating spatial patterns of biodiversity and the degree of anthropogenic pressure seems to be essential in an era of significant environmental transformation. We developed a new comprehensive classification of Global Environmental Systems based on general abiotic gradients, distribution of biodiversity, and spatial differentiation of human impact. This classification is based on 22 variables covering abiotic, biotic, and anthropogenic factors. We identified 10 abiotic, biotic, and anthropogenic classes using cluster analysis; their combination results in 169 unique Global Environmental Systems (GES) showing human-environment interactions. Each class shows an area with similar abiotic and biotic background and human pressure..

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1. Introduction

Today's world faces a multitude of environmental challenges (e.g. IPBES, 2019; Vitousek et al., 1997), that need to be monitored and evaluated within appropriately chosen spatial frameworks. The increasing demand for integration and harmonisation of global environmental, human-pressure, and biodiversity data requires a precise and robust approach in defining such spatial units. Improved computing technologies, wide availability, and the abundance of Earth Observation (EO) data now enable more quantitative and objective methods to global ecosystem mapping with higher spatial resolution. A number of global classifications that combine different environmental conditions (climate, topography, vegetation/land cover, ecological functions, etc.) have been published (e.g. Keith at al., 2020; Metzger et al., 2013; Sayre et al., 2020); however, just a few of them include comprehensive information on human impact on ecosystems (e.g. Ellis et al., 2010; Ellis & Ramankutty, 2008; Gosling et al., 2020; Letourneau et al., 2012 van Asselen & Verburg, 2012;; Václavík et al., 2013) and biodiversity distribution (e.g. Jenkins et al., 2013; Pimm et al., 2014).

Anthropogenic biomes (Ellis & Ramankutty, 2008) are based on an empirical analysis of direct human-nature interaction. A multistage empirical procedure used global data of land use, land cover and population, missing biotic and abiotic factors. Population density played an important role in the categorisation of human-ecosystem interactions. 18 anthropogenic biome classes and 3 wild biome classes were presented in 6 categories. Two years later, Ellis et al. (2010) used a new *a priori* anthrome classification algorithm built on standardised thresholds and presented a slightly different classification. Letourneau et al. (2012) proposed a new classification based on land use systems characterised by land cover, land use, population pressure, livestock density, and accessibility. The classification has 24 land use systems in 6 categories. van Asselen and Verburg (2012) consider land-use intensity as a crucial characteristic of land systems; 30 land systems can be found in a total of eight categories. Land cover, livestock, and agricultural intensity data were used for classification of land systems; population was not used as a classification criterion.

Both the above-mentioned classifications (anthropogenic biomes and anthromes) do not use biotic and abiotic factors. In previous studies, top-down approaches were used, in the study of Václavík et al. (2013) a bottom-up approach was used driven only by the data. Global land system archetypes were identified based on 32 indicators: biotic, abiotic, and socioeconomic. Land system archetypes are different, there

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are only 12 categories, which are not further divided. Sayre et al. (2020) described a new map of terrestrial world ecosystems, which was derived from global temperature domains, global moisture domains, global landforms, and global vegetation and land use. No socioeconomic data were used in the classification. A total of 431 world ecosystems were identified. The IUCN Global Ecosystem Typology (Keith et al., 2020) is created as a hierarchical classification. In its upper three levels, ecosystems are defined by their convergent ecological functions, while in its lower three levels, ecosystems with differing groups of species influencing those ecological functions are defined. The classification consists of 5 global realms, 25 biomes, 108 ecosystem functional groups, etc. These three levels were developed from the top-down approach.

Therefore, the aim of this paper is to present the development of a new approach of multidimensional classification of Global Environmental Systems based on abiotic, biotic, and anthropogenic factors. The results of this complex classification provide a useful spatial framework for the comparison and analysis of ecological and environmental processes in diverse and heterogeneous regions.

2. Materials and methods

The methodological procedure consists of several sequential steps. First, the abiotic conditions of planet Earth were analysed, in which basic segments were defined on the basis of climate and topography gradients. Within these spatial units, biodiversity gradients were further evaluated; these were seen as an indicator of biotic conditions. At the same time, within the same spatial framework, the level of anthropogenic transformation of the environment was assessed. Cluster analysis of K-means cluster analysis was used as the main tool for these particular assessments. Finally, a synthesis of the partial results was performed, representing a comprehensive global classification of environmental conditions.

2.1. Abiotic factors

The first step was to obtain suitable data that characterise abiotic factors. Climate data were obtained from the WorldClim database (Hijmans et al., 2005) and were available at a spatial resolution of 30 s ($0.93 \times 0.93 = 0.86$ km^2 at the equator). In total there were 19 variables. These variables represent annual trends (e.g. mean annual temperature, annual precipitation), seasonality (e.g. annual range in temperature), and extreme or limiting environmental factors (e.g. temperature of the coldest and warmest quarter, and precipitation of the wet and dry quarters). From these variables, we selected seven that were not highly correlated for further analysis, four representing temperature and three representing precipitation. Data on terrain (altitude) were obtained from the same source (Hijmans et al., 2005), and two other variables (vertical heterogeneity and topographic position index) were derived using ArcGIS (Table 1).

Table 1. Abiotic classification factors.

Abiotic classification factor	Reference
Annual Mean Temperature (BIO1)	Hijmans et al. (2005)
Temperature Annual Range (BIO7)	Hijmans et al. (2005)
Mean Temperature of Warmest Quarter (BIO10)	Hijmans et al. (2005)
Mean Temperature of Coldest Quarter (BIO11)	Hijmans et al. (2005)
Annual Precipitation (BIO12)	Hijmans et al. (2005)
Precipitation of Wettest Quarter (BIO16)	Hijmans et al. (2005)
Precipitation of Driest Quarter (BIO17)	Hijmans et al. (2005)
Altitude	Hijmans et al. (2005)
Vertical Heterogeneity	Derived from Hijmans et al. (2005)
Topographic Position Index	Derived from Hijmans et al. (2005)

Secondly, we standardised ten input rasters, when values were reclassified to the range 0-100. Water bodies larger than 200 km^2 were removed from all rasters because they are not areas of interest in this analysis. As usual in such analyses, many of the input data are correlated with each other. Therefore, in the next step, principal component analysis (PCA) was performed to reduce multicollinearity and reduce the input dimension of the dataset. Such a procedure leads to identification of a smaller number of uncorrelated variables (called principal components) from a large set of data. The goal of PCA is to explain the maximum amount of variance with the fewest number of principal components. PCA generated a single multiband raster as output; the most suitable number of principal components was set at four. This raster subsequently underwent a segmentation process in eCognition, specifically we used a multiresolution segmentation that was iterated several times with fixed settings of image layer weights based on PCA and different scale parameters, shape, and compactness. The final parameter setting was set as follows: scale 100, shape 0.1, and compactness 0.5, leading to a segmentation layer consisting of 44 418 segments. Segments covering the water surface and those smaller than 5 km^2 were erased, resulting in a final number of 18 554 segments.

2.2. Biotic factors

Biotic factors were represented by terrestrial vertebrates and plant diversity, which reflects natural conditions and also long-term human management. Data for the total species richness of mammals, birds, and amphibians were obtained from the Biodiversity Mapping website (Jenkins et al., 2013; Pimm et al., 2014); data for plant diversity came from the

Table 2. Biotic classification factors.

Biotic classification factor	Reference
Species Richness of Mammals	Jenkins et al. (2013); Pimm et al. (2014)
Species Richness of Birds	Jenkins et al. (2013); Pimm et al. (2014)
Species Richness of Amphibians	Jenkins et al. (2013); Pimm et al. (2014)
Species Richness of Plants	Kier et al. (2005)

work of Kier et al. (2005) (Table 2). As the next step, the mean, maximum, and minimum values of ten abiotic and four biotic variables were calculated for every segment of the layer.

2.3. Anthropogenic factors

The level of anthropogenic impact was assessed by using data on population density (CIESIN, 2005), average accessibility (Nelson, 2008), and livestock density aggregating partial densities of cattle, pigs, goats, sheep, and chickens (Robinson et al., 2014) within the above-mentioned segments. Furthermore, 17 global land cover classes (ESA Land Cover global raster data, 2017) were analysed within segments. Land cover, which was originally classified into 37 classes, was generalised to 17 categories; these were used in the final anthropogenic classification (Table 3).

Similarly to the previous step, the mean, maximum, and minimum values of anthropogenic variables were calculated within all segments. Land cover was analysed for every segment based on ESA Land Cover global raster data (2017). The total area, number of patches, and percentage of all 37 classes in each segment was calculated using Python script.

The values of all continuous abiotic, biotic, and anthropogenic variables were standardised (mean = 0, standard deviation = 1) to run cluster classification in IBM SPSS software (IBM Corp., 2020). In the case of abiotic and biotic classifications, the K-means method of clustering was used; due to inclusion of categorical variables in the case of anthropogenic classification, the two-step clustering method was used. The number of clusters was set at ten for all particular classifications: abiotic, biotic, and anthropogenic.

The combination of abiotic and biotic classification could potentially create 100 abio + bio classes, but in reality, 59 classes emerged. Classes with similar biotic characteristics belonging to the same abiotic class were merged, resulting in a final number of 30 abio + bio classes. These abio + bio classes were then combined

Table 3. Anthropogenic classification factors.

Anthropogenic classification factor	Reference
Cattle distribution	Robinson et al. (2014)
Pig distribution	Robinson et al. (2014)
Goat distribution	Robinson et al. (2014)
Sheep distribution	Robinson et al. (2014)
Chicken distribution	Robinson et al. (2014)
Population density	CIESIN (2005)
Accessibility	Nelson (2008)
Global land change	ESA Land Cover (2017)

Table 4. Characteristics of abiotic classification.

	Annual Mean Temperature	Mean Temperature of Warmest Quarter	Mean Temperature of Coldest Quarter	Temperature Annual Range	Annual Precipitation	Precipitation of Wettest Quarter	Precipitation of Driest Quarter	Altitude	Vertical Heterogeneity	TPI	Number of Segments	Area [%]
Class 1	−16.03	−0.32	−29.35	38.25	438.19	152.16	80.25	953.26	34.54	−0.57	2 372	3.38
Class 2	−11.20	10.11	−32.25	56.71	327.49	156.00	32.94	452.47	49.64	0.27	1 683	7.11
Class 3	0.42	9.55	−9.34	34.47	452.19	230.06	34.75	3 578.57	191.79	10.88	910	4.42
Class 4	−1.66	14.32	−18.59	47.20	513.37	217.07	64.89	402.25	32.42	−0.20	1 834	10.98
Class 5	5.01	14.18	−4.20	28.86	852.86	294.99	144.33	399.59	68.53	−0.56	2 871	7.08
Class 6	8.57	21.80	−5.52	43.01	366.51	154.99	40.97	843.89	38.59	−1.00	1 275	9.86
Class 7	16.62	23.25	9.50	28.05	769.04	328.89	84.76	701.99	56.96	−0.90	1 910	12.70
Class 8	24.10	30.96	16.20	31.44	169.58	102.84	7.87	430.52	15.74	−0.48	1 351	16.84
Class 9	24.44	26.74	21.73	19.33	1 161.19	608.32	47.04	512.42	37.08	−0.62	1 989	17.73
Class 10	25.39	26.22	24.36	12.62	2 461.61	998.86	268.13	283.97	47.76	−1.20	2 359	9.91

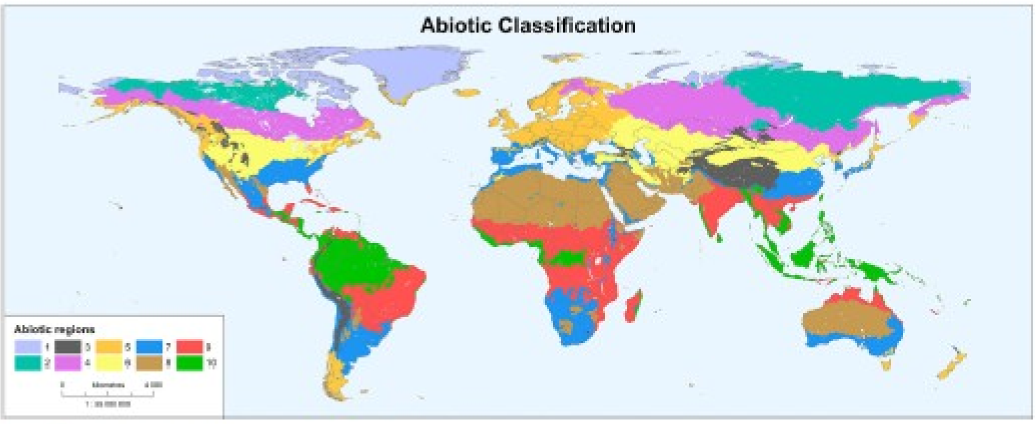

Figure 1. Abiotic classification

with anthropogenic classification. Of the 300 potential classes, just 169 types of Global Environmental Systems (GES) were identified.

3. Results & discussion

Abiotic classes form a logical gradient from the coldest to the warmest (Table 4, Figure 1, Main Map), from the poles to the equator, with one exception: class 3 describes the highest mountain areas (average altitude: 3579 m). Class 1 is the coldest, and can be characterised as a freezing arctic region, with an annual mean temperature of −16.03 ° C; in contrast, Class 10 is the warmest (25.39 °C) with the highest annual precipitation (2462 mm), therefore it can be characterised as a warm and humid equatorial region. Class 2 is a cold northern region with a significant temperature annual range, there is the highest temperature amplitude of 56.71 °C. Class 4 is a colder temperate zone of the northern hemisphere. It is the last class where the annual mean temperature is negative: −1.66 °C. The temperature annual range has a value of 47.2 °C. A humid temperate region, that is Class 5. The annual mean temperature here is 5.01 °C and the annual precipitation is relatively high: 853 mm. And the last of the temperate regions is Class 6 characterised as a warmer and drier temperate zone of the northern hemisphere. Classes 1, 2, 4 and 6 are completely absent in the southern hemisphere. Class 7 can be found in the subtropics of both hemispheres. The annual mean temperature is much higher (16.62 °C) than in the previous class and the coldest quarter of the year is much warmer. Class 8 is located in deserts and semi-deserts of the tropics, is very extensive and typical of high temperatures and the lowest annual precipitation (170 mm). Class 9 occupies 17.73% of the Earth's landmass, which makes this class the most extensive. It is a subequatorial region with a drier period typical of high temperatures and annual precipitation, but the precipitation of the driest quarter is only 47 mm.

Spatial distribution of biotic classes is similar to the idea of biodiversity distribution on Earth (Table 5, Figure 2, Main Map). Class 7 is the poorest in terms of both fauna and flora biodiversity with only 19 mammal species, 53 bird species, 2 amphibian species and 588 plant species on average. This class is very extensive (23.50%) and can be found in high latitude areas and in areas of cold and warm deserts. Class 2 is the second poorest and is even bigger (32.61%), and is located next to class 7. Classes 6, 1, and 9, on the other hand, are the richest. They are found in equatorial regions of America, Africa, and Southeast Asia. Class 6 is typical of the highest fauna biodiversity with 168 mammal species, 492 bird species and 84 amphibian species, Class 1 has the highest flora

Table 5. Characteristics of biotic classification.

	Mammals	Birds	Amphibians	Plants	Number of Segments	Area [%]
Class 1	139.30	418.29	45.27	6 263.24	329	3.31
Class 2	37.65	151.95	4.79	1 283.91	5 257	32.61
Class 3	57.91	214.89	10.28	2 389.73	1 894	14.59
Class 4	104.62	318.49	20.09	5 866.97	445	2.95
Class 5	38.83	145.15	8.10	4 532.68	743	0.52
Class 6	167.87	492.19	84.07	6 168.79	249	3.81
Class 7	18.53	52.55	1.64	588.36	7 696	23.50
Class 8	50.04	215.30	25.31	2 259.29	555	4.76
Class 9	133.74	402.61	38.12	3 123.06	497	5.10
Class 10	99.04	326.78	23.94	2 455.29	889	8.85

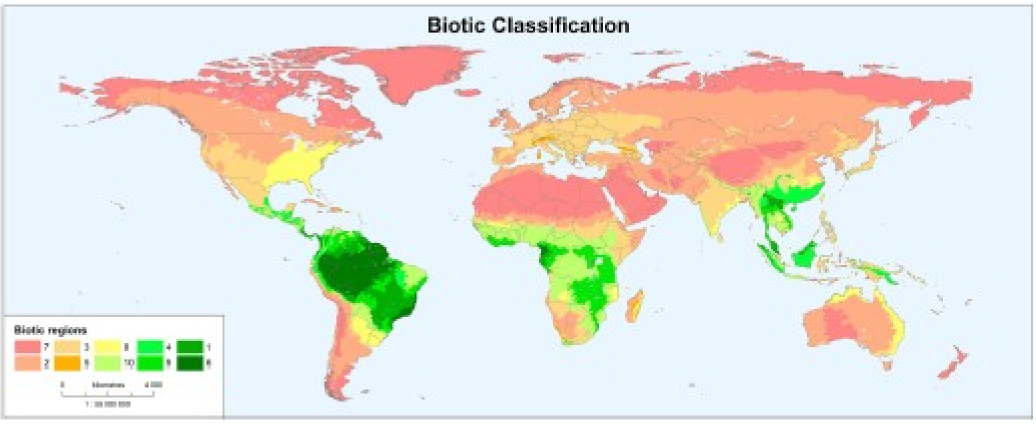

Figure 2. Biotic classification

Table 6. Characteristics of anthropogenic classification.

	Livestock Density	Accessibility	Human Density	Predominant Land Cover	Number of Segments	Area [%]
Class 1	1.50	9 764.58	2.45	GLC 17	689	1.98
Class 2	353.54	156.15	462.43	GLC 1, 2	887	4.26
Class 3	4.46	2 840.49	0.48	GLC 12	1 989	6.17
Class 4	12.70	1 039.64	10.20	GLC 5	2 300	8.19
Class 5	22.18	562.35	24.42	GLC 4, 7, 8, 13	2 175	12.31
Class 6	26.26	1 257.76	21.41	GLC 3	2 330	11.19
Class 7	99.31	175.45	94.92	GLC 1	1 907	15.88
Class 8	30.84	831.99	12.38	GLC 9, 10	2 981	19.94
Class 9	16.50	1 527.45	6.01	GLC 15	1 771	14.25
Class 10	0.72	2 394.74	0.51	GLC 6, 11	1 525	5.82

Land cover classes: **GLC 1** - Cropland, rainfed; Herbaceous cover; Tree or shrub cover; Cropland, irrigated or post-flooding, **GLC 2** - Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%); Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%), **GLC 3** - Tree cover, broadleaved, evergreen, closed to open (>15%), **GLC 4** - Tree cover, broadleaved, deciduous, closed to open (>15%); Tree cover, broadleaved, deciduous, closed (>40%); Tree cover, broadleaved, deciduous, open (15-40%), **GLC 5** - Tree cover, needleleaved, evergreen, closed to open (> 15%); Tree cover, needleleaved, evergreen, closed (>40%); Tree cover, needleleaved, evergreen, open (15-40%), **GLC 6** - Tree cover, needleleaved, deciduous, closed to open (>15%); Tree cover, needleleaved, deciduous, closed (>40%); Tree cover, needleleaved, deciduous, open (15-40%), **GLC 7** - Tree cover, mixed leaf type (broadleaved and needleleaved), **GLC 8** - Mosaic tree and shrub (>50%) / herbaceous cover (<50%); Mosaic herbaceous cover (>50%) / tree and shrub (<50%), **GLC 9** - Shrubland; Evergreen shrubland; Deciduous shrubland, **GLC 10** - Grassland, **GLC 11** - Lichens and mosses, **GLC 12** - Sparse vegetation (tree, shrub, herbaceous cover) (<15%); Sparse tree (< 15%); Sparse shrub (<15%); Sparse herbaceous cover (< 15%), **GLC 13** - Tree cover, flooded, fresh or brakish water; Tree cover, flooded, saline water; Shrub or herbaceous cover, flooded, fresh/saline/brakish water, **GLC 14** - Urban areas, **GLC 15** - Bare areas; Consolidated bare areas; Unconsolidated bare areas, **GLC 16** - Water bodies, **GLC 17** - Permanent snow and ice

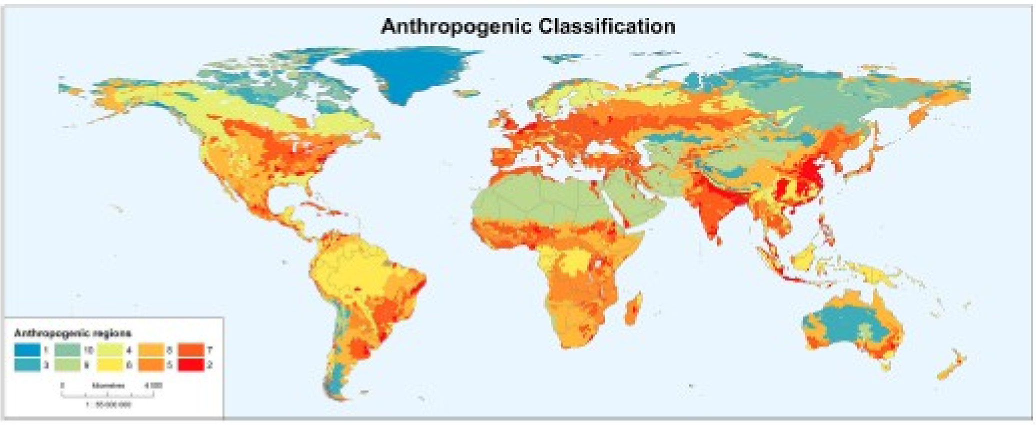

Figure 3. Anthropogenic classification

biodiversity with 6263 plant species on average. Class 5 is the smallest biotic class (0.52%) and is characterised by a large difference in the species richness of fauna and flora. While the diversity of fauna is low, the flora is very rich. All biotic classes are represented in both hemispheres.

Table 7. Characteristics of thirty abio + bio classes.

