Current global land systems classifications: comparison of methods and outputs

Aleš Hrdina*, Dušan Romportl

Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Czechia
* Corresponding author: ales.hrdina@natur.cuni.cz

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

Received: 11 October 2021
Accepted: 1 May 2022
Published online: 10 June 2022

Hrdina, A., Romportl, D. (2022): Current global land systems classifications: comparison of methods and outputs.
AUC Geographica 57(1), 48–60
https://doi.org/10.14712/23361980.2022.5

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 km^2 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 km^2 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 km^2, 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 km^2 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 km^2, 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 km^2 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 km^2 (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 km^2 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 km^2 (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,

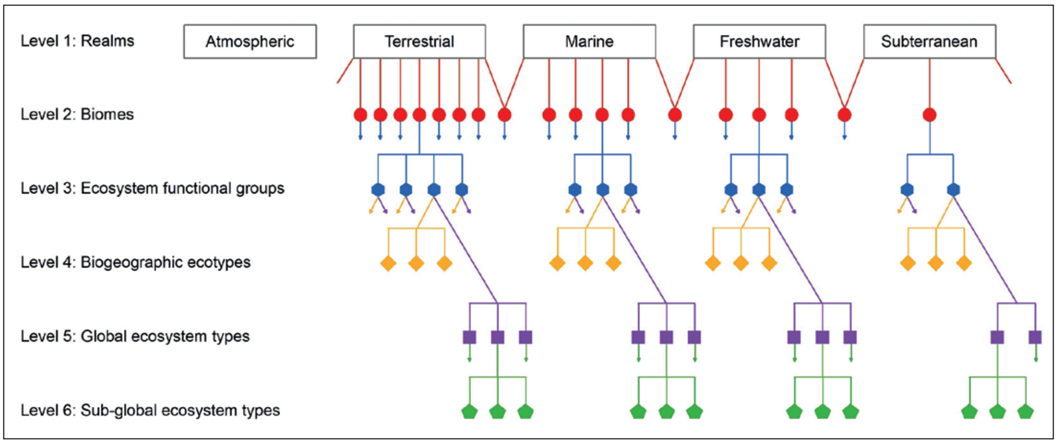

Fig. 1 Hierarchical structure of Global Ecosystem Typology.
Source: Keith et al. 2020