Class	Abio + Bio Codes	Mammals	Birds	Amphibians	Plants	Annual Mean Temp.	Mean Temp. of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp. Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip. of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Number of Segments	Area [km²]	Area [%]
A	17	7.67	24.02	1.00	212.87	−16.03	−0.32	−29.35	38.25	438.19	152.16	80.25	953.26	34.54	−0.57	2372	4 509 843	3.38
B	22; 27	28.05	102.73	1.75	899.57	−11.20	10.11	−32.25	56.71	327.49	156.00	32.94	452.47	49.64	0.27	1683	9 484 710	7.11
Ca	33; 39; 310	69.20	218.01	6.72	2530.86	2.79	11.48	−6.59	33.62	662.50	323.07	48.75	3054.23	230.28	15.43	258	1 418 906	1.06
Cb	34; 35	99.36	258.30	9.09	5066.13	8.29	12.51	3.66	21.68	1063.16	440.86	118.46	2624.64	277.28	23.06	71	412 479	0.31
Cc	32; 37	33.58	108.34	2.69	1219.14	−1.13	8.60	−11.51	35.96	322.12	178.07	22.08	3849.76	170.44	8.17	581	4 065 325	3.05
Da	42; 43	41.75	156.67	4.17	1178.75	−0.98	15.11	−18.22	47.92	507.03	218.48	61.34	426.78	32.43	−0.21	1324	12 605 613	9.45
Db	47	26.28	71.63	1.78	779.29	−5.35	10.07	−20.55	43.35	547.46	209.53	83.97	270.42	32.37	−0.19	510	2 039 862	1.53
Ea	53; 58	55.25	168.33	12.81	2384.78	7.77	17.65	−2.59	31.15	742.50	260.04	127.21	351.21	46.46	0.41	330	3 763 862	2.82
Eb	55	64.86	124.97	8.67	4954.88	3.97	12.04	−4.26	26.37	1293.17	428.19	240.51	1448.17	282.17	12.38	12	76 258	0.06
Ec	52	37.66	144.55	5.80	1328.05	4.28	13.71	−5.03	29.60	860.33	309.84	133.39	436.98	75.86	−1.25	1112	3 682 350	2.76
Ed	57	15.78	83.32	1.59	699.19	1.97	9.61	−5.26	23.96	1000.53	319.51	188.11	376.70	83.66	−1.23	1417	1 925 294	1.44
Fa	63; 65; 68	54.95	169.48	10.36	2434.61	8.64	20.54	−3.69	39.51	546.63	202.95	79.14	864.85	48.67	−1.66	363	3 574 425	2.68
Fb	62; 67	39.16	127.99	4.87	1316.03	8.54	22.27	−6.21	44.31	299.38	137.12	26.75	836.08	34.84	−0.76	912	9 578 430	7.18
Ga	71; 74	92.89	320.21	25.04	5549.39	16.74	23.22	9.31	25.45	1338.01	631.40	115.74	1036.77	144.71	−0.85	118	1 165 589	0.87
Gb	79; 710	102.79	375.48	27.17	2567.00	18.36	21.77	13.76	24.09	969.28	517.81	45.14	1320.54	71.82	1.06	179	2 010 233	1.51
Gc	73; 78	54.90	213.17	18.08	2519.75	16.53	23.83	8.68	29.43	907.35	357.07	121.03	609.92	50.58	−1.09	727	7 860 848	5.89
Gd	75	39.75	144.93	5.21	4012.36	16.01	21.72	10.46	22.89	396.39	170.78	30.65	429.48	67.69	−1.51	133	138 350	0.10
Ge	72; 77	31.52	148.88	6.03	1399.42	16.20	22.98	9.29	28.06	421.72	178.53	43.80	575.65	44.10	−1.26	753	5 764 459	4.32
Ha	83; 88; 89; 810	62.40	257.47	12.99	1840.49	24.17	29.56	18.11	28.52	466.29	294.99	16.86	403.35	16.80	−0.81	126	2 102 486	1.58
Hb	82; 85	31.85	156.01	5.25	1091.61	24.00	30.38	16.64	30.29	256.02	155.47	13.53	380.83	18.16	−0.79	490	7 978 945	5.98
Hc	87	17.53	39.24	1.99	717.06	24.15	31.57	15.60	32.67	64.23	36.77	2.73	467.00	14.00	−0.23	735	12 376 256	9.28
Ia	91; 94; 96	126.57	398.28	44.46	5994.01	22.89	25.01	20.04	18.30	1466.89	695.36	84.47	526.65	57.34	−0.52	333	4 309 194	3.23
Ib	99	131.97	401.53	38.73	3023.79	23.21	24.79	21.02	17.56	1215.67	583.30	60.71	718.05	41.37	−0.12	293	4 415 565	3.31
Ic	93; 98; 910	82.73	298.41	20.42	2223.11	25.28	27.85	22.49	20.23	1070.63	596.22	31.63	459.49	29.11	−0.75	933	13 610 003	10.20
Id	95	16.19	114.51	8.12	3373.74	22.30	24.18	19.47	18.09	1500.12	848.84	66.87	734.05	70.25	−1.62	52	109 879	0.08
Ie	92; 97	27.62	150.45	8.44	1860.00	25.32	27.74	22.09	19.45	845.31	497.62	33.51	293.72	34.80	−1.14	378	1 200 975	0.90
Ja	101; 104; 106	155.21	445.71	62.90	6305.01	25.45	26.05	24.71	12.27	2523.94	959.40	307.22	276.06	42.57	−0.98	528	7 694 919	5.77
Jb	103; 108; 109; 1010	101.18	330.94	25.59	3193.89	25.33	26.50	23.89	13.32	2366.40	1061.40	202.18	301.04	52.46	−1.30	576	5 038 325	3.78
Jc	105	22.52	157.76	12.96	5045.96	24.85	25.90	23.48	10.84	2645.76	996.66	413.20	252.65	72.07	−3.29	512	196 530	0.15
Jd	102; 107	20.96	153.28	5.81	1767.20	25.16	26.11	23.86	10.60	2351.87	948.10	290.21	214.28	86.80	−3.94	743	282 883	0.21

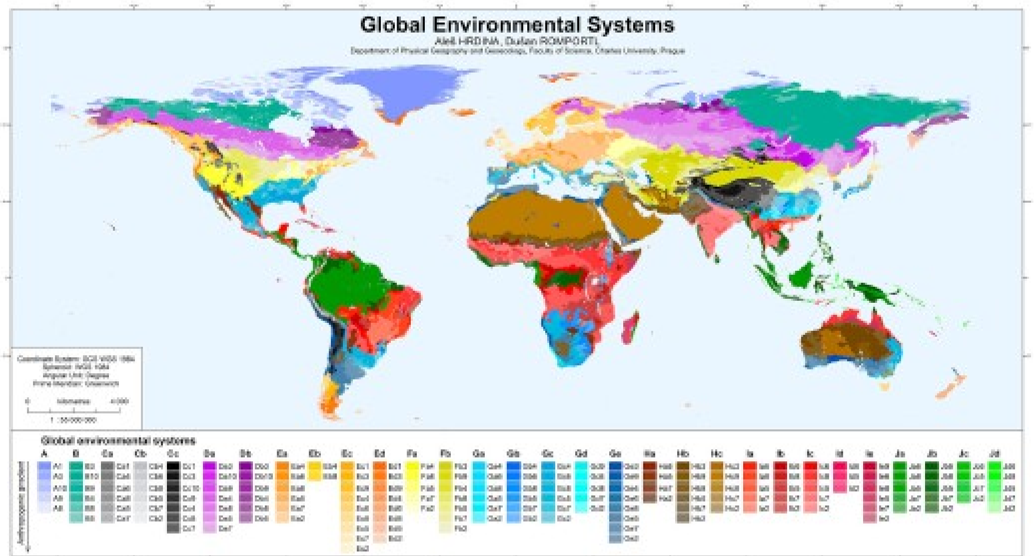

Figure 4. Global Environmental Systems

Anthropogenic classes do not create such a clear pattern (Table 6, Figure 3, Main Map). Class 1 is characterised by one of the lowest livestock density and human density, with the lowest accessibility. This class has the smallest area (1.98%) and is located at the highest altitudes and in the highest mountains of Asia. The typical land cover class is permanent snow and ice. Classes 3 and 10 also have very low values for all attributes and the former is covered with sparse (<15%) vegetation (tree, shrub, herbaceous cover); the latter is typical of tree cover, needle-leaved, deciduous, and lichens and mosses land cover classes. The attributes of other classes are gradually higher and higher: Class 9 is characterised by bare areas land cover class; Class 4 by tree cover, needleleaved, evergreen; Class 6 by tree cover, broadleaved, evergreen; Class 8 is the most extensive anthropogenic class covering almost a fifth of the landmass and is covered by shrubland and grassland; and finally Class 5 mainly by tree cover, broadleaved, deciduous and to a lesser extent by tree, shrub and herbaceous cover, flooded; mosaic tree and shrub / herbaceous cover; or tree cover, mixed leaf type. Classes 7 and 2 can be found at the other end of the anthropogenic classification, with very high human and livestock density and accessibility. The predominant types of land cover are cropland and mosaic cropland / natural vegetation.

The combination of abiotic and biotic classification resulted in the creation of 30 new abio + bio classes (Table 7, Figure 4, Main Map). The letters 'A' to 'J' indicate affiliation with one of the original ten abiotic classes (1–10), and the letters 'a' to 'e' distinguish individual biotic classes or groups of classes. Class A is a simple combination of abiotic Class 1 and biotic Class 7, i.e. the coldest area with the lowest biodiversity. Class B combines abiotic Class 2 with biotic Classes 2 and 7. All other classes 'C' to 'J' are further divided into two, three, four, or five classes. For example, class Cb represents the warmest areas of the abiotic mountain class 3, with the highest annual precipitation, lying at the lowest altitude, and having the highest biodiversity of both fauna and flora. Table 7 gives a detailed overview of each of the 30 abio + bio classes.

These abio + bio classes were combined with the anthropogenic classification, resulting in 169 unique Global Environmental Systems (Figure 4, Main Map). Each GES has its own code assigned, this code consists of one or two letters and a number, e.g. Hc3. The letters indicate abio + bio affiliation, and the number indicates affiliation to the anthropogenic class.

The result of our analyses presented above represents a comprehensive classification of global systems. Several such classifications have already been developed, but the approach we present includes probably the widest range of input variables, uses actual data, and combines modern approaches with their processing.

4. Conclusions

The presented global classification of environmental systems shows the complex output of the geographical synthesis. The classification presents 169 classes – Global Environmental Systems (GES) – that have been developed by a combination of different natural (both abiotic and biotic) and anthropogenic factors.

Each GES is characterised by its own range of values: abiotic (e.g. temperature, precipitation, altitude); biotic (species richness); and anthropogenic (human density, livestock density, accessibility, land cover). The basic spatial unit of classification are segments created using object-oriented image analysis – multiband raster with 1 × 1 km resolution.

The classification of environmental systems is thus applicable from the global to the regional spatial level. Its use is suitable, for example, for assessing the impacts of global climate change, monitoring changes in landscape cover, or monitoring of biodiversity. We therefore believe that it will find its use as a basic spatial framework among geographers, environmental scientists and representatives of biological disciplines.

Data availability statement

The data that support the findings of this study are openly available in Science Data Bank at http://doi.org/10.11922/sciencedb.01665.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Software

The process of segmentation was carried out in eCognition Developer 64, land cover was analysed using the Python 2.7 script, cluster analyses were carried out in IBM SPSS Statistics 25 and 27, and all the other analyses in ArcGIS 10.6-10.8.

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5.4. Global Environmental Systems – A Spatial Framework for Better Understanding the Changing World

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Article

Global Environmental Systems—A Spatial Framework for Better Understanding the Changing World

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Abstract: Purely natural land formations are increasingly rare in today's world, as most areas have been shaped, to varying degrees, by human influence over time. To better understand ongoing changes in the natural environment, we adopted an approach that involves identifying global systems with a significant anthropogenic component. In this study, we developed a new classification of Global Environmental Systems based on over 20 high-resolution datasets, covering abiotic, biotic, and anthropogenic conditions. We created abiotic, biotic, and anthropogenic classifications, each with ten classes. The combinations of these classes result in 169 distinct classes of Global Environmental Systems. This classification provides a suitable spatial framework for monitoring land use dynamics, biodiversity changes, global climate change impacts, and various processes exhibiting complex spatial patterns.

Keywords: global classification; biodiversity hotspots; anthropogenic impact; environmental transformation; Global Environmental Systems

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1. Introduction

The human dominance of ecosystems and natural processes not only deepens the environmental and biodiversity crisis but also worsens the wellbeing of communities and entire societies dependent on natural resources [1]. Addressing these crises must occur within suitable spatial and typological frameworks that enable appropriate measures for regional conditions. Global classifications of biomes considering the level of anthropogenic degradation provide such a suitable spatial typological framework to assess biodiversity status and the degree of threat to it [2]. The quality of the environment and the extent of its degradation by humans are typically assessed by habitat conditions, biodiversity levels, or the provision of ecosystem services. Biodiversity status is then employed as a common measure of the environmental state.

The uneven distribution of biodiversity on Earth is primarily determined by different abiotic conditions [3] and the evolution of biomes, as well as the size, connectivity, and history of specific ecosystems [4]. In recent centuries, human activities have increasingly influenced the distribution of biodiversity, both directly and through various indirect impacts [5,6]. The intensification of anthropogenic pressure in recent decades has led many authors to characterise this period as a new epoch in Earth's evolution—the Anthropocene [7–10]. The Anthropocene is marked by large-scale changes in ecosystems, including their increasing fragmentation [11], threats to biodiversity from biological invasions, and a host of other global challenges. These changes pose significant questions for society on how to effectively address and protect existing biodiversity [6].

Thus, for the effective protection of biodiversity, we require not only knowledge of its spatial distribution but also comprehensive information on the pressures acting upon it and the posing threats [12]. In addition to providing a basic description of the distribution of life conditions on Earth, such as biomes, environmental classification approaches have evolved to incorporate the significant anthropogenic influence [13]. The natural environment has been classified in many different ways in the past. Allee created biome types [14]; Kendeigh later presented different terrestrial and marine biomes [15]; Whittaker presented the classification of biome types [16]; Goodall edited a book on ecosystem types or biomes: terrestrial, underground, and aquatic [17]; Schultz created the classification of eco-zones [18]; Bailey developed a biogeographical classification system of ecoregions [19]; and in 1998, Olson and Dinnerstein came up with biogeographic realms and biomes [20,21]. In recent years, more complex classifications of anthropogenic biomes [6], anthromes [13], land use systems [22], land systems [23], land system archetypes [24], world ecosystems [2] and the IUCN Global Ecosystem Typology [25] have emerged. In this era of a global biodiversity crisis [26], there is a pressing need for a tool to prioritise spatial conservation, which remains the traditional approach for biodiversity conservation.

The aim of this study was to develop a complex classification of Global Environmental Systems (GES) that could be used for a comprehensive assessment of the degree of human influence on the environment in relation to known biodiversity in the context of geographical gradients. This proposal of comprehensive classification more thoroughly captures the wide range of conditions that will be transforming on the Earth in the future—not only in terms of the gradients of natural (especially climatic) factors, but also the intensity and novel spatial differentiation of anthropogenic pressure and the corresponding distribution of biodiversity. This study thus presents a methodological approach for defining Global Environmental Systems, providing their basic characterisation and their use for assessing the urgency of nature and landscape conservation within biodiversity hotspots.

2. Materials and Methods

For the purpose of developing a new global classification and prioritising nature conservation on Earth, we need to classify both the environmental conditions and distribution of biodiversity as well as the degree of anthropogenic degradation. While biodiversity distribution and conservation priorities are well represented, new methodological approaches are needed to assess environmental conditions, including the degree of human impact. The methodological approach therefore consists of two main steps—an assessment of global environmental conditions and a subsequent assessment of biodiversity status within biodiversity hotspots.

The development of the classification of Global Environmental Systems was a long-term process that required several sequential steps. Once the different datasets covering abiotic, biotic, and anthropogenic conditions were selected, the individual analyses could begin. A principal component analysis (PCA) was performed first, followed by multiresolution segmentation. Each segment was filled with values of all abiotic, biotic, and anthropogenic variables; land cover was analysed using a Python script. As the next step, a cluster analysis was performed; both a K-Means cluster analysis and a TwoStep cluster analysis were executed. A synthesis of the resulting abiotic, biotic, and anthropogenic classifications created 169 types of Global Environmental Systems.

2.1. Global Environmental Systems Classification

This classification is complex as it is based on abiotic, biotic, and anthropogenic factors. The first step in the classification process was to obtain suitable abiotic data characterising the Earth's landmass. The climate data come from the WorldClim database [27], where 19 different variables characterising temperature or precipitation were available. The spatial resolution of all data layers is 30 s ($0.93 \times 0.93 = 0.86$ km^2 at the equator). These variables represent seasonality, annual trends, and extreme or limiting environmental factors. From all of these variables, seven not highly correlated variables were selected for further analysis (Table 1).

The annual mean temperature, mean temperature of warmest quarter, mean temperature of coldest quarter, and temperature annual range characterise the temperature conditions; the annual precipitation, precipitation of wettest quarter, and precipitation of driest quarter characterise the precipitation conditions. The altitude data layer comes from the same database [27]; the last two variables (topographic position index and vertical heterogeneity) were derived in ArcGIS (Table 1). Soils and other factors considered were not included because datasets of sufficient resolution and quality were not available at the global level.

Table 1. Abiotic classification factors.

Abiotic Classification Factor	Reference
Annual Mean Temperature (BIO1)	Hijmans et al. (2005) [27]
Temperature Annual Range (BIO7)	Hijmans et al. (2005) [27]
Mean Temperature of Warmest Quarter (BIO10)	Hijmans et al. (2005) [27]
Mean Temperature of Coldest Quarter (BIO11)	Hijmans et al. (2005) [27]
Annual Precipitation (BIO12)	Hijmans et al. (2005) [27]
Precipitation of Wettest Quarter (BIO16)	Hijmans et al. (2005) [27]
Precipitation of Driest Quarter (BIO17)	Hijmans et al. (2005) [27]
Altitude	Hijmans et al. (2005) [27]
Vertical Heterogeneity	Derived from Hijmans et al. (2005) [27]
Topographic Position Index	Derived from Hijmans et al. (2005) [27]

These ten abiotic input rasters were then standardised, and values were reclassified to the range of 0–100 in order to perform a principal component analysis (PCA). This is a procedure that identifies a smaller number of uncorrelated variables called principal components from a large set of data. The analysis is intended to explain the maximum possible amount of variance using the fewest number of principal components. The result of our analysis is a multiband raster with four principal components, which was the most appropriate number of the several variants tested. Once we had the multiband raster, we could run segmentation in eCognition software (eCognition Developer 64), more precisely, the multiresolution segmentation algorithm that was carried out several times. The parameters of the multiresolution segmentation were set as follows—image layer weights L1: 77.4, L2: 12.8, L3: 6.3, L4: 3.4 based on PCA; scale parameter: 100; shape parameter: 0.1; compactness parameter: 0.5. These settings ensured that the number of segments was not too large and that the shape was neither too regular nor irregular. The rough final segmentation layer based on climate and topography gradients consisted of 44,418 segments, which was further reduced to 18,554 segments as all the water areas and segments smaller than 5 km^2 were removed.

As the next step within these spatial units, the mean, maximum, and minimum values of ten abiotic, four biotic, and seven anthropogenic variables were calculated in ArcGIS for each segment out of a total of 18,554 segments. The biotic factors in this study were represented by the terrestrial diversity of plants and vertebrates. The four biotic variables (Table 2) used were the species richness of mammals, birds, and amphibians derived from the Biodiversity Mapping website [28,29]; and plant diversity coming from the work of Kier et al. [30]. All biotic variables mirror natural conditions, long-term evolution, and human impact and management.

Table 2. Biotic classification factors.

Biotic Classification Factor	Reference
Species Richness of Mammals	Jenkins et al. (2013) [28]; Pimm et al. (2014) [29]
Species Richness of Birds	Jenkins et al. (2013) [28]; Pimm et al. (2014) [29]
Species Richness of Amphibians	Jenkins et al. (2013) [28]; Pimm et al. (2014) [29]
Species Richness of Plants	Kier et al. (2005) [30]

Among the variables used for the analysis of the anthropogenic transformation of the environment (Table 3) were livestock density, which is composed of partial densities of cattle, pigs, sheep, goats, and chickens [31]; population density [32]; and accessibility [33]. Global land cover was also analysed within the segments [34]. The total area, number of patches, and percentage of all land cover classes in each segment were calculated using a Python script. Land cover was originally classified in 37 classes and was subsequently generalised into 17 categories (Table 4) that were utilised in the final anthropogenic classification.

Table 3. Anthropogenic classification factors.

Anthropogenic Classification Factor	Reference
Cattle distribution	Robinson et al. (2014) [31]
Pig distribution	Robinson et al. (2014) [31]
Sheep distribution	Robinson et al. (2014) [31]
Goat distribution	Robinson et al. (2014) [31]
Chicken distribution	Robinson et al. (2014) [31]
Population density	CIESIN (2005) [32]
Accessibility	Nelson (2008) [33]
Global land cover	ESA Land Cover (2017) [34]

Table 4. Land cover categories.

GLC Category	Land Cover Classes
GLC1	Cropland, rainfed
	Herbaceous cover
	Tree or shrub cover
	Cropland, irrigated, or post-flooding
GLC2	Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)
	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)
GLC3	Tree cover, broadleaved, evergreen, closed to open (>15%)
GLC4	Tree cover, broadleaved, deciduous, closed to open (>15%)
	Tree cover, broadleaved, deciduous, closed (>40%)
	Tree cover, broadleaved, deciduous, open (15–40%)
GLC5	Tree cover, needleleaved, evergreen, closed to open (>15%)
	Tree cover, needleleaved, evergreen, closed (>40%)
	Tree cover, needleleaved, evergreen, open (15–40%)
GLC6	Tree cover, needleleaved, deciduous, closed to open (>15%)
	Tree cover, needleleaved, deciduous, closed (>40%)
	Tree cover, needleleaved, deciduous, open (15–40%)
GLC7	Tree cover, mixed leaf type (broadleaved and needleleaved)
GLC8	Mosaic tree and shrub (>50%)/herbaceous cover (<50%)
	Mosaic herbaceous cover (>50%)/tree and shrub (<50%)
GLC9	Shrubland
	Evergreen shrubland
	Deciduous shrubland
GLC10	Grassland
GLC11	Lichens and mosses
GLC12	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)
	Sparse tree (<15%)
	Sparse shrub (<15%)
	Sparse herbaceous cover (<15%)
GLC13	Tree cover, flooded, fresh or brackish water
	Tree cover, flooded, saline water
	Shrub or herbaceous cover, flooded, fresh/saline/brackish water
GLC14	Urban areas
GLC15	Bare areas
	Consolidated bare areas
	Unconsolidated bare areas
GLC16	Water bodies
GLC17	Permanent snow and ice

Once all of this was completed, the values of all continuous variables abiotic, biotic, and anthropogenic had to be standardised with a mean equal to 0 and standard deviation equal to 1 in order to run a cluster analysis in IBM SPSS software (IBM SPSS Statistics 25 and 27) [35]. Different types of classifications were executed for abiotic and biotic data and for anthropogenic data, respectively. In the case of the cluster analyses of abiotic and biotic data, the K-Means cluster analysis was performed (with a setting of a maximum of 100 iterations). In the case of anthropogenic data, where both continuous (population density, livestock density, accessibility) and categorical variables (land cover) are present, the TwoStep cluster analysis was executed. The classification process was performed many times with different settings for the number of clusters; finally, the number of ten clusters was set for all particular classifications: abiotic, biotic, and anthropogenic. A synthesis of the partial results was then performed; the abiotic and biotic classifications were combined in ArcGIS, and potentially, they could have created 100 natural (abiotic + biotic) classes. But the result was actually the creation of 59 classes. Classes with distinctly similar biotic characteristics that belonged to the same abiotic class were merged, which led to a reduction in the number of classes to a final 30 natural classes. The natural classes were then combined with the anthropogenic classification. Of the 300 possible combinations, 169 types of Global Environmental Systems were created. That was the final result of this complex classification process.

2.2. *Biodiversity Hotspots Evaluation*

Global Environmental Systems not only reflect the conditions and gradients of inanimate and living nature, but also human activities. Biodiversity hotspots are the areas where immense natural wealth and significant human influence and loss of natural habitat intersect most strongly. The proportion of each abiotic, biotic, anthropogenic, and natural class was calculated using ArcGIS (ArcGIS 10.6–10.8) for all 36 hotspots, as was the representation of each Global Environmental System. The data were then further processed in Excel. The global significance of each biodiversity hotspot was based on the work of Myers et al. [36] and Hrdina and Romportl [37].

3. Results

3.1. *Global Environmental Systems Classification*

The global classification consists of three sub-typologies based on separate analyses of abiotic conditions, biodiversity gradients of selected taxonomic groups, and the magnitude of anthropogenic dominance. The integration of these sub-classifications then led to a comprehensive classification of Global Environmental Systems.

3.1.1. Abiotic Classification

The abiotic classification is the fundamental classification that forms the basic framework for the subsequent classification of Global Environmental Systems. It consists of ten classes. A clear gradient from the poles to the equator can be observed for these abiotic classes (Figure 1), ranging from Class 1 being the coldest to Class 10 being the warmest one. Classes 1, 2, 4, and 6 are completely absent in the Southern Hemisphere. But there is one major exception: Class 3. It is an azonal class, covering the area of the highest mountain systems in both North and South America, Africa, Europe, and Asia. The different classes of abiotic classification are basically characterised as follows. The full details of each class can be found in Table 5.

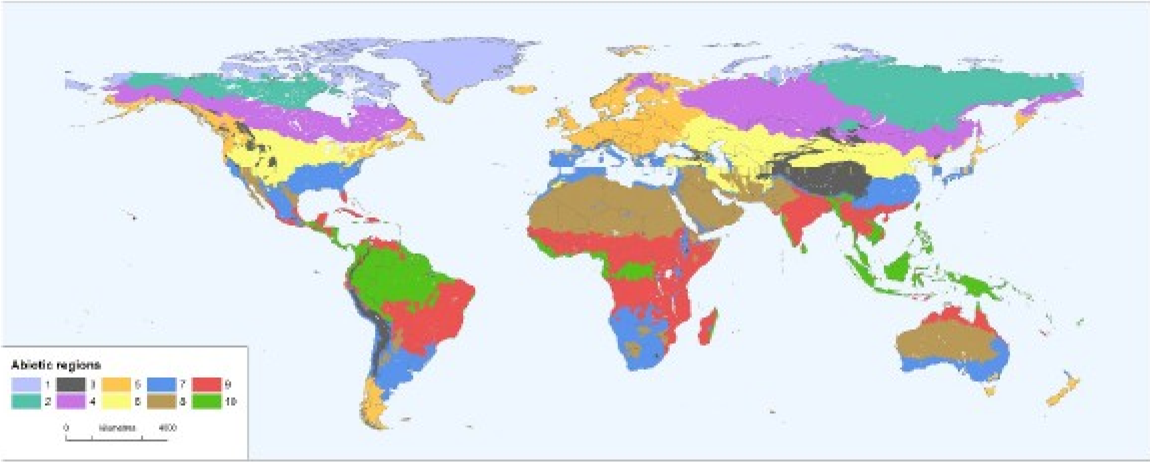

Figure 1. Abiotic classification (Table 5).

Table 5. Characteristics of abiotic classes.

Class	Annual Mean Temperature	Mean Temperature of Warmest Quarter	Mean Temperature of Coldest Quarter	Temperature Annual Range	Annual Precipitation	Precipitation of Wettest Quarter	Precipitation of Driest Quarter	Altitude	Vertical Heterogeneity	TPI	Number of Segments	Area [%]
Class 1	−16.03	−0.32	−29.35	38.25	438.19	152.16	80.25	953.26	34.54	−0.57	2372	3.38
Class 2	−11.20	10.11	−32.25	56.71	327.49	156.00	32.94	452.47	49.64	0.27	1683	7.11
Class 3	0.42	9.55	−9.34	34.47	452.19	230.06	34.75	3578.57	191.79	10.88	910	4.42
Class 4	−1.66	14.32	−18.59	47.20	513.37	217.07	64.89	402.25	32.42	−0.20	1834	10.98
Class 5	5.01	14.18	−4.20	28.86	852.86	294.99	144.33	399.59	68.53	−0.56	2871	7.08
Class 6	8.57	21.80	−5.52	43.01	366.51	154.99	40.97	843.89	38.59	−1.00	1275	9.86
Class 7	16.62	23.25	9.50	28.05	769.04	328.89	84.76	701.99	56.96	−0.90	1910	12.70
Class 8	24.10	30.96	16.20	31.44	169.58	102.84	7.87	430.52	15.74	−0.48	1351	16.84
Class 9	24.44	26.74	21.73	19.33	1161.19	608.32	47.04	512.42	37.08	−0.62	1989	17.73
Class 10	25.39	26.22	24.36	12.62	2 461.61	998.86	268.13	283.97	47.76	−1.20	2359	9.91

- Class 1—Freezing arctic region

This class covers 3.38% of the land area, mainly in the Arctic. It is located in northern Alaska, Canada, and Russia in Kamchatka and Chukotka and covers most of Greenland and the islands in the Arctic Ocean. This region is characterised by very low temperatures, with an annual mean temperature of −16.03 °C. Even during the warmest quarter of the year, the mean temperature is negative (−0.32 °C); during the coldest quarter, the mean temperature in this region is −29.35 °C. Annual precipitation is 438 mm, and the difference in precipitation between the wettest and driest quarter of the year is the smallest among all abiotic classes. The region extends from sea level to an altitude of over 4700 m; the average altitude is about 950 m, and the area is not very vertically heterogeneous.

- Class 2—Cold northern region with a significant temperature annual range

Class 2 is located mainly in the subarctic zone; it also extends into the Arctic and temperate zones and covers 7.11% of the landmass of northern Alaska and Canada, northeastern Russia, and the Sayan Mountains. The annual mean temperature of the region is −11.2 °C. The temperature annual range is very high, ranging between 38.8 °C and 72.5 °C. Temperatures are extremely low during the coldest quarter of the year, averaging below −32 °C. The annual precipitation is only 327 mm, and the average altitude of the area is approximately 450 m above sea level.

- Class 3—Region of the highest mountains

An azonal class, which occupies 4.42% of the landmass and covers the highest mountain ranges in the world, such as the American Cordillera, the Drakensberg, the mountains of East Africa, the Sierra Nevada, the Pyrenees, the Alps, the Caucasus, the Taurus Mountains, and the mountain systems of Central Asia and North Korea. This mountain class stretches to the highest peaks of the Himalayas; the average altitude is 3579 m above sea level, and it is the most vertically heterogeneous region by a lot. The annual mean temperature is just 0.42 °C, and the annual precipitation is 452 mm. In this region, we can observe large differences between the minimum and maximum values of individual indicators.

- Class 4—Colder temperate zone of the Northern Hemisphere

A wide belt from Alaska to eastern Canada; Lapland; a vast area from the White Sea through Kazakhstan, Mongolia and China to Sakhalin; a belt along the Sea of Japan; the Sea of Okhotsk; and the Bering Sea, covering a large area (10.98%). The last class where the annual mean temperature is negative (−1.66 °C). The temperature annual range in this region is very high (47.2 °C), and the annual precipitation is 513 mm. The territory of this class has an average altitude of 402 m, and is the second flattest of all classes.

- Class 5—Humid temperate region

Class 5 can be found predominantly in the temperate zone of both hemispheres and occupies 7.08% of the land area in the Aleutian Islands, a wide belt from Alaska to California, eastern US/Canada, Patagonia, the Falkland Islands, the southern coast of Greenland, Iceland, Svalbard, most of Europe (except parts of southern Europe and Lapland), Koreas, Honshu, Hokkaido, southern Kamchatka, southeastern Australia, Tasmania and, finally, New Zealand. The annual mean temperature is 5.01 °C, and the annual precipitation is relatively high (853 mm), as is the precipitation of the driest quarter (144 mm). The average altitude is just under 400 m, but the region is the second most vertically heterogeneous.

- Class 6—Warmer and drier temperate zone of the Northern Hemisphere

This class occupies almost a tenth of the land mass (9.86%) in the Northern Hemisphere only and includes the south of Canada, the interior of the United States, the north of Mexico, Morocco, a vast territory from Ukraine and Turkey to the Sea of Japan, and from Russia and Kazakhstan to Iran and Pakistan. This region has an annual mean temperature of 8.57 °C, and the mean temperature of the warmest quarter is significantly higher (21.8 °C) than in the previous two adjacent classes. The temperature annual range is high (43.01 °C), the annual precipitation is low (366.5 mm), and this region lies at quite a high altitude (844 m).

- Class 7—Subtropics of both hemispheres

Class 7 is the third largest of all abiotic classes (12.7%) and is placed in the southwestern and southeastern United States, in the interior of Mexico, in a belt from Ecuador to Chile; in Bolivia, Argentina, Uruguay, and southern Brazil; in southern Africa; in the East African Rift region, in Madagascar, in the mountainous regions of the Sahara; in the Mediterranean, around the Black and Caspian Seas; in Saudi Arabia and Yemen, in a narrow disjointed belt of Turkey–Iraq–Iran; from Afghanistan to eastern China; in South Korea; on the islands of Honshu, Kyushu and Shikoku; and in southern Australia and northern New Zealand. The annual mean temperature is much higher (16.62 °C) than in the previous Class 6; especially, the mean temperature of the coldest quarter differs by a lot: 9.5 °C vs. −5.52 °C. The temperature annual range is only 28.05 °C, the annual precipitation is 769 mm, the average altitude is 702 m, and this region has the third highest vertical heterogeneity.

- Class 8—Deserts and semi-deserts of the tropics

This class is very extensive (16.84%) and can be found in desert and semi-desert areas of the world: the southern United States, northern Mexico, Peru, Bolivia–Paraguay–Argentina, Namibia–South Africa–Botswana, Zimbabwe–Mozambique, a large territory from the Western Sahara to India, and western and interior Australia. The annual mean temperature of this distinctive region is high (24.1 °C), and the mean temperature of the warmest quarter is almost 31 °C on average, being up to 38.3 °C in some places. The annual precipitation is extremely low (170 mm), and the precipitation of the driest quarter is just under 8 mm. The whole region is very flat.

- Class 9—Extensive subequatorial region with a drier period

Class 9 occupies 17.73% of the Earth's landmass, making it the most extensive class. The area of occurrence is: Hawaii, an area from Mexico to Nicaragua, Florida, Cuba, Hispaniola, the Bahamas, part of the Lesser Antilles, a discontinuous arc from Guyana to Peru, the Galápagos Islands, Bolivia, Brazil, Paraguay, Argentina, most of Africa between Cape Verde–Eritrea and Angola–Mozambique, Eswatini, eastern South Africa, Madagascar, Réunion, Yemen, Sri Lanka, the peninsulas of India and Farther India, southern China, Hainan, Taiwan, Sumatra, Sulawesi, Sumba, Flores, Timor, Wetar, northern and north-eastern Australia, New Caledonia, and Vanuatu. High temperature, low temperature amplitude, or high precipitation are typical for this region; the mean annual temperature is 24.44 °C, the temperature annual range is 19.33 °C, and the annual precipitation is 1161 mm, but the precipitation of the driest quarter is only 47 mm.

- Class 10—Warm and humid equatorial region

The last abiotic class lies in the equatorial zone and covers 9.91% of the land area. Class 10 is typical of Hawaii, a vast territory from Mexico to Bolivia–Brazil, Jamaica, Puerto Rico, the Lesser Antilles, a coastal belt from Guinea-Bissau to Ghana and from Ghana to Gabon, Congo, the Democratic Republic of the Congo, Madagascar, the Comoros, the Seychelles, Mauritius, the west coast of India, Sri Lanka, Nepal, from Bhutan to Singapore, Farther India, the Sunda Islands, the Moluccas, the Philippines, Taiwan, New Guinea, northern Australia, and Oceania. The annual mean temperature is the highest (25.39 °C), as well as the mean temperature of the coldest quarter (24.36 °C). The temperature annual range is the lowest (12.62 °C), and the annual precipitation is the highest (2462 mm), in places over 11,000 mm. The precipitation of the wettest quarter is around 1000 mm, in places over 8000 mm, and the precipitation of the driest quarter is 268 mm, in places around 2500 mm. The altitude is only 284 m above sea level.

3.1.2. Biotic Classification

The biotic classification also consists of ten classes. The distribution of biotic classes corresponds to the idea of the distribution of biodiversity on the planet (Figure 2). Classes 6 and 1 are the richest. They are found in the equatorial regions of Africa, America, and Southeast Asia. Classes 7 and 2, on the other hand, are the poorest in terms of both fauna and flora biodiversity, and both are very extensive. Class 7 can be found in areas of cold and warm deserts and in high-latitude areas. Class 2 is located next to Class 7. In contrast to the abiotic classification, all biotic classes are represented in both hemispheres. All classes are ordered according to the gradient of species richness of fauna and flora, from the most species-poor to the most species-rich. The different classes of biotic classification are basically characterised as follows. The full details of each class can be found in Table 6.

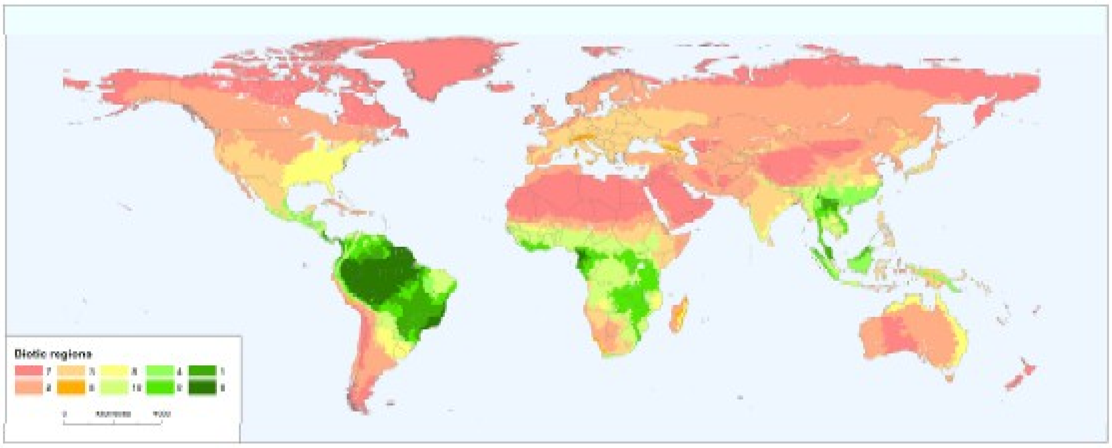

Figure 2. Biotic classification (Table 6).

Table 6. Characteristics of biotic classes.

Class	Mammal Species	Bird Species	Amphibian Species	Plant Species	Number of Segments	Area [%]
Class 7	18.53	52.55	1.64	588.36	7696	23.50
Class 2	37.65	151.95	4.79	1283.91	5257	32.61
Class 3	57.91	214.89	10.28	2389.73	1894	14.59
Class 5	38.83	145.15	8.10	4532.68	743	0.52
Class 8	50.04	215.30	25.31	2259.29	555	4.76
Class 10	99.04	326.78	23.94	2455.29	889	8.85
Class 4	104.62	318.49	20.09	5866.97	445	2.95
Class 9	133.74	402.61	38.12	3123.06	497	5.10
Class 1	139.30	418.29	45.27	6263.24	329	3.31
Class 6	167.87	492.19	84.07	6168.79	249	3.81

- Class 7—Region with the lowest species richness

  This is the poorest class in all monitored biodiversity indicators. It is very extensive (23.5%), located in: a belt from Alaska, through northern Canada, Greenland, Iceland, Ireland, Scotland, northern Scandinavia, Russia to Chukotka, the Bahamas, the Lesser Antilles, the Azores, the Canary Islands, Cape Verde, the Mascarene Islands, the Comoros, Oceania, from Peru through Patagonia to Tierra del Fuego and the Falklands, a discontinuous desert belt from the Sahara through the Arabian Peninsula to the Gobi, Australia, and New Zealand.

- Class 2

  The most extensive biotic class of all, occupying 32.61% of the land area: the USA incl. Alaska, Canada, the Baja California peninsula, the Greater Antilles, a belt from Peru to the south of Chile and Argentina, northern Africa, a belt from Mali to the Horn of Africa, an area from Angola to South Africa, Madagascar, a belt from the Iberian Peninsula, through the British Isles, Scandinavia to the east of Russia and from Greece through Central Asia, Korea, to Hokkaido; Australia, Tasmania, New Caledonia, the Lesser Sunda Islands, and the Moluccas. It is the second poorest class, but the diversity of mammals, birds, amphibians, and plants is 2–3 times greater than the previous class.

- Class 3

  Class 3 is still one of the poorer classes in the classification, although the diversity of fauna and flora is roughly average from a global perspective. It is the third largest class (14.59%) of the biotic classification, typical of the western United States; Mexico; a narrow strip from Ecuador to Argentina; a belt from Senegal to Eritrea and on to Kenya;

from Angola to South Africa incl. Lesotho; western, southern, central, and eastern Europe; Turkey; the Caucasus region; parts of Central Asia; a belt from Pakistan to Japan; India–Bangladesh–Sri Lanka; the Philippines; Sulawesi; Bali; Lombok; Flores; Papua New Guinea; and a small part of Australia.

- Class 5

This biotic class is definitely the smallest of all, occupying only 0.52% of the world's land area, and it is highly specific as the species richness of fauna is quite below average; meanwhile, the species richness of flora is very high at over 4500 species and locally up to 10,000 species. Class 5 is typical of the Dominican Republic, Peru, Namibia–South Africa, Madagascar, the Alps, Ibiza, Sardinia, Sicily, the Caucasus, Lebanon–Syria, Indonesia, the Solomon Islands, and New Caledonia.

- Class 8

Class 8 can be found in the southeastern USA, Paraguay, Argentina, Uruguay, Brazil, Burkina Faso, Mali, Angola, Mozambique, Madagascar, on the east coast of India, in Thailand, Laos, China, Taiwan, Honshu, and on the north and east coasts of Australia over a total area of 4.76%. This region has an above-average amphibian diversity (25 species, max. 93 species), while other indicators are quite average.

- Class 10

The fourth largest biotic class (8.85%), typical of an area from Mexico to Costa Rica; Panama; from Ecuador to Trinidad; from Peru to Brazil; northeastern Brazil; the territory south of the Senegal–Ethiopia line to South Africa; the west coast of India; a belt from India through Nepal, Bhutan, and Myanmar to China; Farther India; Sumatra; and Java. This is the first biotic class having above average values for all indicators. The species richness of birds is the fourth highest, with an average of 327 bird species and a max. of 578 bird species.

- Class 4

The second smallest class (2.95%) situated in a belt from Mexico to Bolivia, in Paraguay, Argentina, Brazil, in the Western Cape, from Myanmar to southern China, and in Sumatra, Borneo, and Papua New Guinea. This region hosts 105 species of mammals (max. 197 species) and 5867 species of plants, with a maximum of around 10,000 species.

- Class 9

Class 9 is very rich in fauna species; the plant diversity is not so substantial (3123 species). The sites with the highest number of mammal (217) and bird (666) species are within this class. It is located from Colombia to Guyana, in Peru, Bolivia, and Brazil, from Sierra Leone to Ghana, from Nigeria to the Democratic Republic of the Congo, from South Sudan to South Africa, in Farther India, and Sumatra. This class is located right here on 5.1% of the landmass.

- Class 1

Together with Class 6, the two most species-rich classes. Class 1 is the second richest in mammal (139 species), bird (418 species), and amphibian (45 species) diversity and the richest in plant diversity (6263 species). It occupies 3.31% of the land area in a belt from Nicaragua to Ecuador; from Guyana to Peru; in Peru–Bolivia, and Brazil–Paraguay–Argentina; from Congo through Gabon, Equatorial Guinea to Cameroon; in Madagascar; from Myanmar through China, Vietnam, and Laos to Thailand; and in the Malay Peninsula, Borneo, and Sumatra.