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

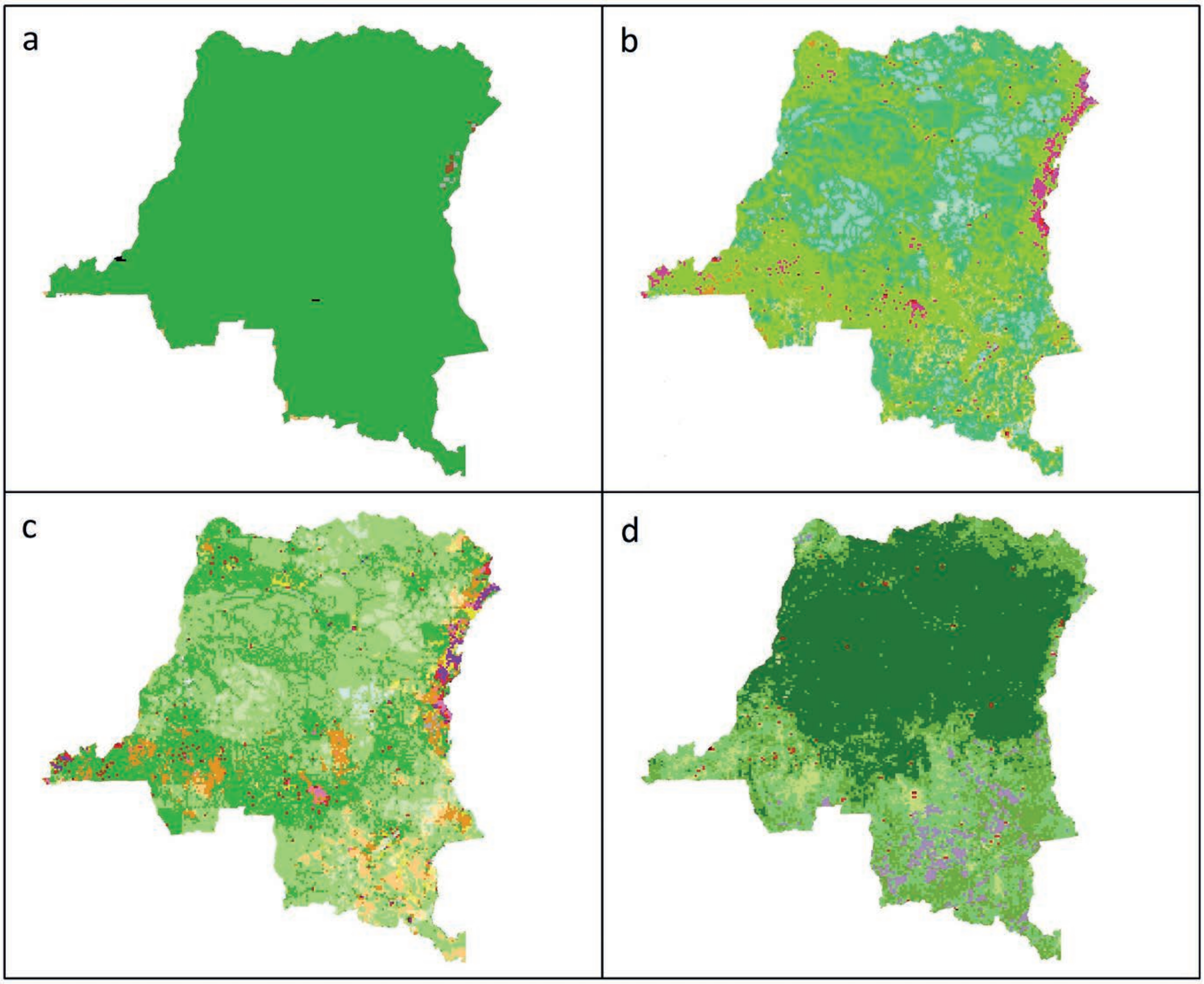

Fig. 2 Comparison of land system archetypes (a), anthropogenic biomes (b), anthromes (c) and land systems (d) on the example of The Democratic Republic of the Congo.

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.

Acknowledgements

Supported by the Charles University Grant Agency (GAUK) project No. 387115.

References

Alessa, L., Chapin, F. S. (2008): Anthropogenic biomes: a key contribution to earth-system science. Trends in ecology and evolution 23(10), 529–531, https://doi.org/10.1016/j.tree.2008.07.002.

Bailey, R. G. (2004): Identifying ecoregion boundaries. Environmental management 34(1), S14–S26, https://doi.org/10.1007/s00267-003-0163-6.

Batjes, N. H. (2006): ISRIC-WISE Derived Soil Properties on a 5 by 5 arcminutes Global Grid (Ver. 1.1), Report 2006/02. ISRIC – World Soils Information, Wageningen, https://www.isric.org/sites/default/files/isric_report_2006_02.pdf.

CIESIN (2005): Gridded Population of the World Version 3 (GPWv3): Population Density Grids. Socioeconomic Data and Applications Center (SEDAC)/Columbia University/Centro Internacional de Agricultura Tropical (CIAT), Palisades, NY, https://doi.org/10.7927/H4XK8CG2.