- Class 6—Region with the highest species richness

Class 6 is the territory with the highest biodiversity in the world. It has a land area of 3.81% in only three areas in South America and Africa: the Amazon rainforest, the Atlantic Forest, and Cameroon, Equatorial Guinea, and Gabon. Class 6 is the richest in mammal

(168 species), bird (492 species), and amphibian (84 species) diversity, and it is the second richest in plant diversity (6169 species).

3.1.3. Anthropogenic Classification

The anthropogenic classification consists of ten classes too but does not create such a clear and obvious pattern. The distribution of individual classes is much more heterogeneous, and classes do not form such large and homogeneous units (Figure 3). All classes are ordered according to the anthropogenic gradient, from the most remote with little anthropogenic impact to the most easily accessible with significant anthropogenic impact. The different classes of anthropogenic classification are basically characterised as follows. The full details of each class can be found in Table 7.

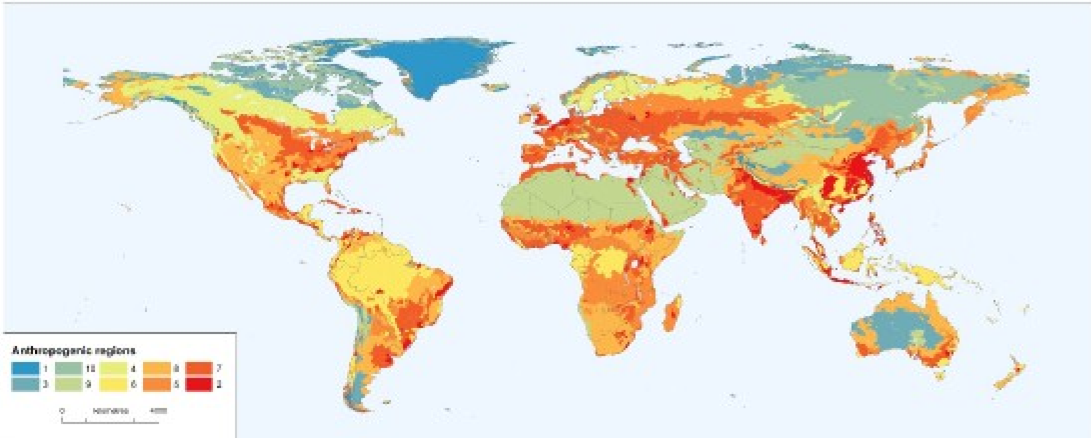

Figure 3. Anthropogenic classification (Table 7).

Table 7. Characteristics of anthropogenic classes.

Class	Livestock Density	Accessibility	Human Density	Predominant Land Cover	Number of Segments	Area [%]
Class 1	1.50	9764.58	2.45	GLC 17	689	1.98
Class 3	4.46	2840.49	0.48	GLC 12	1989	6.17
Class 10	0.72	2394.74	0.51	GLC 6, 11	1525	5.82
Class 9	16.50	1527.45	6.01	GLC 15	1771	14.25
Class 4	12.70	1039.64	10.20	GLC 5	2300	8.19
Class 6	26.26	1257.76	21.41	GLC 3	2330	11.19
Class 8	30.84	831.99	12.38	GLC 9, 10	2981	19.94
Class 5	22.18	562.35	24.42	GLC 4, 7, 8, 13	2175	12.31
Class 7	99.31	175.45	94.92	GLC 1	1907	15.88
Class 2	353.54	156.15	462.43	GLC 1, 2	887	4.26

- Class 1—Highly remote areas with very little anthropogenic impact

The first class of the anthropogenic classification occupies the smallest area (1.98%) with an extremely low accessibility and can be found only at very high latitudes or altitudes: Alaska, northern Canada, Greenland, Iceland, the Arctic Ocean islands, the mountains of Central Asia, Patagonia, and the small islands of the southernmost waters of the World Ocean. The completely dominant land cover class is permanent snow and ice. It is no surprise that the densities of both population and livestock are very low.

- Class 3

Another class with a very low accessibility, low livestock density, and even the lowest human density (0.48 people/km^2). This class is typical of Alaska, northern Canada, the coast of Greenland, Iceland, north of Scandinavia, Russia, the Arctic Ocean islands, Central Asia, Tibet, Mongolia, the Andes, Patagonia, and Australia. The completely predominant land cover class is sparse (<15%) vegetation (tree, shrub, herbaceous cover), sparse tree, sparse shrub, and sparse herbaceous cover. It is rather a smaller class (6.17%).

- Class 10

Class 10, like the previous one, has very low values of population and livestock density and accessibility. It covers a similar land area (5.82%) in northern Alaska and Canada and eastern Siberia. There are two main land cover types in the area: tree cover, needleleaved, deciduous, closed to open (>15%); tree cover, needleleaved, deciduous, closed (>40%); tree cover, needleleaved, deciduous, open (15–40%); and lichens and mosses.

- Class 9

The area of this class is much larger (14.25%), and it occurs in Chukotka, Alaska, in the northern part of the Canadian Archipelago, Iceland, Svalbard, the Arctic Ocean islands, in a belt from Peru through Bolivia to Chile and Argentina, in Namibia and Angola, in a desert region from the Western Sahara to Mongolia, and in central Australia. Bare areas, consolidated bare areas, and unconsolidated bare areas are the dominant land cover type of this large region. Human density (6.01 people/km^2), livestock density, and accessibility are higher than previous classes.

- Class 4

This class covers 8.19% of the land area in the United States and Canada, in parts of Europe, in Scandinavia, in Russia, in a continuous belt from Afghanistan to China, and in southeastern China and Japan. Class 4 has one dominant land cover type: tree cover, needleleaved, evergreen, closed to open (>15%); tree cover, needleleaved, evergreen, closed (>40%); and tree cover, needleleaved, evergreen, open (15–40%), and it has similar human and livestock density to Class 9 and better accessibility.

- Class 6

Oceania, Hawaii, Central America, the Caribbean, Amazonia, Paraguay, the coast of Brazil, central Chile, central Africa, Madagascar, Farther India, the Malay Archipelago, the southeastern coast of Australia, Tasmania, and New Zealand are covered with Class 6, with an area of 11.19%. The predominant land cover type is tree cover, broadleaved, evergreen, closed to open (>15%). Human and livestock density is roughly double that of the previous class; accessibility is quite average.

- Class 8

This class occupies almost a fifth of the land mass (19.94%) and includes Alaska, the western half of the USA, Newfoundland, Mexico, a belt from Guyana to Argentina, Uruguay, eastern Brazil, the Sahel, the Horn of Africa, southern Africa, Iceland, the British Isles, the Alps, the Pyrenees, the French Central Highlands, Central Asia, eastern Russia, Australia, and New Zealand. Human density is 12.38 people/km^2, livestock density is the third highest (30.84 livestock units/km^2), and this region has better than average accessibility. The region is dominated by two land cover classes: shrubland, evergreen shrubland, and deciduous shrubland; and grassland.

- Class 5

The typical land cover type of this class with an area of 12.31% is primarily tree cover, broadleaved, deciduous, closed to open (>15%); tree cover, broadleaved, deciduous, closed (>40%); and tree cover, broadleaved, deciduous, open (15–40%). This is followed by tree cover, mixed leaf type (broadleaved and needleleaved); mosaic tree and shrub (>50%)/herbaceous cover (<50%); and mosaic herbaceous cover (>50%)/tree and shrub (<50%). Lastly, this is followed by tree cover, flooded, fresh or brackish water; tree cover, flooded, saline water; and shrub or herbaceous cover, flooded, fresh/saline/brackish water. Class 5 is typical of southeastern Canada, the eastern USA, an area from Mexico to Nicaragua, Brazil, Bolivia, Paraguay, Argentina, southern Chile, much of Africa south of the Sahel, Madagascar, Europe, western and central Russia, Turkey, the Caucasus, the peninsulas of India and Farther India, and an area from China to Kamchatka. This class has the third highest human density (24.42 people/km^2), and the region is the third most accessible too.

- Class 7

The second largest (15.88%) and the second most anthropogenically impacted region with very good accessibility. Human density is 94.92 people/km^2, and livestock density is 99.31 livestock units/km^2. The location of this class is southern Canada, central USA, Cuba, Colombia, Brazil, Argentina, a belt from Senegal to Ethiopia and from Sierra Leone to Nigeria, much of Europe except for mountainous areas and northern Europe up to Iran and Kazakhstan, the peninsulas of India and Farther India, eastern China, the Korean Peninsula, and southwestern and southeastern Australia. Cropland, rainfed; herbaceous cover; tree or shrub cover; and cropland, irrigated or post-flooding type of land cover dominates here.

- Class 2—Easily accessible areas with significant anthropogenic impact

And finally, there is Class 2, which is by far the most anthropogenically exploited. Class 2 is located in areas (4.26%) with significant livestock farming (353.54 livestock units/km^2), human density (462.43 people/km^2), and the highest accessibility from all anthropogenic classes, such as India, eastern China, Indonesia, Malaysia, Japan, the Philippines, Benelux, England, etc. There are two main land cover types: cropland, rainfed; herbaceous cover; tree or shrub cover; cropland, irrigated or post-flooding. Andmosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%); and mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%).

3.1.4. Classification of Natural Conditions

This natural classification (Figure 4, Table 8) is the penultimate step in the creation of Global Environmental Systems. It is a combination of abiotic and biotic classification, having 30 classes out of 100 theoretically possible classes (10 abiotic classes × 10 biotic classes) (Figure 5). The letters 'A' to 'J' indicate affiliation with one of the ten abiotic classes (1 to 10), which are further subdivided into one to five classes and the letters 'a' to 'e' distinguish individual biotic classes or groups of classes.

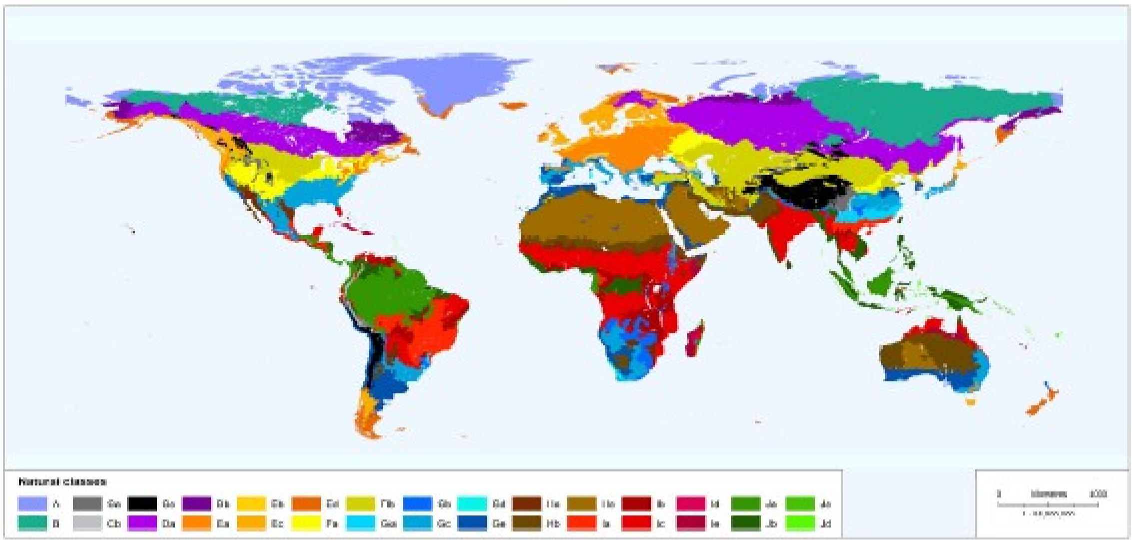

Figure 4. Classification of natural (abiotic + biotic) conditions (Table 8).

Table 8. Characteristics of 30 natural classes.

Class	Abio + Bio Codes	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp. of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp. Annual Range	Annual Precipit.	Precipit. of Wettest Quarter	Precipit. of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Number of Segments	Area [km²]	Area [%]
A	17	7.67	24.02	1.00	212.87	−16.03	−0.32	−29.35	38.25	438.19	152.16	80.25	953.26	34.54	−0.57	2372	4,509,843	3.38
B	22; 27	28.05	102.73	1.75	899.57	−11.20	10.11	−32.25	56.71	327.49	156.00	32.94	452.47	49.64	0.27	1683	9,484,710	7.11
Ca	33; 39; 310	69.20	218.01	6.72	2530.86	2.79	11.48	−6.59	33.62	662.50	323.07	48.75	3054.23	230.28	15.43	258	1,418,906	1.06
Cb	34; 35	99.36	258.30	9.09	5066.13	8.29	12.51	3.66	21.68	1063.16	440.86	118.46	2624.64	277.28	23.06	71	412,479	0.31
Cc	32; 37	33.58	108.34	2.69	1219.14	−1.13	8.60	−11.51	35.96	322.12	178.07	22.08	3849.76	170.44	8.17	581	4,065,325	3.05
Da	42; 43	41.75	156.67	4.17	1178.75	−0.98	15.11	−18.22	47.92	507.03	218.48	61.34	426.78	32.43	−0.21	1324	12,605,613	9.45
Db	47	26.28	71.63	1.78	779.29	−5.35	10.07	−20.55	43.35	547.46	209.53	83.97	270.42	32.37	−0.19	510	2,039,862	1.53
Ea	53; 58	55.25	168.33	12.81	2384.78	7.77	17.65	−2.59	31.15	742.50	260.04	127.21	351.21	46.46	0.41	330	3,763,862	2.82
Eb	55	64.86	124.97	8.67	4954.88	3.97	12.04	−4.26	26.37	1293.17	428.19	240.51	1448.17	282.17	12.38	12	76,258	0.06
Ec	52	37.66	144.55	5.80	1328.05	4.28	13.71	−5.03	29.60	860.33	309.84	133.39	436.98	75.86	−1.25	1112	3,682,350	2.76
Ed	57	15.78	83.32	1.59	699.19	1.97	9.61	−5.26	23.96	1000.53	319.51	188.11	376.70	83.66	−1.23	1417	1,925,294	1.44
Fa	63; 65; 68	54.95	169.48	10.36	2434.61	8.64	20.54	−3.69	39.51	546.63	202.95	79.14	864.85	48.67	−1.66	363	3,574,425	2.68
Fb	62; 67	39.16	127.99	4.87	1316.03	8.54	22.27	−6.21	44.31	299.38	137.12	26.75	836.08	34.84	−0.76	912	9,578,430	7.18
Ga	71; 74	92.89	320.21	25.04	5549.39	16.74	23.22	9.31	25.45	1338.01	631.40	115.74	1036.77	144.71	−0.85	118	1,165,589	0.87
Gb	79; 710	102.79	375.48	27.17	2567.00	18.36	21.77	13.76	24.09	969.28	517.81	45.14	1320.54	71.82	1.06	179	2,010,233	1.51
Gc	73; 78	54.90	213.17	18.08	2519.75	16.53	23.88	8.68	29.43	907.35	357.07	121.03	609.92	50.58	−1.09	727	7,860,848	5.89
Gd	75	39.75	144.93	5.21	4012.36	16.01	21.72	10.46	22.89	396.39	170.78	30.65	429.48	67.69	−1.51	133	138,350	0.10
Ge	72; 77	31.52	148.88	6.03	1399.42	16.20	22.98	9.29	28.06	421.72	178.53	43.80	575.65	44.10	−1.26	753	5,764,459	4.32
Ha	83; 88; 89; 810	62.40	257.47	12.99	1840.49	24.17	29.56	18.11	28.52	466.29	294.99	16.86	403.35	16.80	−0.81	126	2,102,486	1.58
Hb	82; 85	31.85	156.01	5.25	1091.61	24.00	30.38	16.64	30.29	256.02	155.47	13.53	380.83	18.16	−0.79	490	7,978,945	5.98
Hc	87	17.53	39.24	1.99	717.06	24.15	31.57	15.60	32.67	64.23	36.77	2.73	467.00	14.00	−0.23	735	12,376,256	9.28
Ia	91; 94; 96	126.57	398.28	44.46	5994.01	22.89	25.01	20.04	18.30	1466.89	695.36	84.47	526.65	57.34	−0.52	333	4,309,194	3.23
Ib	99	131.97	401.53	38.73	3023.79	23.21	24.79	21.02	17.56	1215.67	583.30	60.71	718.05	41.37	−0.12	293	4,415,565	3.31
Ic	93; 98; 910	82.73	298.41	20.42	2223.11	25.28	27.85	22.49	20.23	1070.63	596.22	31.63	459.49	29.11	−0.75	933	13,610,003	10.20
Id	95	16.19	114.51	8.12	3373.74	22.30	24.18	19.47	18.09	1500.12	848.84	66.87	734.05	70.25	−1.62	52	109,879	0.08
Ie	92; 97	27.62	150.45	8.44	1860.00	25.32	27.74	22.09	19.45	845.31	497.62	33.51	293.72	34.80	−1.14	378	1,200,975	0.90
Ja	101; 104; 106	155.21	445.71	62.90	6305.01	25.45	26.05	24.71	12.27	2523.94	959.40	307.22	276.06	42.57	−0.98	528	7,694,919	5.77
Jb	103; 108; 109; 1010	101.18	330.94	25.59	3193.89	25.33	26.50	23.89	13.32	2366.40	1061.40	202.18	301.04	52.46	−1.30	576	5,038,325	3.78
Jc	105	22.52	157.76	12.96	5045.96	24.85	25.90	23.48	10.84	2645.76	996.66	413.20	252.65	72.07	−3.29	512	196,530	0.15
Jd	102; 107	20.96	153.28	5.81	1767.20	25.16	26.11	23.86	10.60	2351.87	948.10	290.21	214.28	86.80	−3.94	743	282,883	0.21

Temp. = Temperature; Precipit. = Precipitation; Heterogen. = Heterogeneity; TPI = Topographic Position Index.

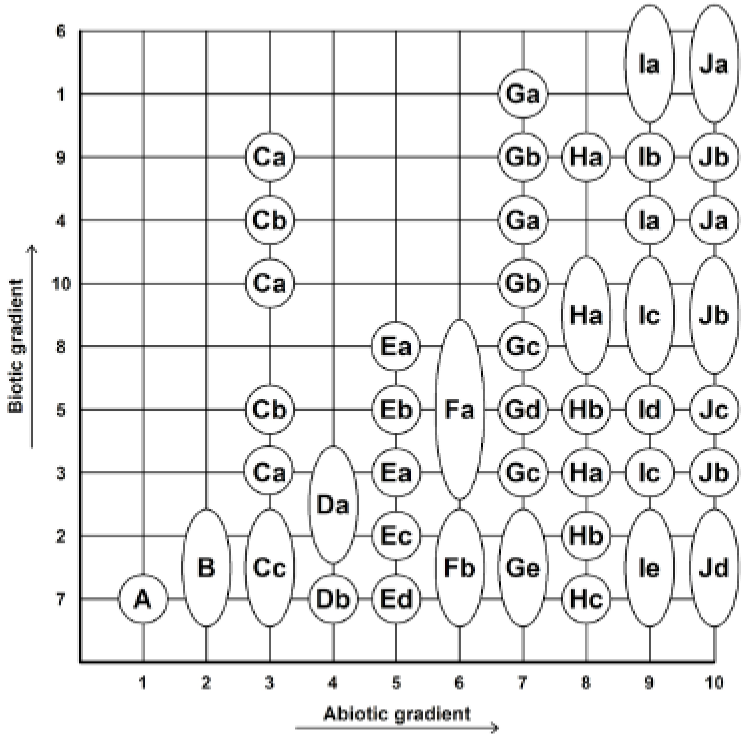

Figure 5. Synthetic diagram of the combination of natural conditions (Tables 5, 6 and 8).

On one side of the classification is Class A, which represents the freezing arctic region with the lowest species richness. Class B is located in the northern part of America and northeastern Asia. It is a cold world that is extensive, with the greatest temperature annual range and low biodiversity. Class C lies in the highest mountains. This class is divided into three classes: Ca, Cb, and Cc. Class Cb lies at the lowest altitude, has the highest annual mean temperature, the highest precipitation, and the highest species richness of mammals, birds, amphibians, and plants. Class Cc, on the other hand, lies at the absolute highest altitude and has the lowest annual mean temperature, the lowest precipitation, and the lowest species richness of fauna and flora. And finally, there is Class Ca, with all values being somewhere in between. Class D can be found in the temperate zone of the Northern Hemisphere, and it is divided into two classes: Da, and Db. In both classes, there is an annual mean temperature of below zero, with Class Db being colder. The temperature annual range is very high, the annual precipitation is below average, and the altitude is low, especially in Class Db. Both classes show low biodiversity, with Class Db being the poorer one. Class E includes four classes: Ea, Eb, Ec, and Ed, which lie in the humid temperate zone. The annual mean temperature is below average but is above zero in all classes. Classes Ea, Ec, and Ed lie at a low altitude. Class Eb is the smallest and is typical of the Alps; it has an above average annual precipitation and a high number of mammal species and especially plant species. Class Ea shows an average biodiversity, Class Ec a below average species richness, and Class Ed is very species-poor. Class F is typical mainly of the temperate zone too, but it is located in the warmer and drier area. This class is divided into two classes, both of which are found only in the Northern Hemisphere. Especially Class Fb lacks significant precipitation; therefore, the biodiversity is rather below average. In the subtropics of both the Northern and Southern Hemispheres, there are five G classes. The annual mean temperature of Class Ga, as in the Gc–Ge regions, is over 16 °C. Class Gb is warmer, with an annual mean temperature of over 18 °C. Classes Ga and Gb lie at a higher altitude of over 1000 m, and they are generously endowed with precipitation and being species-rich, while classes Gd and Ge lie at a lower altitude and are relatively poor in rainfall and biodiversity; however, Class Gd is very rich in plant diversity. Class H covers deserts and semi-deserts of the tropics in three classes, Ha–Hc. The annual mean temperature is over 24 °C, the mean temperature of the warmest quarter is around 30 °C, and the precipitation is extremely low, especially in classes Hb and Hc, with most of the precipitation occurring during the wettest quarter and less than 5% occurring during the driest quarter. The area is at a low altitude and the terrain is very flat. Class Ha is the smallest of these three classes and has a higher diversity of mammals and birds. Class Hb is species-poor, and the extensive Class Hc is very species-poor. The subequatorial region with a drier period is described by Class I, further subdivided into five classes, Ia–Ie. The annual mean temperature is high, the temperature annual range is low, and the precipitation is above average but only 3 to 6% falls during the driest quarter. Classes Ia and Ib are extremely species-rich, and Classes Id and Ie have below average faunal species richness, but Class Id is rich in plant species due to high rainfall. And finally, on the other side of the classification is Class J, characterising the warm and humid equatorial region, subdivided into four classes Ja–Jd. The annual mean temperature is around 25 °C in all classes, the temperature annual range is extremely low, and the precipitation is very high at over 2300 mm, with plenty even in the driest quarter. The altitude is very low. Class Ja is the richest of all thirty classes in the diversity of mammals, birds, amphibians, and plants, Class Jb is also above average rich in fauna and flora. Classes Jc and Jd do not have a very diverse fauna, but there are over 5000 species of plants in Class Jc.