Crutzen, P. J. (2002): Geology of mankind. Nature 415(6867), 23, https://doi.org/10.1038/415023a.
Dinerstein, E., Olson, D., Joshi, A.,Vynne, C., Burgess, N. D., Wikramanayake, E., Hahn, N., Palminteri, S., Hedao, P., Noss, R., Hansen, M., Locke, H., Ellis, E. C., Jones, B., Barber, Ch. V., Hayes, R., Kormos, C., Martin, V., Crist, E., Sechrest, W., Price, L., Baillie, J. E. M., Weeden, D., Suckling, K., Davis, C., Sizer, N., Moore, R., Thau, D., Birch, T., Potapov, P., Turubanova, S., Tyukavina, A., de Souza, N., Pintea, L., Brito, J. C., Llewellyn, O. A., Miller, A. G., Patzelt, A., Ghazanfar, S. A., Timberlake, J., Klöser, H., Shennan-Farpón, Y., Kindt, R., Lillesø, J.-P. B., van Breugel, P., Graudal, L., Voge, M., Al-Shammari, K. F., Saleem, M. (2017): An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67(6), 534–545, https://doi.org/10.1093/biosci/bix014.
Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D., Ramankutty, N. (2010): Anthropogenic transformation of the biomes, 1700 to 2000. Global Ecology and Biogeography 19(5), 589–606, https://doi.org/10.1111/j.1466-8238.2010.00540.x.
Ellis, E. C., Ramankutty, N. (2008): Putting people in the map: anthropogenic biomes of the world. Frontiers in Ecology and the Environment 6(8), 439–447, https://doi.org/10.1890/070062.
Ellis, E., Gauthier, N., Klein Goldewijk, K., Bird, R., Boivin, N., Diaz, S., Fuller, D., Gill, J., Kaplan, J., Kingston, N., Locke, H., Mcmichael, C., Ranco, D., Rick, T., Shaw, M., Stephens, L., Svenning, J.-Ch., Watson, J. (2021): People have shaped most of terrestrial nature for at least 12,000 years. Proceedings of the National Academy of Sciences 118 (17): e2023483118, https://doi.org/10.1073/pnas.202348311.
ESA (European Space Agency) (2017). Land cover CCI product user guide version 2.0. http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf
FAO (2007). Gridded Livestock of the World, 141 p., FAO, Rome.
FAO – FAOSTAT, http://www.fao.org/faostat/en/#data.
Fick, S. E., Hijmans, R. J. (2017): WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37, 4302–4315, https://doi.org/10.1002/joc.5086.
Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, Ch. J., Monfreda, Ch., Patz, J. A., Prentice, C., Ramankutty, N., Snyder, P. K. (2005): Global consequences of land use. Science, 309(5734), 570–574, https://doi.org/10.1126/science.1111772.
Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D. P. M. (2011): Solutions for a cultivated planet. Nature 478, 337–342, https://doi.org/10.1038/nature10452.
Gosden, C. (2003). Prehistory: A Very Short Introduction. OUP Oxford, https://doi.org/10.1093/actrade/9780192803436.001.0001.
Goudie, A. S. (2013): The human impact on the natural environment: past, present, and future. John Wiley and Sons.
Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M. (2007): Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences of the United States of America 104 (31), 12942–12945, https://doi.org/10.1073/pnas.0704243104.
Hansen, M., DeFries, R., Townshend, J.R., Carroll, M., Dimiceli, C., Sohlberg, R. (2003): Vegetation Continuous Fields MOD44B. University of Maryland, College Park.
Higgins, S. I., Buitenwerf, R., Moncrieff, G. R. (2016). Defining functional biomes and monitoring their change globally. Global Change Biology 22(11), 3583–3593, https://doi.org/10.1111/gcb.13367.
Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., Jarvis, A. (2005): Very high resolution interpolated climate surfaces for global land areas. International journal of climatology 25(15), 1965–1978, https://doi.org/10.1002/joc.1276.
IIASA/FAO (2012): Global Agro-Ecological Zones (GAEZ v3.0) IIASA/FAO, Laxenburg, Austria/Rome, Italy.
IUCN – The IUCN Red List of Threatened Species, http://www.iucnredlist.org/technical-documents/spatial-data.
Jenkins, C. N., Pimm, S. L., Joppa, L. N. (2013): Global patterns of terrestrial vertebrate diversity and conservation. Proceedings of the National Academy of Sciences 110(28), E2602–E2610, https://doi.org/10.1073/pnas.1302251110.
Karagulle, D., Frye, C., Sayre, R. (2017): Modeling global Hammond landform regions from 250-m elevation data. Transactions in GIS 21(5), 1040–1060, https://doi.org/10.1111/tgis.12265.
Kaufmann, D., Kraay, A., Mastruzzi, M. (2010): The worldwide governance indicators: methodology and analytical issues. The World Bank Policy Research Working Paper Series, 5430. World Bank, http://hdl.handle.net/10986/3913.
Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Kingsford, R. T. (eds.) (2020): The IUCN Global Ecosystem Typology 2.0: Descriptive profiles for biomes and ecosystem functional groups. Gland, Switzerland: IUCN, https://doi.org/10.2305/IUCN.CH.2020.13.en.
Kier, G., Mutke, J., Dinerstein, E., Ricketts, T.H., Küper, W., Kreft, H., Barthlott, W. (2005): Global patterns of plant diversity and floristic knowledge. Journal of Biogeography 32(7), 1107–1116, https://doi.org/10.1111/j.1365-2699.2005.01272.x.
Klein Goldewijk, K., Beusen, A., van Drecht, G., de Vos, M. (2011): The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Global Ecology and Biogeography 20(1), 73–86, https://doi.org/10.1111/j.1466-8238.2010.00587.x.
Kriticos, D. J., Webber, B. L., Leriche, A., Ota, N., Macadam, I., Bathols, J., Scott, J. K. (2012): CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. Methods in Ecology and Evolution 3(1), 53–64, https://doi.org/10.1111/j.2041-210X.2011.00134.x.
Letourneau, A., Verburg, P. H., Stehfest, E. (2012): A land-use systems approach to represent land-use dynamics at continental and global scales. Environmental Modelling