- Class A

This class is a combination of abiotic Class 1 as a whole and a part of biotic Class 7, which makes this area the coldest one with the lowest biodiversity. In this arctic region, there can be found on average 8 species of mammals, 24 species of birds, or 213 species of plants.

- Class B

Class B combines abiotic Class 2 with parts of biotic Class 2 and 7. Biodiversity is low, with an average of 28 mammal species, 103 bird species, or 900 plant species. All other classes from 'C' to 'J' are further divided into two, three, four, or five classes.

- Class Ca

The mountain region, occupying 1.06% of the landmass, is found on all continents except Australia and Oceania, represented in the American Cordillera, eastern Africa, Lesotho, Sierra Nevada and the Pyrenees, the Caucasus, the Taurus Mountains, and the mountain systems of Central Asia and North Korea. The annual mean temperature across the region ranges from −21.4 °C to +23.6 °C, with an average annual precipitation of about 660 mm. The region hosts an average of 69 mammal species, 218 bird species, and over 2500 plant species. There are also sites with more than 650 bird species (Africa) and 6500 plant species (South America).

- Class Cb

Also a mountainous region, it occupies a smaller share of the world (0.31%) in Central and South America and Eurasia (Mexico, Guatemala, the Andes from Colombia to Peru, the Alps, the Caucasus, and southwestern China). It extends a little lower at an average altitude of about 2600 m above sea level, peaking at over 5.5 km. The territory has a very rugged character. The average temperature here is 5.5 °C higher at 8.3 °C. In particular, the coldest quarter is significantly warmer (+3.7 °C) compared with class Ca (−6.6 °C) and Cc (−11.5 °C). The annual precipitation is higher, with 1063 mm falling. Biodiversity indicators also show higher numbers, with an average of 99 mammal species, 258 bird species, and over 5000 plant species inhabiting the region, with a local maximum of 8500 plant species.

- Class Cc

Another of the high mountain regions. It occurs in North and South America and Asia, extending to the peaks of the Himalayas, the largest in area (3.05%). The highest placed class at an average altitude of 3850 m above sea level. The climate is cool, with an annual mean temperature of −1.1 °C and annual precipitation of 322 mm. The biodiversity of fauna and flora is below average, as there are 34 species of mammals, 108 species of birds, and 1219 species of plants.

- Class Da

A wide belt from Alaska to eastern Canada, Lapland, a vast area from the White Sea through Kazakhstan, Mongolia and China to Sakhalin, and a belt along the Sea of Okhotsk. It is the second largest region of all (9.45%) and lies in the subarctic and temperate zone of the Northern Hemisphere. The annual mean temperature is negative, namely −0.98 °C. The region has a high temperature annual range of almost 48 °C, with some places being even over 62 °C. The mean temperature of the warmest quarter is over +15 °C, while during the coldest quarter it is below −18 °C. The annual precipitation is below average at 507 mm. The area is situated at an average altitude of 427 m above sea level, and the vertical heterogeneity is low. The diversity of fauna and flora is slightly below average.

- Class Db

The region occupies a much smaller area (1.53%) in the subarctic and temperate zone of western Alaska, eastern Canada, northern Scandinavia, northern Russia from the Pechora Sea to the Yenisei, Mongolia, Kamchatka, and the Bering Sea belt. It is located in a cooler area with an annual mean temperature of −5.35 °C, and it is slightly richer in precipitation (547 mm/year). The territory is not very rugged, and it lies at a low altitude of 270 m above sea level. Biodiversity is rather low, with an average of only 26 mammal species, 72 bird species, and 779 plant species. Even the most species-rich sites here are below the normal average.

- Class Ea

The region has most of its land area (2.82%) in the temperate zone, with a small part of the area extending into the subtropics, located in the west and east of the USA, Europe from Spain to Russia, North Korea, Honshu, and southeastern Australia. In most indicators, the defined territory appears very average. The number of species of mammals (55), birds (168), amphibians (13), and plants (2385) is slightly below average. The average annual temperature is 7.77 °C; a total of 743 mm of rainfall can be measured per year, and 127 mm falls during the driest quarter. The area is moderately rugged and lies at an average altitude of around 350 m above sea level.

- Class Eb

A very small region in the Alps, it occupies only 0.06% of the land area. It has higher species richness of mammals (65 species) and especially plants (4955 species). It is a very rugged area, lying at a higher altitude of 1448 m above sea level, which corresponds to a lower annual mean temperature (3.97 °C) and higher annual precipitation (1293 mm).

- Class Ec

A belt from Alaska to the north of the USA, then eastern USA/Canada; Patagonia; a wide belt from northern Spain, along the English Channel, the North Sea, and the Baltic Sea; the British Isles; Jutland; Scandinavia; from Estonia to Russia; Korea; Hokkaido; Sakhalin; the Kuril Islands; and Tasmania. The region occupies the entire width of the temperate zone of the Northern and Southern Hemisphere and the nearest adjacent subtropics with a proportion of 2.76%. It lies at an altitude of 437 m above sea level. The annual precipitation is around 860 mm, with higher totals on the windward side of the coasts of North and South America and Scandinavia, and the annual mean temperature is 4.28 °C. Biodiversity here is below average.

- Class Ed

Class Ed can be found in Alaska, the Aleutian Islands, Newfoundland, Labrador, Patagonia, the Falkland Islands, the south coast of Greenland, Iceland, Svalbard, the north of the British Isles and Scandinavia, the south of Kamchatka, and New Zealand, and it occupies 1.44% of the land area. The area has an altitude of about 375 m above sea level. It is the coldest area of abiotic Class E, with an annual mean temperature of less than 2 °C and in some segments almost −9 °C. Annual precipitation is 1000 mm, but the windward side of the South Island of New Zealand and Patagonia has rainfall of 5900 and 6700 mm/year, respectively. Biodiversity of flora and fauna is very low.

- Class Fa

The temperate latitudes and subtropics of North America and Eurasia, with a share of 2.68% (southern Canada, the interior of the United States, northern Mexico, a territory from Turkey through Transcaucasia to southwestern Russia, Central Asia, China, and a strip of land by the Sea of Japan). The region has an annual mean temperature of 8.64 °C, a temperature annual range of almost 40 °C, an annual precipitation of 547 mm, and an altitude of 865 m above sea level. The diversity of the fauna is slightly below average; the flora is richer with an average of 2435 plant species, but there are up to 5000 in places.

- Class Fb

A large region (7.18%) of the Northern Hemisphere also in the temperate latitudes and subtropics. Class Fb is located in southern Canada, the interior of the USA, Morocco, a vast territory from Turkey to North Korea, and from Russia and Kazakhstan to Iran and Pakistan. There is a very similar annual mean temperature (8.54 °C) and an even higher temperature annual range of over 44 °C. Annual precipitation in the region is less than 300 mm, with only 9% of the total falling during the driest quarter. The area lies at an altitude of 836 m above sea level, but there are also sites above 5000 m. The diversity of fauna and flora is lower and rather below average.

- Class Ga

One of the smaller regions (0.87%); it lies between the subtropical and subequatorial zones in Central (Mexico) and South America (a discontinuous belt from Ecuador to Bolivia, south of Brazil), south of South Africa, and especially eastern Asia (Myanmar, China). This class has an altitude of 1037 m above sea level and high ruggedness. The annual mean temperature, as in the Gc–Ge regions, is over 16 °C. Annual precipitation is high at 1338 mm. The biodiversity of the region's fauna is high, and flora has an average of 5549 plant species and, in some places, 9000 species.

- Class Gb

A region with a proportion of 1.51% occupying similar locations that are only higher (1321 m above sea level, maximum around 5500 m), in America (Mexico, Venezuela, Bolivia, Argentina, southern Brazil) and Asia (India, Nepal, Bhutan, Myanmar, and China) and most abundant in Africa (southern Africa, the East African Rift). The annual mean temperature of 18.36 °C is higher than in the other four regions. The annual precipitation is 969 mm, more than half of which falls during the wettest quarter of the year, while only 5% falls during the driest quarter. The biodiversity of the fauna is even higher, with an average of 103 mammal species, 375 bird species, and 27 amphibian species. The flora, on the other hand, is not so rich; the region hosts 2567 plant species.

- Class Gc

A region occupying 5.89% with significant latitudinal banding. The core is in the subtropics of the Northern Hemisphere and around the Tropic of Capricorn: the southwestern and southeastern USA; the interior of Mexico; Bolivia; Argentina; Uruguay; southern Brazil; southern Africa; Madagascar; Ethiopia; Eritrea; the Mediterranean; the Black and Caspian Sea area; a discontinuous belt from Pakistan to eastern China; Honshu; Kyushu;

Shikoku; and the southern and southeastern part of Australia. On average, this is a lower lying area around 610 m above sea level. The annual rainfall is 907 mm, which is more regularly distributed throughout the year. Diversity of fauna is still above average but is considerably lower; this class has a similar number of plant species (2520) as the Gb region.

- Class Gd

Class Gd is a very small region (0.10%) occurring in the subtropics of the Mediterranean (Sardinia, Sicily, Malta, Lebanon, etc.), South Africa, Namibia, and Japan. It is very similar in temperature and poorer in rainfall (396 mm/year). It lies at the lowest altitude within class G, around 429 m above sea level. The diversity of mammals, birds, and amphibians is below average, but the flora is very rich, with the area hosting 4012 plant species on average. The region lies in the biodiversity hotspots of the Mediterranean, Cape Floristic Region, Succulent Karoo, or Japan.

- Class Ge

One of the larger-than-average regions (4.32%) found on all continents at an altitude of 576 m above sea level on average. Its distribution is strikingly reminiscent of the Mediterranean vegetation type, found in the southwestern USA, a belt from Peru to Chile, Bolivia, Argentina, from Angola to South Africa, in the mountainous areas of Sahara, the Mediterranean, the Caspian Sea area, Saudi Arabia, Yemen, a narrow discontinuous belt of Turkey–Iraq–Iran, Afghanistan–Pakistan, eastern China, South Korea, Honshu, in a southern part of Australia, and northern New Zealand. The average annual precipitation is 422 mm. The diversity of fauna is similar to that of the Gd region, but here, the diversity of plant species is below average.

- Class Ha

The region occupies 1.58% of the land area in the southern USA and northern Mexico; Bolivia; Paraguay; Argentina; Botswana; Zimbabwe; South Africa; Mozambique; in a discontinuous belt from Senegal to Ethiopia; Pakistan; India; and eastern Australia. It lies at an altitude of 403 m above sea level, and the surface is not very rugged. The annual mean temperature in all three regions is around 24 °C, with the highest rainfall in the area of this class (466 mm/year). As in the Hb and Hc regions, only about 4–5% of the rainfall falls in the driest quarter. Mammal and bird diversity is above average, while amphibian and plant diversity is slightly below average.

- Class Hb

This region has a larger share of 5.98% and is typical of the southwestern USA, Baja California peninsula, Argentina, Namibia, South Africa, Botswana, a continuous belt from Mauritania to Sudan, the area around the Red Sea and the Gulf of Aden, Morocco, Algeria, Tunisia, Libya, Egypt, from Syria to India, and the west and interior of Australia. It is situated at an altitude of 381 m above sea level on average and is not very vertically heterogeneous too. It extends up to an altitude of about 420 m below the world ocean level. The annual precipitation is only 256 mm. Biodiversity here is lower than in Ha and is overall below average.

- Class Hc

A very extensive area (9.28%) of the tropics and subtropics from the Western Sahara to the Arabian Peninsula, Iran, Afghanistan, Pakistan, and inland Australia. The least vertically heterogeneous region of all, it lies at an altitude of 467 m above sea level. The temperature is very similar, with only a slightly higher temperature annual range. It is a very dry area with an average of only 64 mm of rainfall per year, with less than 3 mm in the driest quarter. It has the second poorest fauna and the third poorest flora, averaging only 18 species of mammals, 39 species of birds, 2 species of amphibians, and 717 species of plants.

- Class Ia

A tropical region with an area share of 3.23%, it is most represented in Central (from Mexico to Nicaragua) and South America (a discontinuous arc from Guyana to Peru, Bolivia, Brazil, Paraguay, Argentina), and then from Cameroon to Gabon, from Myanmar to southern China, and Hainan. This region, situated at an altitude of around 527 m above sea level, has an annual mean temperature of 22.89 °C and an annual precipitation of 1467 mm, with a temperature annual range only ranging between 8 and 28 °C. Very rich fauna and flora, on average 127 mammal species, 398 bird species, 44 amphibian species (max. 135), and 5994 plant species (max. 9000).

- Class Ib

The region occupies 3.31% of the world's land area, much of which is in Africa (Ivory Coast, Ghana, central and eastern Africa), South America (Venezuela, Peru, Bolivia, Brazil) and Farther India at an altitude around 718 m above sea level. It is very similar in temperature and slightly poorer in precipitation (1216 mm/year). The fauna is also very rich, on average having 132 species of mammals, 402 species of birds (max. 666), 39 species of amphibians, and the flora is only about half as rich, on average having 3024 species of plants growing in the region.

- Class Ic

A very large region (10.20%), typical especially of the subequatorial belt; it can be found everywhere except Europe: from Mexico to Nicaragua, Florida, Cuba, from Venezuela to Ecuador, Bolivia, Brazil, Paraguay, Argentina, a continuous belt from Senegal to Somalia, central and eastern Africa, Madagascar, Sri Lanka, the peninsulas of India and Farther India, Taiwan, Sumatra, Sulawesi, Flores, and northern and northeastern Australia. It is located at an altitude of 459 m above sea level and is not very rugged. The annual mean temperature is higher at 25.28 °C. The annual rainfall is 1071 mm but is only 3% during the driest quarter. For this reason, the region hosts on average 'only' 2223 plant species. The diversity of fauna is also lower here but is still well above average.

- Class Id

The area of this class is very small (0.08%), and it is located, e.g., in the Dominican Republic, Madagascar, or New Caledonia at an altitude from sea level to about 1800 metres above sea level. The annual mean temperature is 22.3 °C and rainfall is 1500 mm/year. The diversity of fauna is very low within Class I and is also rather below average overall. On the contrary, 3374 plant species can be found in this small class.

- Class Ie

One of the smaller regions (0.90%) comprising many islands of the tropical and subequatorial belt (Hawaii, Cuba, western Hispaniola, the Bahamas, a part of the Lesser Antilles, the Galápagos Islands, Reunion, Sumba, Timor, Wetar, New Caledonia, Vanuatu...), plus Madagascar, the Horn of Africa and surroundings, southern Florida, Peru, and the northern part of Australia. It lies at a low altitude of 294 m above sea level but extends to the summit of Maui. The annual mean temperature is 25.32 °C, and the annual precipitation is lower at only 845 mm. Compared with Class Id, the fauna is slightly richer, but the flora poorer, with 1860 plant species on average.

- Class Ja

Class Ja, with a share of 5.77% of the land mass, is mainly located in the equatorial belt in Americas, and especially in Amazonia (from Mexico to Bolivia and Brazil), Africa (from Cameroon to Gabon) and southeastern Asia (the Malay Peninsula, Borneo, Sumatra, New Guinea). The Ja–Jd regions all have a high annual mean temperature of 24.9 to 25.5 °C, a very low temperature annual range of 10.6 to 13.3 °C, similar precipitation totals of 2350 to 2650 mm/year, and a similarly low altitude of 214 to 301 m above sea level on average. In some areas, however, the annual precipitation can exceed 11,300 mm. The diversity of flora and fauna is the highest of any region. On average, there are 155 mammal species, 446 bird species, 63 amphibian species (max. 135), and 6305 plant species (max. 10,000).

- Class Jb

The region is slightly smaller in area (3.78%) and has a significantly smaller presence in the Americas (coastal areas of Central America, from Peru to Guyana, Brazil, Trinidad), while it occupies a significant area in Africa (a coastal belt from Guinea-Bissau to Ghana and from Benin to Cameroon, Gabon, Congo, the Democratic Republic of the Congo, and Madagascar), southern and southeastern Asia (a west coast of India, Sri Lanka, Nepal, from Bhutan to Malaysia, Farther India, the Sunda Islands, the Moluccas, the Philippines, Taiwan, New Guinea), and northern Australia (the Cape York Peninsula). The maximum annual precipitation exceeds 11,400 mm. There is a greater difference between the wettest and the driest quarters. Biodiversity is lower, at about two-thirds for fauna and one-half for flora, but it is still well above average.

- Class Jc

One of the smallest regions (0.15%) which, apart from the east of Madagascar, comprises mainly small islands and islets (smaller islands of the Malay Archipelago, or the Solomon Islands). The diversity of the fauna is slightly below average, but the flora is very rich, with 5046 plant species on average and a maximum of about 10,000 species.

- Class Jd

This is also a very small region (0.21%) that spreads over tropical islands and archipelagos (Jamaica, Puerto Rico, the Lesser Antilles, São Tomé and Príncipe, Madagascar, the Comoros, the Seychelles, Mauritius, the Maldives, the Andaman and Nicobar Islands, small islands of the Malay Archipelago, and Oceania). It has the lowest temperature annual range of 10.6 °C and an altitude of 214 m above sea level. The diversity of the fauna is slightly lower, and the diversity of the flora is significantly lower, with a below average 1767 plant species.

3.1.5. GES Classification

Global Environmental Systems are the final result of the classification process. The classification of natural conditions (30 classes) was combined with the anthropogenic classification (10 classes), resulting in 169 unique Global Environmental Systems out of 300 possible (Figures 6 and 7). Each GES has its own code assigned. The code consists of one or two letters ('A' to 'J', and 'a' to 'e') and a number (1 to 10), e.g., A9, Hc7, or Db10. The letters in the title indicate abiotic + biotic affiliation, and the number indicates affiliation to the anthropogenic class.

A Global Environmental System with the designation Hc9 is the most widespread in the world, occupying 8.32% of the world's land area from the Western Sahara to the Arabian Peninsula, Iran, Afghanistan, and Pakistan. It is a region of bare areas with high temperature, the lowest precipitation, and low vertical heterogeneity, human impact, and biodiversity. Class Ja6 occupies 5.3% of the world in the equatorial region of America, Africa, and Asia. The dominant land cover is broadleaved, evergreen forest with the highest diversity of mammals, birds, and amphibians and the third highest diversity of flora. This region is typical of high temperature and precipitation and has a low temperature annual range. The third largest GES is B10 (4.41%) in Alaska, Canada, and Russia. It is a very cold region of needleleaved, deciduous forest with the second highest temperature annual range, low biodiversity, and human impact. Global Environmental Systems Ic5 and Da4 cover over 3%; Ic8, Ic7, Da5, Fb9, Fb8, Gc8, and Hb8 cover over 2%. In contrast, classes Gd2 and Hc2 cover only about 0.001% of the Earth's landmass.

The full details of each of the 169 GES classes can be found in Appendix A; the Global Environmental Systems classification is openly available in the Science Data Bank [38].

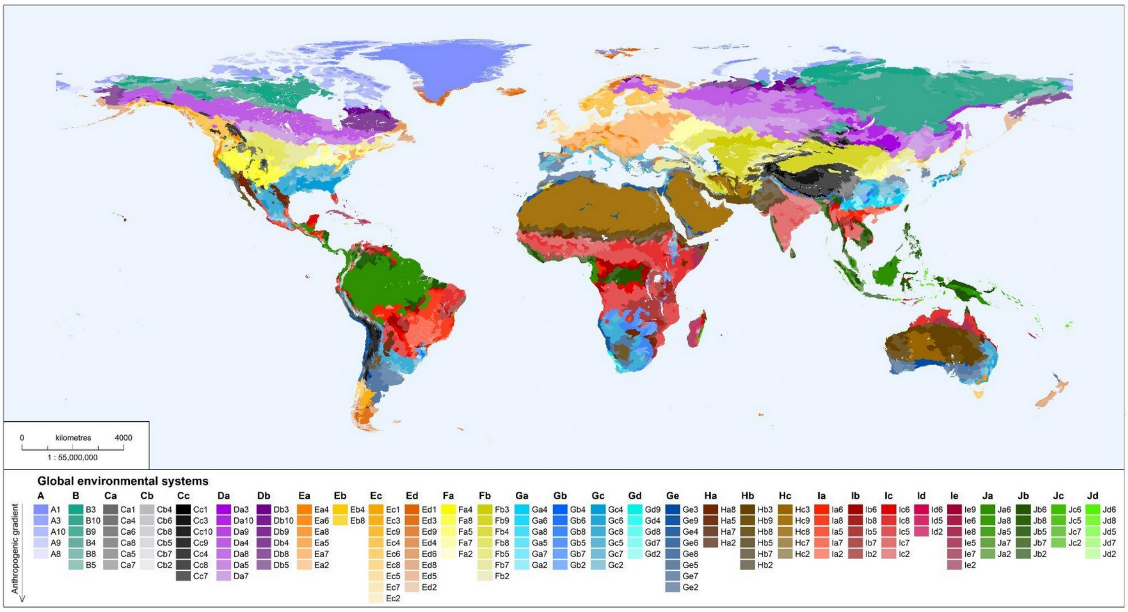

Figure 6. Global Environmental Systems (Tables 7 and 8).

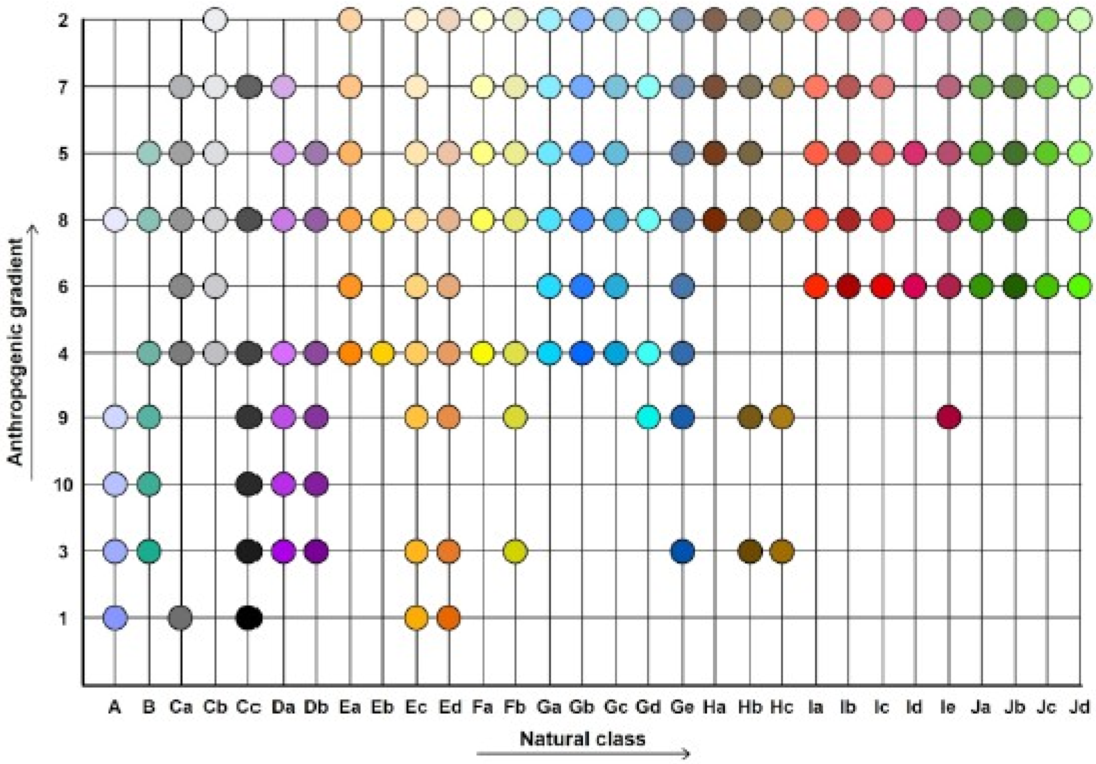

Figure 7. Synthetic diagram of the combination of natural conditions and anthropogenic gradient (Tables 7 and 8).

3.2. Biodiversity Conservation Prioritisation—Biodiversity Hotspots Concept

Biodiversity hotspots are those areas where the highest concentrations of endemic species can be found. At the same time, however, these are areas that are facing enormous loss of natural habitat. The concept of terrestrial biodiversity hotspots, very important areas for biological conservation, was first introduced by the British ecologist Norman Myers [39] and adopted by Conservation International a year later [40]. Biodiversity hotspots must meet two strict criteria: every hotspot must contain at least 1500 endemic vascular plant species and must have lost at least 70 percent of its primary native vegetation. There are currently 36 biodiversity hotspots on Earth, the last one having been established in 2016. Biodiversity hotspots cover 2.4% of the Earth's land area and harbour about 50% of endemic plant species and 42% of endemic terrestrial vertebrate species [41].

Thus, it is no great surprise that abiotic classes 1: freezing arctic region; 2: cold northern region with a significant temperature annual range; and 4: colder temperate zone of the Northern Hemisphere are not present in the biodiversity hotspots. Many hotspots are located partially or completely in the mountains, so Class 3: region of the highest mountains covers more than 9% of the total area of hotspots (Table 9). Two other temperate regions, Class 5: humid temperate region; and 6: Warmer and drier temperate zone of the Northern Hemisphere, cover 3.37% and 5.66%, respectively. Class 8: deserts and semi-deserts of the tropics is found in 4.81% of the hotspot area. The most suitable conditions for the existence of biodiversity hotspots have Class 7: subtropics of both hemispheres; 9: extensive subequatorial region with a drier period; and 10: warm and humid equatorial region. These classes occupy 24.10%, 33.39%, and 19.51% of the area of biodiversity hotspots, respectively.

Table 9. Abiotic classes within biodiversity hotspots.

Abiotic Class	Class Area in Hotspots [%]	Global Class Area [%]	Representation in Hotspots [%]
1	0.00	3.38	0.00
2	0.00	7.11	0.00
3	9.16	4.42	38.66
4	0.00	10.98	0.00
5	3.37	7.08	8.87
6	5.66	9.86	10.71
7	24.10	12.70	35.38
8	4.81	16.84	5.32
9	33.39	17.73	35.11
10	19.51	9.91	36.71

The abiotic classes of the Arctic and temperate zones (1, 2, 4, to 6) account for 38.41% of the world's land area but only 9.03% of the area of biodiversity hotspots. An azonal mountain Class 3 covers 4.42% of the Earth's landmass but 9.16% of the hotspots area. This means that almost 40% of the area of this class lies in hotspot territory (Figure 8). The abiotic classes of the subtropic and tropic zones (7 to 10) account for 57.18% of the world's land area but 81.80% of the area of biodiversity hotspots. And without the inhospitable desert Class 8, it is 40.34% globally and 77% within hotspots. These three classes have over 35% of their area in hotspots, while Class 8 has only 5.32% (Figure 8).

Biotic Class 7: region with the lowest species richness is very extensive, but only around 3% of its total area is in hotspots (Table 10, Figure 9). This class is found in only 4.21% of the hotspots area, which is the third lowest share. Class 2 is the largest globally and in hotspots, where it occupies 22.30% of the area. However, this is only 12.75% of the global class area. Class 3 has a richer fauna and flora and is thus the first with a larger proportion in the hotspots than at the global level. This is true for all subsequent classes except the richest one: Class 6. Class 3 occurs in almost one-fifth of the hotspot area. Class 5 is very specific with a low diversity of fauna but very high diversity of flora. This class is very small, so it covers only

2% of the area in the hotspots. However, this is almost 75% of the global area of this unique class. Class 8 covers 6.25% of hotspots area, and the slightly richer Class 10 covers 13.34%. The next class is Class 4, which does not differ much from the previous one in diversity of fauna but has a very rich flora. It accounts for 10.51% of the area of hotspots. The class with the third highest faunal biodiversity, but no exceptional flora, is Class 9, covering 7.65% of the hotspots territory. Class 1 again shows a slightly higher diversity of fauna than the previous class, the second highest, but the diversity of flora is twice as high and is the highest overall. Class 1 is abundant in biodiversity hotspots. Classes 3, 8, 10, and 9 have progressively higher species richness, but the diversity of flora is only slightly above average in all of them. They all have a very similar representation in hotspots, ranging from 24.47% to 28.11% of the total class area. Classes 4 and 1 both show very rich flora, and both are abundant in hotspots at 66.43% and 69.22%, respectively. The same pattern works for Class 5, which even shows a representation of 74.92%. Classes with high floral diversity are concentrated in biodiversity hotspots areas. Class 6 is the richest class, but it occupies only 1.39% of hotspots. Here in the biodiversity hotspots, it is a smaller proportion than at the global level (3.81%). This is due to the fact that most of the species-richest Class 6 is fortunately located in wilderness areas such as Amazonia or the Congo Forests of Central Africa and not in the anthropogenically heavily impacted biodiversity hotspots.

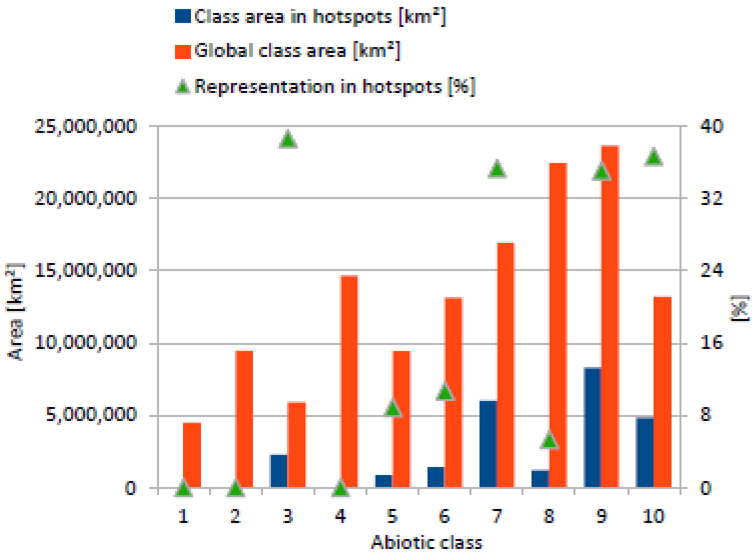

Figure 8. Abiotic classes within biodiversity hotspots.

Table 10. Biotic classes within biodiversity hotspots.

Biotic Class	Class Area in Hotspots [%]	Global Class Area [%]	Representation in Hotspots [%]
7	4.21	23.50	3.34
2	22.30	32.61	12.75
3	19.98	14.59	25.54
5	2.09	0.52	74.92
8	6.25	4.76	24.47
10	13.34	8.85	28.11
4	10.51	2.95	66.43
9	7.65	5.10	27.96
1	12.29	3.31	69.22
6	1.39	3.81	6.81

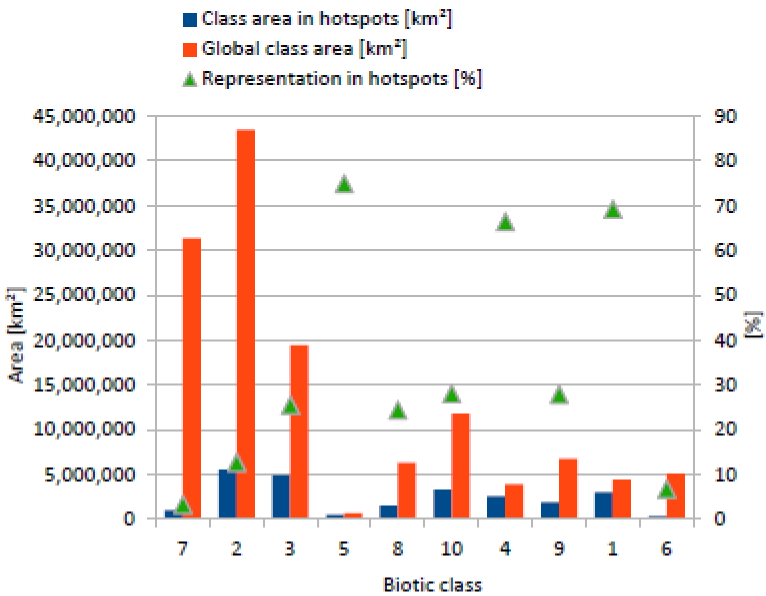

Figure 9. Biotic classes within biodiversity hotspots.

From 30 combined natural classes, 26 are present in the hotspots. Classes A, B, Da, and Db are missing. Four classes cover more than 10% of the total hotspot area. Class Ia, characterised as an extensive subequatorial region with a drier period with very high biodiversity, occupies the largest share with 14.12%. Class Gc, a region of moderately species-rich subtropics, covers 12.02%. Class Ic is also an extensive subequatorial region with a drier period, this time with slightly above average biodiversity. This class covers 11.47% of the hotspots area. And finally, Class Jb, a warm and humid equatorial region with well above average biodiversity, covers 10.31%. Classes Ja and Ge are next with a share of over 7.5%, then classes Cc, Fb, and Ib with a share of over 4%, and so on up to class Id (0.44%, i.e., 109,082 km^2). And finally, Class Eb is by far the least represented with only 11 km^2.

Anthropogenic Class 1 does not occupy a large share globally (1.98%) and even less in biodiversity hotspots (0.92%), being found mostly in Asian mountain hotspots with permanent snow and ice. Only 2.91% of the Class 3 global area lies in hotspots (Table 11, Figure 10), where sparse vegetation land cover class covers 0.96% of the total hotspot area. Class 10, characterised by very low human and livestock density and needle leaved, deciduous tree cover and lichens and mosses, is not present in the biodiversity hotspots area at all. Class 9, characterised by different bare areas, occupies the third largest area globally but only 4.44% in the hotspots. Another class with a relatively small representation in biodiversity hotspots is Class 4 (4.85%), dominated by tree cover, needle leaved, evergreen. Class 6, on the other hand, accounts for 19.6% of the hotspots area, which is the third highest share. Almost one-third of this class is in hotspots. Human and livestock density is already a bit higher in this region, and the typical land cover is tree cover, broadleaved, evergreen. Class 8 is the second most represented in the hotspots territory (20.75%). It is the area of shrublands and grasslands. Another important class is Class 5 (11.51%), which has the third highest human density and accessibility, and broadleaved, deciduous, or mixed leaf type tree cover, mosaic tree and shrub/herbaceous cover, or flooded tree/shrub/herbaceous cover. The last two classes are Class 7 and Class 2, both with more than 34% of their total global area being located in biodiversity hotspots. Class 7 has the second highest values of all anthropogenic indicators; it is typical of cropland land cover and occupies 28.99% of the hotspots area. Class 2 has the highest values of all anthropogenic indicators; it is typical of cropland land cover or mosaic cropland/natural vegetation and occupies 7.98% of the hotspots area.

Table 11. Anthropogenic classes within biodiversity hotspots.

Anthropogenic Class	Class Area in Hotspots [%]	Global Class Area [%]	Representation in Hotspots [%]
1	0.92	1.98	8.66
3	0.96	6.17	2.91
10	0.00	5.82	0.00
9	4.44	14.25	5.81
4	4.85	8.19	11.03
6	19.60	11.19	32.67
8	20.75	19.94	19.40
5	11.51	12.31	17.43
7	28.99	15.88	34.04
2	7.98	4.26	34.95

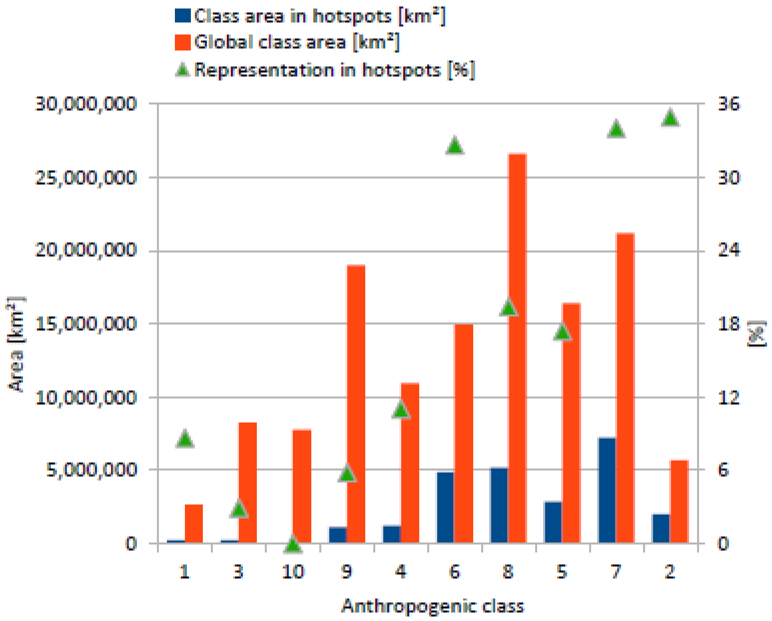

Figure 10. Anthropogenic classes within biodiversity hotspots.

Biodiversity hotspots are areas with significant fauna and flora but also intense human impact. Anthropogenic classes with lower human impact (1, 3, 10, 9, and 4) cover only 11.17% of biodiversity hotspots while anthropogenic classes with higher human impact (6, 8, 5, 7, and 2) cover 88.83% of the area of biodiversity hotspots, and globally, the ratio is 36.41% to 63.58%. This shows that valuable hotspot areas are more threatened by different types of human activity than the rest of the world.

Biodiversity hotspots can be classified to identify the most significant hotspots. The analysis of hotspots' importance by Myers et al. [36] was driven by two criteria: species endemism and the degree of threat, and it considered five factors: numbers of endemics and endemic/species ratios for plants and vertebrates and habitat loss. Hotspots, which appeared the most often in the top ten listings for each factor, were the most important. The analysis by Hrdina and Romportl [37] considered thirteen factors: the numbers of endemics and endemic/species ratios for plants, mammals, birds, amphibians, reptiles and freshwater fish, and habitat loss. For the purposes of qualitative comparison, the rankings of each factor were compiled and the top twelve listings for each factor were considered. Biodiversity hotspots, appearing for all thirteen factors in the top twelve listings, are the most important.

From articles by Myers et al. [36] and Hrdina and Romportl [37], it is clear that these six biodiversity hotspots are clearly the most significant: Madagascar and the Indian Ocean Islands, Sundaland, the Philippines, the Caribbean Islands, Indo-Burma, and Atlantic Forest. Five of them contain only anthropogenic classes with higher human impact (2, 7, 5, 8, or 6); only in Indo-Burma is 2.62% of this hotspot occupied by anthropogenic Class 4, which is nevertheless the class with the sixth highest human impact. A closer look at individual biodiversity hotspots shows that the most important ones face a great anthropogenic impact.

Out of a total of 169 Global Environmental Systems, 134 are located in hotspots. The most widespread GESs in hotspots is an equatorial Class Ja6 with the highest species richness of amphibians, birds, and mammals and the third highest number of plants, with predominant tree cover, broadleaved, evergreen, which covers 5.62% of the total area of biodiversity hotspots. Over 5% of the area is also occupied by tropical Class Ia7 (5.39%), which is also very rich in species but is under much greater human pressure. Then, there are three classes over 4%: Ge7, Ia8, and Jb6; three classes over 3%: Gc7, Ic8, and Ic7; seven classes over 2%: Gc4, Jb7, Ic5, Ia6, Fb7, Gc8, and Jb2; and ten classes over 1%: Cc8, Ic6, Ca8, Gc2, Ib7, Gc5, Ie5, Hb9, Ja2, and Ib5. The remaining 109 GESs occupy less than 1% of the area. The most unique GES is Hb5 with an area of only 5.7 km^2. All five A classes, six B classes, seven Da classes, and six Db classes are not located in hotspots. Furthermore, there are no GESs Cc10, Ea6, Eb4, Ec1, Ec9, Ed4, Ed9, Fb3, Fb4, Hc2, and Hc3 in biodiversity hotspots.

The presented combination of both spatial concepts of environmental quality assessment and the level of its human degradation across abiotic gradients gives us information about the areal distribution, the level of vulnerability, and the priority of the natural protection of specific regions of our planet.

4. Discussion

Several different classifications have emerged over the years. In 2008, Ellis and Ramankutty [6] published the classification of anthropogenic biomes, followed by Ellis' anthromes in 2010 [13]. In 2012, Letourneau et al. [22] presented the classification of land-use systems and Van Asselen and Verburg [23] the classification of land systems. A year later, Václavík et al. [24] came up with the classification of land system archetypes. In 2020, the classifications of world ecosystems [2] and the IUCN Global Ecosystem Typology [25] were released.

Anthropogenic biomes and anthromes are based on the global data of population, land use, and land cover, not using biotic or abiotic factors. Land-use systems are characterised by land cover, land use, and population data too, plus livestock density and accessibility. Land cover, livestock, and agricultural intensity data were used for the classification of land systems, with land use intensity being a crucial characteristic, while population density was not used as a classification criterion at all. Land system archetypes are based on 32 indicators that are socioeconomic, but also biotic and abiotic. All five classifications have a resolution of 5 arc minutes. The classification of GESs has a resolution of 30 s, as does the IUCN Global Ecosystem Typology. The finest resolution of 8 arc seconds has the classification of world ecosystems that is based on global moisture domains, global temperature domains, global landforms, and finally global vegetation and land use. In this classification, no socioeconomic data were used. GES classification uses 22 variables characterising abiotic, biotic, and anthropogenic conditions.

The authors of anthropogenic biomes, anthromes, land-use systems, and land systems classifications all applied top-down approaches based on expert's rules or a priori classification; Václavík et al. [24] used a bottom-up approach for the classification of land system archetypes, while Keith et al. [25] used the combination of both bottom-up and top-down approaches for the IUCN Global Ecosystem Typology. It was created as a hierarchical classification, where functional variation among ecosystems is represented in the upper three levels developed from the top-down approach, while compositional variation is represented in the lower three levels. Sayre et al. [2] used the structural approach. The map of world ecosystems was derived from the objective development and integration of different global natural elements.

The classification of Global Environmental Systems consists of ten abiotic classes at the upper level. A total of 10 biotic classes are added at the middle hierarchical level, resulting in 30 natural classes. And finally, at the bottom level, ten anthropogenic classes enter the classification. There are 169 different GESs at this level of classification. It is the most similar to the IUCN Global Ecosystem Typology that consists of 5 global realms, 25 biomes, and then 108 ecosystem functional groups, etc. Anthropogenic biomes, anthromes, land-use systems, and land systems all have a very similar structure. These classifications are grouped into six or eight categories in the case of land systems. Each category is further divided into individual classes; in total, there are 21, 19, 24, and 30 classes, respectively. Land system archetypes and world ecosystems have a different structure, and they also differ from each other; there are 12 and 431 classes, respectively, which are not further divided.

5. Conclusions

The new classification of Global Environmental Systems is a high-resolution spatial delineation of many different combinations of partial abiotic and biotic classifications based on gradients of inanimate and living nature and anthropogenic classification reflecting the degree of human impact. A total of 169 GESs were identified and mapped. The proposed procedure of defining Global Environmental Systems outperforms previously developed classifications mainly by the complexity of the input data and their thematic and spatial resolution.

The Global Environmental Systems presented in this article can serve in many ways to better understand the changing world, human pressure on the natural sphere, interactions between humans and the natural environment, etc., not just at the global level, which would help to find common patterns across continents where similar actions can be taken or to help with conservation activities.