and Software 33, 61–79, https://doi.org/10.1016/j.envsoft.2012.01.007.
McNeill, J. R. (2003): Resource exploitation and over-exploitation: a look at the 20th century. Exploitation and overexploitation in societies past and present. Münster: LIT Verlag, 51–60.
Menne, M. J., Williams, C. N., Vose, R. S. (2009). The US historical climatology network monthly temperature data, version 2. Bulletin of the American Meteorological Society 90(7), 993–1007, https://doi.org/10.1175/2008BAMS2613.1.
Mittermeier, R. A., Mittermeier, C. G., Brooks, T. M., Pilgrim, J. D., Konstant, W. R., Da Fonseca, G. A., Kormos, C. (2003): Wilderness and biodiversity conservation. Proceedings of the National Academy of Sciences 100(18), 10309–10313, https://doi.org/10.1073/pnas.1732458100.
Neumann, K., Verburg, P. H., Stehfest, E., Müller, C. (2010): The yield gap of global grain production: a spatial analysis. Agricultural Systems 103 (5), 316–326, https://doi.org/10.1016/j.agsy.2010.02.004.
Newbold, T., Hudson, L., Hill, S. et al. (2015): Global effects of land use on local terrestrial biodiversity. Nature 520, 45–50. https://doi.org/10.1038/nature14324.
Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., Kassem, K. R. (2001): Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience 51(11), 933–938, https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.
Pimm, S. L., Jenkins, C. N., Abell, R., Brooks, T. M., Gittleman, J. L., Joppa, L. N., Raven, P. H., Robertsand, C. M., Sexton, J. O. (2014): The biodiversity of species and their rates of extinction, distribution, and protection. Science 344(6187): 1246752, https://doi.org/10.1126/science.1246752.
Potter, P., Ramankutty, N., Bennett, E. M., Donner, S. D. (2010): Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interactions 14(2), 1–22, https://doi.org/10.1175/2009EI288.1.
Ramankutty, N., Evan, A. T., Monfreda, C., Foley, J. A. (2008): Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles 22(1): GB1003, https://doi.org/10.1029/2007GB002952.
Sanderson, E. W., Jaiteh, M., Levy, M. A., Redford, K. H., Wannebo, A. V., Woolmer, G. (2002): The human footprint and the last of the wild. BioScience 52(10), 891–904, https://doi.org/10.1641/0006-3568(2002)052[0891:THFATL]2.0.CO;2.
Sayre, R., Karagulle, D., Frye, C., Boucher, T., Wolff, N. H., Breyer, S., Wright, D., Martin, M., Butler, K., Van Graafeiland, K., Touval, J., Sotomayor, L., McGowan, J., Game, E. T., Possingham, H. (2020): An assessment of the representation of ecosystems in global protected areas using new maps of World Climate Regions and World Ecosystems. Global Ecology and Conservation 21: e00860, https://doi.org/10.1016/j.gecco.2019.e00860.
Schneider, A., Friedl, M. A., Potere, D. (2009): A new map of global urban extent from MODIS satellite data. Environmental Research Letters 4:044003, https://doi.org/10.1088/1748-9326/4/4/044003.
Schulze, K., Knights, K., Coad, L. et.al (2018): An assessment of threats to terrestrial protected areas. Conservation Letters 11(3): e12435, https://doi.org/10.1111/conl.12435.
Seppelt, R., Dormann, C. F., Eppink, F. V., Lautenbach, S., Schmidt, S. (2011): A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology 48(3), 630–636, https://doi.org/10.1111/j.1365-2664.2010.01952.x.
Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K. (2007): Global Map of Irrigation Areas Version 4.0.1. Johann Wolfgang Goethe University/Food and Agriculture Organization of the United Nations, Frankfurt am Main, Germany/Rome, Italy.
Steffen, W., Crutzen, P. J., McNeill, J. R. (2007): The Anthropocene: are humans now overwhelming the great forces of nature. AMBIO: A Journal of the Human Environment 36(8), 614–621, https://doi.org/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2.
Steffen, W. (2010): Observed trends in Earth System behaviour. Wiley Interdisciplinary Reviews: Climate Change 1(3), 428–449, https://doi.org/10.1002/wcc.36.
Takács-Sánta, A. (2004): The major transitions in the history of human transformation of the biosphere. Human Ecology Review 11(1), 51–66, http://www.jstor.org/stable/24707019.
Trabucco, A., Zomer, R. J. (2009): Global aridity index (Global-Aridity) and global potential evapo-transpiration (Global-PET) geospatial Database. CGIAR consortium for spatial information, http://www.csi.cgiar.org.
Tucker, C. J., Pinzon, J. E., Brown, M. E., Slayback, D. A., Pak, E. W., Mahoney, R., Vermote, E. F., El Saleous, N. (2005): An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. International Journal of Remote Sensing 26(20), 4485–4498, https://doi.org/10.1080/01431160500168686.
Uchida, H., Nelson, A. (2009): Agglomeration Index: Towards a New Measure of Urban Concentration. World Bank, Washington, DC, https://doi.org/10.1093/acprof:oso/9780199590148.003.0003.
Udvardy, M. D., Udvardy, M. D. F. (1975): A classification of the biogeographical provinces of the world (Vol. 8). Morges, Switzerland: International Union for Conservation of Nature and Natural Resources, http://fnad.org/Documentos/A%20Classification%20of%20the%20Biogeographical%20Provinces%20of%20the%20World%20Miklos%20D.F.%20Udvardy.pdf.
van Asselen, S., Verburg, P. H. (2012): A Land System representation for global assessments and land-use modeling. Global Change Biology 18(10), 3125–3148, https://doi.org/10.1111/j.1365-2486.2012.02759.x.
van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., da Silva, J. R. M., Merckx, R. (2007): The impact of agricultural soil erosion on the global carbon cycle. Science 318(5850), 626–629, https://doi.org/10.1126/science.1145724.
Václavík, T., Lautenbach, S., Kuemmerle, T., Seppelt, R. (2013): Mapping global land system archetypes. Global Environmental Change 23(6), 1637–1647, https://doi.org/10.1016/j.gloenvcha.2013.09.004.

Venter, O., Sanderson, E., Magrach, A. et al. (2016): Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nature Communications 7: 12558, https://doi.org/10.1038/ncomms12558.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., Melillo, J. M. (1997): Human domination of Earth's ecosystems. Science 277(5325), 494–499, https://doi.org/10.1126/science.277.5325.494.

Waters, C. N., Zalasiewicz, J., Summerhayes, C. et al. (2016): The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science 351(6269), https://doi.org/10.1126/science.aad2622.

Williams, B., Venter, O., Allan, J. et al. (2020): Change in terrestrial human footprint drives continued loss of intact ecosystems. One Earth 3(3), 371–382, https://doi.org/10.1016/j.oneear.2020.08.009.