The use of delineated GESs can be applied as a typological spatial framework for assessing global environmental processes, whether they be climate change impacts, land use/land cover changes, ecosystem service dynamics, or changes in biodiversity distribution. Similarly, GESs can be used to monitor these processes; the changes in the defined GESs will indicate changes in the whole complex of environmental conditions.

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Abbreviations

GES	Global Environmental System
Temp.	Temperature
Precip.	Precipitation
Heterogen.	Heterogeneity
TPI	Topographic Position Index
GLC	Global land cover

Appendix A

Table A1. GES of the freezing arctic region.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
A1	3.26	9.59	0.00	36.48	−18.27	−3.66	−30.14	34.74	656.36	209.42	132.29	1699.82	25.78	1.25	0.61	0.01	10,750.06	17	79.76	1,996,425	1.487
A3	11.04	33.45	1.00	393.10	−13.44	2.68	−27.43	40.21	265.57	104.23	39.65	272.70	41.47	−2.36	0.61	0.04	4802.29	12	43.29	1,036,034	0.777
A8	37.82	53.11	1.00	606.19	−9.44	5.15	−22.61	38.17	295.32	122.30	41.41	218.19	49.03	0.57	0.07	0.17	3368.53	16	27.17	194,643	0.146
A9	9.48	25.53	1.00	287.08	−17.37	1.29	−32.80	43.56	156.29	70.79	19.49	278.67	57.88	−3.91	8.40	0.02	6894.79	15	57.65	433,748	0.325
A10	11.23	30.74	1.00	393.89	−12.96	3.64	−28.24	42.56	241.30	107.73	27.53	221.16	31.12	−1.40	1.56	0.03	4464.17	11	51.85	848,981	0.636

Table A2. GES of the cold northern region with a significant temperature annual range.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
B3	20.42	57.86	1.06	664.34	−12.79	7.38	−31.38	52.34	298.02	127.43	36.34	351.20	39.74	1.01	0.36	0.24	2898.07	12	42.80	1,408,494	1.056
B4	33.23	104.94	1.31	748.01	−7.38	11.76	−26.64	52.71	378.96	160.65	38.31	467.70	36.98	−0.23	0.25	0.17	2076.56	5	54.60	1,131,864	0.848
B5	27.41	93.58	1.67	808.22	−11.16	9.28	−30.25	52.80	297.21	136.14	31.36	207.26	36.17	−0.01	0.18	0.29	3026.34	16	22.71	172,523	0.129
B6	26.24	81.15	1.23	746.80	−11.91	8.40	−30.34	51.99	267.30	123.93	30.94	257.14	52.63	0.24	0.57	0.32	2892.03	10	22.66	680,258	0.510
B9	24.00	88.94	1.84	562.32	−37.81	6.50	−41.95	62.45	360.90	187.52	34.10	1174.17	166.55	11.18	0.06	0.11	2366.08	15	45.27	232,831	0.175
B10	29.29	114.32	1.95	1062.45	−11.05	11.03	−33.45	59.27	348.02	170.99	31.06	470.98	50.69	−0.33	0.40	0.36	2187.36	6	47.46	5,976,459	4.485

Table A3. GES of the region of the highest mountains.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
Ca1	48.00	192.24	2.97	2649.14	−3.72	7.07	−16.24	37.07	436.67	242.29	16.45	3946.26	317.47	52.00	14.73	10.49	1650.47	10	41.80	67,562	0.051
Ca4	73.49	226.92	7.88	2254.52	3.81	12.74	−5.35	34.11	681.69	317.74	67.02	2702.22	230.08	5.57	24.97	16.15	703.61	5	59.68	472,816	0.354
Ca5	57.71	168.43	8.33	3038.30	4.50	15.68	−7.51	37.54	726.68	353.08	61.08	1785.83	175.91	16.23	27.39	57.47	387.96	4	31.42	79,636	0.060
Ca6	123.87	363.74	14.61	3083.47	12.25	13.07	11.08	16.22	1211.71	495.85	114.75	2979.21	279.95	30.26	87.47	61.79	587.94	3	50.51	44,836	0.036
Ca7	77.39	225.12	6.81	2884.77	8.28	11.47	4.58	22.89	831.58	412.91	51.24	3270.84	170.09	16.59	152.47	81.29	412.18	10	31.24	82,034	0.062
Ca8	64.91	210.79	5.17	2628.18	1.40	10.63	−8.48	34.52	608.48	312.53	33.49	3354.21	231.78	17.72	44.10	19.64	1080.85	10	48.80	672,024	0.504
Cb2	137.23	314.70	11.15	5460.77	12.09	12.56	11.41	12.97	1061.48	397.48	137.58	2876.92	192.66	16.48	282.93	272.48	211.25	3	32.57	32,165	0.024
Cb4	91.46	286.90	14.69	4854.33	7.74	14.59	0.08	26.85	1007.56	536.07	42.40	2627.10	329.60	15.77	124.86	68.69	835.53	5	56.61	69,170	0.052
Cb5	61.74	164.92	6.59	4823.74	6.22	14.46	−2.23	28.24	1040.50	245.51	175.71	1401.15	281.80	−14.84	24.99	63.29	292.02	4	50.21	31,775	0.024
Cb6	128.69	328.85	8.83	5303.33	12.08	12.60	11.37	14.15	1251.91	464.16	162.43	2982.08	284.19	40.28	68.84	65.15	703.03	3	64.52	128,668	0.097
Cb7	89.08	203.18	10.20	5285.01	11.81	13.87	9.23	20.68	1010.27	487.72	68.67	2789.93	209.96	4.10	112.14	147.98	261.19	3	24.36	53,721	0.040
Cb8	64.33	165.84	4.80	4409.59	2.80	9.74	−4.50	26.62	933.67	373.01	124.78	2526.61	286.90	28.42	48.31	29.19	346.41	10	26.28	95,979	0.072
Cc1	38.90	135.31	3.05	1030.14	−4.79	5.69	−15.68	35.48	433.71	199.86	41.23	4489.00	318.80	46.06	7.59	14.88	2802.43	10	37.93	318,956	0.239
Cc3	24.02	73.84	2.29	837.71	−1.35	6.93	−10.05	33.41	205.28	135.67	8.15	4344.67	111.73	4.64	8.36	2.12	8537.38	12	32.70	582,002	0.436
Cc4	54.19	168.41	4.47	1482.35	0.37	10.42	−9.38	35.36	631.65	223.21	111.44	2049.21	231.93	13.46	4.40	2.22	694.70	5	55.95	264,018	0.199
Cc7	51.86	137.67	4.13	1757.88	6.53	13.20	−0.48	30.15	568.35	284.47	26.21	3103.58	166.56	12.59	105.70	61.76	302.06	10	31.33	85,263	0.064
Cc8	33.20	108.87	2.27	1183.13	−1.33	8.64	−12.03	36.44	336.42	193.58	34.00	3985.67	168.72	3.85	30.91	8.12	3734.94	10	62.59	2,225,494	1.668
Cc9	28.18	82.62	2.16	911.57	0.63	10.04	−9.76	36.66	108.37	73.49	3.90	3754.81	107.96	1.06	13.53	2.02	2987.65	15	61.65	570,074	0.427
Cc10	53.73	225.46	2.04	1099.37	−8.09	9.28	−27.62	52.38	456.29	281.07	20.27	2021.12	160.85	6.46	6.20	1.16	1065.09	6	39.05	37,197	0.028

Table A4. GES of the colder temperate zone of the Northern Hemisphere.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km²]	Area [%]
Da3	36.14	117.38	1.52	1165.19	−0.18	17.19	−19.08	51.83	240.08	160.91	11.75	1012.27	29.55	0.44	32.54	1.53	611.35	12	64.42	360,767	0.270
Da4	37.84	124.24	3.27	1010.76	−2.29	13.57	−19.12	47.47	531.79	211.09	72.87	405.21	34.43	−0.22	0.58	1.11	1073.21	5	58.24	4,428,326	3.320
Da6	43.10	187.23	5.81	1271.79	−0.09	15.68	−16.88	46.65	587.72	242.74	72.75	219.87	22.22	−0.07	7.82	11.33	618.27	4	27.71	3,556,810	2.666
Da7	46.89	183.11	5.37	1190.28	2.12	19.04	−15.39	48.02	441.81	210.18	47.18	318.36	13.49	−0.11	41.60	39.41	223.12	1	60.76	2,002,789	1.501
Da8	43.88	166.71	2.49	1216.93	−0.32	16.41	−18.55	49.82	308.82	181.59	30.18	481.58	47.44	−0.96	23.51	6.94	546.08	10	43.69	1,157,900	0.868
Da9	40.38	146.20	1.23	688.30	−3.47	12.58	−20.64	46.31	275.98	143.01	28.53	1488.84	115.45	1.86	13.94	0.67	1301.29	15	57.06	183,572	0.138
Da10	43.23	170.62	2.75	1158.75	−4.23	13.49	−23.21	51.65	508.25	252.77	41.82	626.48	67.33	−0.61	1.80	2.33	1161.77	6	51.33	914,537	0.686
Db3	21.82	55.92	1.26	639.91	−6.94	8.77	−22.39	43.61	447.73	181.04	69.80	191.21	22.82	0.57	1.79	0.48	2301.09	12	37.52	327,037	0.245
Db4	29.19	64.62	2.40	946.75	−4.37	10.66	−20.61	45.06	731.55	266.78	117.45	262.72	26.54	0.07	0.03	0.12	1891.61	5	58.84	817,812	0.613
Db6	24.66	102.27	1.18	687.65	−4.82	10.25	−19.12	41.01	548.58	187.49	74.85	185.35	42.24	−2.19	0.38	0.51	1625.88	13	23.46	128,460	0.096
Db8	24.94	81.25	1.17	712.62	−5.66	8.83	−18.58	41.33	428.75	174.35	61.37	204.23	43.32	−0.40	0.56	0.48	2324.14	9	34.70	618,647	0.479
Db9	35.40	85.84	1.00	711.33	1.90	19.34	−17.31	51.80	181.90	128.74	4.59	1036.98	17.31	−0.37	24.11	0.68	400.18	15	46.63	35,221	0.026
Db10	24.34	74.89	1.61	699.71	−6.90	9.91	−22.07	45.77	475.69	180.85	70.91	345.62	20.25	−0.02	1.37	0.78	1780.23	11	48.22	92,727	0.070

Table A5. GES of the humid temperate region.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km²]	Area [%]
Ea2	50.74	178.85	14.26	1866.56	6.91	18.08	−4.76	34.00	717.82	257.06	153.24	161.38	37.15	−0.53	36.64	395.26	86.75	4	21.22	83,067	0.062
Ea4	61.30	162.67	11.54	2308.41	7.32	15.64	−0.95	28.87	948.28	399.90	121.34	477.81	137.15	2.61	50.93	44.76	219.52	5	57.51	324,539	0.240
Ea5	55.00	166.23	13.48	2372.11	6.66	17.33	−4.30	33.44	837.76	295.82	148.05	520.75	73.41	2.49	38.03	59.42	170.23	4	42.36	978,211	0.733
Ea6	37.40	260.83	15.81	2097.60	10.09	15.84	4.23	24.64	1104.73	248.65	195.24	897.67	111.39	10.18	36.00	3.01	321.74	3	70.44	49,216	0.037
Ea7	54.90	168.35	12.54	2383.59	8.26	18.35	−2.21	30.77	642.82	223.54	113.83	194.98	20.13	−0.62	85.31	108.75	91.36	1	55.69	2,230,581	1.672
Ea8	58.56	139.38	13.50	3053.47	8.61	16.01	1.11	24.90	966.75	284.85	202.35	406.52	88.60	−4.77	97.51	105.23	104.14	10	35.42	100,188	0.075
Eb4	63.96	125.91	9.74	4962.47	4.96	13.21	−3.72	27.62	1166.86	414.71	198.22	1197.98	252.99	−4.23	61.27	72.08	169.90	5	39.42	56,709	0.043
Eb8	67.45	122.26	5.59	4980.91	1.06	8.28	−5.88	22.68	1661.71	468.15	365.87	2188.90	368.68	61.75	22.19	24.54	312.98	10	36.10	19,568	0.015
Ec1	37.18	122.11	2.54	610.61	−1.52	8.15	−10.58	30.28	1356.78	401.70	183.50	1376.79	237.54	10.57	8.75	0.23	2084.14	17	51.81	87,859	0.066
Ec2	39.70	143.19	9.99	1570.29	9.26	15.76	2.86	21.00	868.07	269.72	164.15	92.21	24.80	−0.98	421.41	406.75	36.91	1	25.56	221,897	0.166
Ec3	27.01	109.22	1.93	1102.64	5.40	12.03	−1.18	24.62	568.67	205.18	93.31	805.92	96.11	4.27	18.29	1.22	501.71	12	49.87	253,794	0.190
Ec4	38.00	163.70	4.73	1300.71	2.81	13.01	−7.18	31.54	830.78	304.37	123.42	480.91	81.79	−2.81	8.75	11.54	434.72	5	58.12	1,586,819	1.187
Ec5	40.30	166.50	7.34	1406.47	3.82	15.16	−7.75	33.88	898.46	318.41	142.56	261.16	51.71	−1.01	20.83	27.27	282.01	4	25.14	773,736	0.580
Ec6	25.54	121.10	6.57	910.65	9.55	13.80	5.43	19.24	1550.69	642.86	194.48	529.53	174.86	−3.45	24.09	14.03	398.02	3	50.56	177,777	0.133
Ec7	39.91	152.23	9.10	1598.10	8.24	16.12	0.64	24.88	778.72	266.90	129.84	125.93	21.09	−1.09	160.91	158.41	68.20	1	45.09	341,468	0.256
Ec8	35.73	126.63	4.07	1376.52	6.76	13.79	0.22	23.96	840.36	282.59	133.63	405.98	83.88	−1.32	117.24	40.94	309.16	10	26.68	196,787	0.148
Ec9	34.08	109.83	1.52	727.82	−2.61	9.04	−12.02	31.23	815.48	293.97	128.86	1099.38	252.04	6.51	3.28	0.55	1480.79	15	39.66	32,012	0.024
Ed1	6.92	48.10	1.18	232.12	−3.38	3.73	−9.46	20.64	1100.01	324.92	221.88	381.68	106.27	2.80	6.46	0.26	2824.52	17	51.49	164,708	0.123
Ed2	2.49	68.06	2.05	870.44	8.12	13.19	4.90	17.71	1234.22	360.51	255.12	460.78	92.68	0.67	481.47	18.31	377.77	16	26.37	10,717	0.008
Ed3	16.06	83.57	1.05	887.85	2.79	8.84	−3.99	23.45	575.82	182.66	107.08	462.75	73.12	−2.40	24.12	1.21	1087.72	12	36.06	309,080	0.232
Ed4	20.85	93.93	1.76	928.11	1.39	10.93	−8.10	29.41	1320.21	445.93	227.33	258.08	61.90	−1.26	3.89	4.08	1232.73	5	53.46	202,841	0.152
Ed5	17.69	108.90	1.66	597.09	2.10	9.46	−5.08	22.83	1300.85	407.85	250.40	282.84	115.36	−3.22	7.05	2.33	998.39	16	30.86	340,044	0.255
Ed6	5.18	80.42	5.56	966.07	8.12	13.44	4.59	18.61	2270.23	685.90	455.37	588.66	191.81	−2.75	48.32	4.62	676.54	3	43.67	112,068	0.084
Ed8	17.03	81.59	1.32	767.14	3.07	11.29	−4.73	25.61	820.10	273.44	149.69	251.12	59.72	−0.47	40.69	4.64	1212.49	16	23.71	712,265	0.534
Ed9	4.27	22.24	1.00	268.58	−2.55	4.45	−8.30	19.49	725.59	217.57	134.83	371.12	79.41	−3.12	23.42	0.44	1606.18	15	37.68	61,571	0.046

Table A6. GES of the warmer and drier temperate zone of the Northern Hemisphere.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km²]	Area [%]
Fa2	48.75	159.76	10.93	2580.35	10.35	22.48	−2.57	39.34	618.28	295.34	83.38	524.91	47.72	−5.10	281.69	376.91	131.84	1	45.88	204,608	0.158
Fa4	69.24	176.75	8.91	2100.50	7.06	17.25	−2.79	38.88	456.85	176.12	65.39	2022.44	95.23	−0.78	3.46	3.66	301.01	5	56.99	221,485	0.166
Fa6	52.28	168.35	15.39	2285.23	7.85	18.61	−4.71	38.44	836.75	312.22	123.28	614.23	70.18	−0.62	51.37	68.14	237.36	4	37.05	492,641	0.369
Fa7	49.36	174.35	10.51	2464.29	7.74	20.72	−5.57	39.38	606.57	206.67	96.97	323.68	25.55	−0.98	52.50	62.50	139.60	1	57.62	1,359,413	1.019
Fa8	60.34	164.71	8.39	2516.87	9.98	20.94	−0.85	40.22	335.52	145.52	42.13	1471.95	60.12	−2.36	22.95	12.28	291.01	9	48.24	1,296,477	0.972
Fb2	33.87	149.42	7.65	2598.11	11.47	24.30	−2.70	40.04	569.30	373.24	20.16	282.77	31.26	−0.67	784.06	535.96	140.41	1	43.52	372,278	0.279
Fb3	34.32	124.20	1.50	795.22	6.88	23.33	−10.51	48.45	176.42	55.58	31.20	222.28	8.38	0.02	5.62	1.68	484.74	12	65.51	567,528	0.430
Fb4	61.05	177.65	5.84	1466.66	5.35	15.61	−4.52	37.41	491.07	187.42	71.36	1387.34	112.04	−4.06	5.19	3.48	279.43	5	52.58	107,690	0.081
Fb5	46.22	160.71	11.96	1587.22	5.63	17.98	−7.94	40.87	796.62	264.92	125.61	689.25	56.93	2.16	29.17	25.57	247.10	4	23.79	218,889	0.164
Fb7	45.08	150.59	6.83	1811.58	9.07	21.62	−4.45	41.55	522.11	228.17	41.31	786.01	45.18	−0.42	99.49	67.81	184.14	1	49.63	1,921,360	1.440
Fb8	42.11	163.95	4.39	1480.73	7.20	20.99	−7.38	44.43	311.32	140.98	31.18	816.83	36.50	−1.11	38.95	18.53	350.60	10	45.83	3,059,132	2.293
Fb9	33.28	95.00	1.42	815.63	9.82	23.99	−5.62	45.96	112.56	59.51	5.70	985.31	28.26	−0.85	26.38	10.38	773.18	15	76.64	3,351,483	2.512

Table A7. GES of the subtropics of both hemispheres.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km²]	Area [%]
Ga2	82.29	306.65	23.04	5518.52	16.53	22.65	8.18	26.38	1324.80	607.57	127.05	854.30	104.96	−4.62	270.93	272.51	214.05	2	31.67	316,168	0.237
Ga4	96.53	362.55	26.39	5856.51	16.64	23.16	8.87	25.98	1433.10	702.83	107.65	1161.46	170.78	1.58	165.96	160.79	312.69	5	36.17	275,991	0.207
Ga5	121.73	379.86	18.31	5988.96	18.13	20.87	14.29	22.22	1370.70	774.98	42.93	1539.37	187.02	3.79	54.54	41.90	298.65	7	43.13	35,002	0.026
Ga6	94.95	317.48	25.91	5464.58	16.86	23.49	9.25	25.45	1372.91	650.64	111.21	999.83	164.57	−0.90	160.99	118.00	490.47	3	53.39	419,638	0.315
Ga7	98.04	265.74	32.23	5019.31	17.64	21.57	13.23	21.69	1292.08	543.61	172.73	1028.42	84.27	−2.02	162.83	113.26	138.98	1	22.58	83,565	0.063
Ga8	70.34	288.20	11.75	5597.06	14.73	18.50	8.75	24.73	441.16	160.32	70.18	781.42	142.17	11.85	35.52	10.67	272.69	9	80.83	35,205	0.026
Gb2	98.54	367.58	22.67	3030.23	16.48	21.33	10.96	23.05	1070.25	509.66	79.21	1239.56	88.67	2.74	254.19	246.85	259.59	1	29.22	195,333	0.146
Gb4	91.24	394.08	11.90	2553.60	14.48	19.61	7.72	24.21	1548.11	964.60	65.17	1979.75	222.79	−18.06	97.27	89.89	608.94	5	46.59	67,823	0.051
Gb5	105.40	368.98	33.60	2581.95	18.77	22.46	15.69	25.27	990.05	591.06	8.98	1257.21	45.86	0.38	22.60	23.42	590.76	4	54.15	580,638	0.435
Gb6	96.13	362.33	22.78	3698.61	16.05	21.38	9.86	23.02	1510.11	705.38	121.60	1333.20	181.59	−1.29	106.60	78.58	471.81	3	48.83	150,260	0.113
Gb7	113.23	406.88	27.94	2499.63	17.78	20.34	14.37	21.55	1023.36	500.41	74.30	1514.09	64.02	5.72	117.91	90.27	244.13	1	41.24	479,632	0.360
Gb8	95.51	365.94	24.29	1975.96	19.25	22.82	14.22	25.74	631.26	246.65	18.70	1156.00	34.10	0.21	38.12	30.19	520.29	9	44.92	536,747	0.402
Gc2	52.12	215.02	16.99	2900.92	15.99	24.53	7.02	29.41	1113.74	464.23	136.41	382.57	47.00	−2.28	361.37	461.77	151.94	1	34.27	1,160,906	0.870
Gc4	48.23	188.94	27.42	2486.56	16.52	24.85	7.64	30.94	1373.24	492.87	216.97	437.68	57.72	0.04	99.75	50.14	170.16	5	49.14	867,248	0.650
Gc5	56.79	205.30	20.29	2598.81	15.55	23.24	7.16	30.80	980.50	372.41	138.16	679.18	70.27	−1.39	44.98	39.61	201.74	4	32.82	983,261	0.737
Gc6	60.24	251.50	21.25	3290.71	14.54	21.28	7.26	25.58	1101.90	435.93	123.43	860.65	125.84	−2.42	113.00	70.16	342.20	2	54.86	291,981	0.219
Gc7	48.50	192.95	15.50	2598.39	15.17	23.13	7.03	28.08	871.30	318.94	125.96	398.32	46.35	−2.89	125.79	108.53	168.11	1	40.24	1,686,622	1.264
Gc8	60.02	290.38	16.12	2153.62	18.18	24.14	11.46	29.13	657.38	279.16	74.80	573.83	37.56	0.34	41.39	13.72	309.94	9	36.85	2,870,822	2.152
Gd2	14.67	126.07	3.62	4087.50	17.65	26.14	9.28	24.94	1096.22	421.86	119.91	51.09	44.24	−1.48	282.82	1366.96	113.61	1	30.10	1405	0.001
Gd4	10.05	117.13	6.75	3318.46	15.16	24.15	6.88	26.59	1702.86	678.78	216.60	122.33	84.29	−5.79	32.10	92.56	223.54	5	37.37	4401	0.003
Gd7	31.57	118.87	4.68	3318.61	15.12	22.51	8.47	23.60	642.19	260.55	37.91	437.83	91.11	−1.17	126.71	132.25	100.09	1	31.87	56,800	0.043
Gd8	37.94	184.39	6.66	4007.59	17.37	21.92	12.46	24.57	161.26	73.20	14.41	428.35	54.03	−2.12	16.58	3.98	500.19	9	43.20	50,160	0.038
Gd9	28.65	120.50	3.37	2960.65	15.54	18.63	12.16	16.92	67.25	31.72	5.30	490.31	34.67	−0.31	25.42	1.00	1017.57	15	55.28	25,585	0.019
Ge2	32.32	154.16	8.26	2206.26	14.98	24.38	5.11	31.22	831.92	390.80	81.32	375.22	41.51	−3.76	592.11	537.53	135.57	1	36.13	378,197	0.284
Ge3	16.56	98.65	2.10	730.21	14.64	21.72	11.09	25.83	202.85	75.12	33.53	579.61	41.49	−3.15	5.40	1.91	987.51	12	56.52	344,904	0.259
Ge4	41.55	164.10	10.39	1865.24	13.59	21.87	5.43	26.98	1280.22	443.46	222.30	407.54	99.80	−11.95	91.29	134.91	149.51	5	33.63	30,636	0.023
Ge5	29.23	137.99	7.56	2261.00	14.86	21.28	8.49	25.47	671.58	274.36	72.36	486.23	62.29	0.26	64.30	29.25	539.32	4	24.63	204,628	0.153

Table A7. *Cont.*

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
Ga6	23.17	162.40	7.24	1971.56	14.50	19.61	9.83	22.73	936.45	509.24	50.82	200.41	38.12	−0.25	52.10	29.14	191.55	3	37.01	77,663	0.058
Ga7	33.98	169.84	7.25	1726.95	15.66	23.20	6.25	28.69	556.35	224.90	55.25	459.61	44.78	−1.48	100.12	70.17	165.64	1	46.25	2,085,108	1.569
Ga8	33.13	161.11	5.16	1081.52	16.44	22.79	9.73	28.91	330.56	130.41	36.18	666.52	35.58	−0.71	22.05	7.40	431.26	9	34.30	1,798,058	1.348
Ga9	29.89	93.27	3.15	1025.28	19.00	23.56	12.08	24.89	95.72	51.05	4.18	862.58	56.47	−0.27	33.85	12.76	438.20	15	81.52	888,165	0.666

Table A8. GES of the deserts and semi-deserts of the tropics.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
IIa2	49.37	378.97	8.41	1483.55	25.27	32.12	16.98	32.15	698.37	472.27	20.29	256.43	4.17	−0.27	201.40	640.78	96.37	1	70.74	103,401	0.078
IIa5	69.78	378.58	24.95	1304.27	23.11	27.74	17.69	25.67	594.35	312.05	21.30	253.74	9.71	−0.37	21.78	5.16	474.53	4	48.17	234,192	0.176
IIa7	51.57	372.12	10.67	1674.41	25.82	30.72	20.35	28.16	508.46	363.92	11.93	365.32	12.17	−0.39	107.06	108.98	186.88	1	56.50	733,896	0.550
IIa8	64.04	260.09	12.53	2112.68	23.15	28.91	16.78	28.99	396.49	225.21	18.92	482.50	22.90	−1.26	29.26	15.12	371.21	9	60.06	1,030,946	0.773
IIb2	36.04	170.72	4.52	1003.53	22.44	30.53	13.00	30.48	168.06	110.49	9.40	234.81	16.51	−3.23	218.60	638.00	141.21	15	40.51	168,294	0.126
IIb5	22.82	149.77	6.54	669.13	23.44	29.82	15.90	30.22	322.32	173.46	24.72	268.74	7.75	−0.03	3.17	0.08	1255.88	12	69.32	2,068,297	1.550
IIb6	45.13	207.16	5.49	784.11	27.06	32.81	18.23	33.62	378.59	279.26	3.03	30.96	7.72	−0.03	150.21	55.86	415.23	13	44.73	36,542	0.027
IIb7	38.37	183.76	4.86	1187.51	24.44	31.73	16.05	32.58	271.80	186.90	5.76	285.11	15.71	−1.37	166.57	130.75	191.49	1	41.10	927,982	0.696
IIb8	35.00	164.82	5.92	1205.42	23.96	29.69	17.42	29.25	285.95	177.36	13.69	451.44	18.87	−0.59	27.69	10.68	580.15	9	29.75	2,722,297	2.042
IIb9	32.25	110.16	3.17	1113.83	24.67	31.15	16.90	30.33	148.75	95.95	6.24	465.24	28.13	−1.36	37.06	13.55	633.63	15	76.60	2,085,483	1.563
IIc2	7.27	57.71	1.00	350.00	25.65	34.44	15.72	31.21	107.30	64.32	0.00	7.47	4.42	−0.29	124.85	523.22	177.11	14	49.32	1589	0.001
IIc5	20.73	98.83	3.09	511.98	22.37	28.98	14.40	31.12	220.57	98.80	23.34	303.12	8.54	−0.01	2.52	0.02	1897.19	12	70.33	998,147	0.748
IIc7	24.14	82.73	2.15	730.62	24.03	31.02	15.49	29.67	78.90	47.16	0.64	167.17	20.06	−1.56	80.62	85.19	224.95	15	68.23	233,537	0.175
IIc8	24.18	98.64	3.76	626.32	21.77	28.02	16.98	27.58	165.79	74.02	17.17	622.65	67.51	3.68	30.80	13.44	727.11	9	33.34	49,709	0.037
IIc9	17.08	32.69	1.67	733.77	24.33	31.83	15.49	32.89	49.31	30.75	0.84	479.97	14.13	−0.26	9.47	4.21	1166.68	15	92.95	11,093,274	8.316

Table A9. GES of the extensive subequatorial region with a drier period.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
Ia2	96.33	378.62	42.27	6129.57	21.57	25.83	16.39	20.00	1598.56	752.73	101.97	339.67	62.40	−0.77	385.74	460.08	150.94	1	27.44	316,662	0.237
Ia5	124.21	411.03	29.24	5528.76	22.28	24.59	18.95	21.67	1400.45	738.26	39.24	846.81	114.00	2.19	31.05	27.56	309.20	4	18.10	258,153	0.194
Ia6	133.85	423.40	48.60	5183.74	21.07	25.06	20.49	17.54	1583.20	712.82	114.54	498.18	71.80	−1.71	42.48	29.78	603.82	3	56.52	1,248,758	0.937
Ia7	122.90	397.51	42.96	6261.85	22.43	24.77	19.16	18.70	1439.49	666.00	100.59	327.12	38.84	−0.77	127.62	57.60	170.36	1	47.16	1,346,960	1.020
Ia8	132.13	373.79	45.78	6251.50	22.79	25.13	21.90	17.25	1347.52	685.68	35.94	521.81	49.48	−0.06	41.56	14.80	275.08	9	44.36	1,119,679	0.839
Ib2	138.42	373.67	35.74	2189.77	22.80	24.01	21.12	14.26	963.38	397.87	84.98	661.81	52.37	−0.31	135.02	142.07	153.10	1	46.75	261,265	0.196
Ib5	124.57	411.99	40.70	2967.93	22.71	24.77	19.78	20.60	1141.28	634.39	21.31	989.52	37.52	−0.42	16.09	20.08	515.58	4	51.06	1,530,460	1.150
Ib6	133.09	381.49	41.53	3486.36	23.90	25.00	22.40	15.31	1559.92	639.80	110.40	369.70	44.38	1.32	16.18	15.43	727.53	3	64.18	1,166,776	0.875
Ib7	134.26	410.36	35.07	2377.56	23.00	24.54	21.05	16.23	1100.56	502.26	77.21	756.03	38.41	−1.47	76.10	86.30	231.73	1	50.60	823,943	0.618
Ib8	142.09	411.96	34.83	2966.16	23.57	25.09	21.46	17.24	1018.00	531.72	35.16	663.03	44.84	0.28	33.62	21.22	328.42	9	44.01	652,122	0.489
Ic2	56.67	301.03	14.86	2283.68	23.51	29.95	19.47	24.84	1204.54	782.55	29.92	336.21	22.08	−3.06	398.42	646.48	121.36	1	56.90	805,659	0.604
Ic5	93.21	399.86	25.22	2468.29	24.09	26.01	21.96	18.97	1228.19	625.50	33.59	622.08	36.62	−0.44	28.84	25.03	500.85	4	52.88	4,694,371	3.519
Ic6	94.28	306.14	21.74	2094.37	24.15	25.92	21.83	16.69	1476.35	642.60	108.19	435.92	46.31	−0.16	24.58	24.85	509.10	3	48.02	963,594	0.721
Ic7	76.29	306.21	18.22	1916.64	26.31	28.90	22.78	22.75	1006.31	624.01	22.71	337.53	22.61	−0.78	111.57	151.36	195.06	1	57.50	3,508,482	2.676
Ic8	77.58	373.47	17.22	2029.68	24.07	28.21	23.78	19.20	795.51	467.00	17.63	414.67	23.34	−0.49	37.60	13.47	555.64	9	54.71	3,578,497	2.698

Table A9. *Cont.*

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
Id2	15.85	136.91	10.03	3578.63	22.84	24.62	20.37	15.75	1547.96	691.34	140.37	571.50	50.12	0.25	201.13	248.26	112.43	16	28.69	31,125	0.023
Id5	13.69	99.45	5.33	2012.23	22.02	23.91	19.02	19.71	1458.30	929.34	19.39	854.68	68.25	−1.49	20.08	19.11	264.38	8	61.85	65,970	0.049
Id6	30.05	138.03	18.60	4284.67	22.37	24.48	18.59	15.37	1600.65	837.56	133.47	505.00	130.07	−6.92	62.27	28.12	488.01	3	45.26	12,785	0.010
Ie2	30.38	162.24	6.19	1275.28	24.54	26.29	22.42	14.38	1036.09	521.27	65.57	509.06	113.12	−3.75	172.73	258.06	339.32	16	24.46	42,342	0.032
Ie5	22.15	122.36	5.95	1576.89	24.73	26.97	21.42	19.84	1077.52	715.17	19.75	282.42	31.79	−1.16	30.64	18.54	311.20	16	33.12	310,121	0.232
Ie6	11.34	123.86	5.57	1808.19	22.29	24.38	19.86	13.93	1404.00	632.29	142.89	450.60	127.38	−1.68	33.92	51.42	485.81	16	25.77	61,751	0.046
Ie7	21.17	182.44	7.91	2407.50	24.83	26.68	22.47	15.72	1381.06	572.94	111.17	518.15	50.87	−1.96	166.02	128.77	372.96	1	33.07	143,918	0.108
Ie8	33.12	162.40	10.35	1803.52	26.22	28.96	22.63	21.25	541.46	375.01	8.54	270.45	14.52	−0.37	24.02	6.07	797.08	9	45.35	600,881	0.450
Ie9	24.48	104.06	4.83	1592.48	23.98	26.48	21.34	17.33	218.42	95.67	25.12	674.35	73.53	−2.78	24.73	8.63	812.28	16	36.42	41,964	0.031

Table A10. GES of the warm and humid equatorial region.

GES	Mammal Species	Bird Species	Amphibian Species	Plant Species	Annual Mean Temp.	Mean Temp of Warmest Quarter	Mean Temp. of Coldest Quarter	Temp Annual Range	Annual Precip.	Precip. of Wettest Quarter	Precip of Driest Quarter	Altitude	Vertical Heterogen.	TPI	Livestock	Human Density	Accessibility	Prevailing GLC Class	Prevailing GLC Class [%]	Area [km^2]	Area [%]
Ja2	130.91	371.95	29.41	6372.64	26.22	26.81	25.52	11.15	2633.33	999.99	259.99	131.89	21.76	−3.68	118.96	138.27	275.16	2	39.17	281,185	0.211
Ja5	120.92	309.37	18.02	6764.52	25.65	26.13	25.08	10.71	2847.62	992.86	430.33	250.55	45.98	−2.03	25.06	50.34	490.35	2	29.71	85,499	0.064
Ja6	157.34	453.43	65.62	6328.00	25.44	26.02	24.69	12.26	2534.65	959.85	310.65	277.11	42.20	−0.75	11.84	7.26	1081.32	3	81.49	7,075,502	5.305
Ja7	138.23	360.77	36.08	5380.49	23.38	24.25	22.42	12.56	2178.26	904.40	200.24	619.99	115.46	−9.35	124.44	175.65	169.14	2	57.53	121,994	0.091
Ja8	123.94	356.24	41.24	5535.52	26.64	27.17	25.98	16.03	1840.29	880.07	35.03	222.23	15.29	−0.45	40.65	5.25	366.37	9	48.82	132,739	0.100
Jb2	79.02	322.14	19.45	3657.58	25.78	27.21	23.92	13.46	2520.09	1264.97	160.76	178.01	55.58	−4.77	314.03	537.93	187.29	2	27.85	697,359	0.523
Jb5	106.22	327.76	31.80	2814.01	25.55	26.68	24.46	13.24	2217.31	1003.41	184.29	290.46	28.00	−0.08	25.17	40.71	728.10	13	27.61	519,187	0.389
Jb6	102.20	325.73	26.03	2850.02	24.74	25.70	23.49	12.76	2414.91	978.56	267.48	402.23	66.99	−0.32	17.99	25.65	991.73	3	60.05	2,656,305	1.991
Jb7	87.34	361.02	24.17	2665.04	26.20	27.82	26.26	14.87	2224.53	1162.95	92.84	137.22	27.65	−2.03	98.29	376.57	222.42	1	42.93	774,340	0.580
Jb8	134.70	364.24	28.11	2863.14	26.53	27.75	25.11	13.88	2240.21	1128.76	74.35	178.63	30.24	−2.73	32.98	12.90	612.93	9	23.51	391,133	0.293
Jc2	19.41	195.68	6.28	4859.43	26.39	27.00	25.57	10.42	2153.21	780.07	274.50	99.33	52.65	−2.75	260.31	150.36	289.46	16	38.86	21,094	0.016
Jc5	24.82	165.98	21.64	5428.07	24.33	26.28	21.93	13.13	2405.52	1037.63	299.33	87.88	38.66	−6.03	19.10	58.34	248.81	13	37.11	67,106	0.050
Jc6	21.92	165.18	8.31	4806.88	24.85	25.40	24.06	9.42	2916.39	1016.03	520.27	387.03	98.05	−1.86	34.00	36.92	1003.93	16	51.30	105,858	0.079
Jc7	10.48	161.17	7.17	4580.77	26.47	27.48	25.15	10.74	2118.50	938.66	224.59	29.19	18.37	−1.40	155.05	261.93	299.11	1	43.32	2374	0.002
Jd2	19.58	174.26	8.10	1205.04	25.42	26.80	23.28	13.22	2212.05	1031.45	223.54	125.66	58.63	−3.55	267.05	465.65	179.78	16	50.21	33,025	0.025
Jd5	26.06	190.62	6.24	2082.04	26.07	27.17	26.43	12.26	2087.34	998.66	177.91	44.22	22.94	−3.28	9.49	15.09	1429.79	13	34.75	33,783	0.025
Jd6	20.48	142.38	5.36	1758.74	24.95	25.73	23.93	9.66	2467.70	933.73	340.40	265.28	106.48	−4.41	21.70	41.95	856.05	16	49.03	190,330	0.143
Jd7	17.13	152.03	6.10	2209.06	24.59	25.99	22.90	11.13	1986.94	633.71	203.66	224.07	77.51	−2.45	123.93	246.39	173.47	1	46.40	19,250	0.015
Jd8	26.94	174.84	2.88	2419.23	27.03	28.41	26.79	14.43	1674.01	1024.72	19.96	40.49	19.58	−0.59	5.70	0.46	655.63	16	29.58	6296	0.005

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6. Conclusion and discussion

The main objective of this thesis, the creation of a classification and a map of global environmental systems, as well as the issue of the current status of global environmental classifications and biodiversity hotspots areas, were addressed within four scientific articles presented in the section 'Publications' of this thesis.

The dataset of global environmental systems, the main result of this thesis, is openly available in the Science Data Bank at http://doi.org/10.11922/sciencedb.01665. The classification of global environmental systems is a high-resolution spatial delineation of many unique combinations of abiotic and biotic classifications with anthropogenic classification that reflects differences in human impact.

The classifications of anthropogenic biomes, anthromes, land-use systems, land systems and land system archetypes (Ellis and Ramankutty, 2008; Ellis et al., 2010; Letourneau et al., 2012; van Asselen and Verburg, 2012; Václavík et al., 2013) have a resolution of 5 arc minutes. The classification of global environmental systems has a finer resolution of 30 seconds, making it applicable from the regional to the global scale. The IUCN global ecosystem typology (Keith et al., 2020) has the same resolution and the finest resolution of 8 arc seconds has the classification of world ecosystems (Sayre et al., 2020).

The individual classifications differ not only in the resolution of datasets but also in the amount and types of data selected. Anthropogenic biomes and anthromes are both based on seven global datasets of population, land cover and land use. Land-use systems use 15 datasets of land cover, land use, population, livestock density and accessibility. Land systems are based on land cover, livestock and agricultural intensity represented by six datasets. These classifications do not use abiotic or biotic factors. Land system archetypes were created using a larger number of 32 datasets of socioeconomic as well as biotic and abiotic data. The classification of world ecosystems is based on four indicators: global moisture domains, global temperature domains, global landforms, and global vegetation and land use. No socioeconomic datasets were used for the change in this classification. Global environmental systems use 22 variables, ten abiotic datasets on temperature, precipitation and relief, four biotic datasets on diversity of fauna and flora and eight anthropogenic datasets on population density, livestock density, accessibility, and global land cover.

The structure of the classification of global environmental systems is as follows: there are ten abiotic classes at the upper level that form a base level characterising the basic gradients of inanimate nature. At the middle hierarchical level, there are 30 natural classes. These are made up of a combination of ten abiotic and ten biotic classes. Finally, at the bottom level, there are 169 different global environmental systems, which were created by combining the classification of natural conditions and ten anthropogenic classes. This classification is the most similar to the IUCN global ecosystem typology. The global ecosystem typology consists of 5 global realms, 25 biomes and 108 ecosystem functional groups. The classifications of world ecosystems and land system archetypes have a different structure. They also differ a lot from each other. World ecosystems have 431 classes that are not further divided, whereas land system archetypes have only 12 classes. The classifications of anthropogenic biomes, anthromes, land-use systems and land systems share a very similar structure but differ from the classification of global environmental systems. Anthropogenic biomes, anthromes and land-use systems are grouped into six categories, land systems into eight categories. Each category is further divided into a certain number of classes. In total, these classifications have 21, 19, 24, and 30 classes, respectively.

The classifications of anthropogenic biomes, anthromes, land-use systems and land systems use top-down approaches. It is usually based on expert's rules or a priori classification. The IUCN global ecosystem typology uses this approach too in the upper four levels and a bottom-up approach in the lower two levels. Land system archetypes also used a bottom-up approach for the classification. World ecosystems were derived from the objective development and integration of different global natural elements, this classification used the structural approach.

Biodiversity hotspots range from temperate to equatorial regions. No biodiversity hotspot is located within the abiotic classes of the freezing arctic region, the cold northern region with a significant temperature annual range, or the colder temperate zone of the Northern Hemisphere. Only about 10% of the global area of classes – humid temperate region, and warmer and drier temperate zone of the Northern Hemisphere – is located in hotspots. These five classes occupy more than 38% of the world's land area, but only 9% of the area of biodiversity hotspots. Many hotspots are found in the mountains, so the class – region of the highest mountains – is very common in the area of hotspots. Only about 5% of the area of class – deserts and semi-deserts of the tropics – exists in biodiversity hotspots. On the other hand, subtropical and tropical classes, namely subtropics of both hemispheres, an extensive subequatorial region with a drier period, and a warm and humid equatorial region, have a very large representation in hotspots. These three classes occupy about 40% globally, but 77% within hotspots. They have over 35% of their area in hotspots, as well as the region of the highest mountains.

The two most species-poor biotic classes are very extensive, they cover more than 56% of the world, but only a small proportion is located in biodiversity hotspot areas. The most species-rich class occupies only 1.39% of hotspots. This is due to the fact that most of this class is fortunately located in wilderness areas and not in the anthropogenically heavily impacted areas of biodiversity hotspots. All the other classes have a larger proportion in hotspots than at the global level. Of these classes, those with exceptional diversity of flora are represented in hotspots by over 65%, while the remaining ones by around 25%. Classes with high floral diversity are concentrated in areas designed as biodiversity hotspots.

Five anthropogenic classes with lower human impact cover only 11% of the area of biodiversity hotspots, whereas five anthropogenic classes with higher human impact cover 89% of this area. Globally, the ratio is 36.5% to 63.5%. Biodiversity hotspots are areas with significant biodiversity, but also very intense human impact, they are more threatened by different types of human activity than the rest of the world. The six clearly most significant biodiversity hotspots contain almost only five anthropogenic classes with higher human impact, only in Indo-Burma 2.62% of this hotspot is occupied by anthropogenic class with the sixth highest human impact. The most important hotspots face a great anthropogenic impact.

Global environmental systems can aid in understanding the changing world, the impact of human activity on the natural environment, and the interactions between the natural environment and humans. This understanding can be applied at various levels, including the global level, to identify common patterns across continents and to help with conservation efforts.

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