



Land Use Cover Datasets: A Review

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Abstract

This chapter presents a review of Land Use Cover (LUC) datasets at global and supranational scales. To this end, we differentiate between LUC maps (Sect. 3) and reference LUC datasets (Sect. 4). The former map how different land uses or covers are distributed across the Earth's surface. The latter provides a sample of LUC data for specific points on Earth and are normally used in LUC mapping and modelling calibration and validation exercises. We also include a brief presentation of the main producers of LUC datasets (Sect. 2). The LUC maps reviewed here are classified according to different criteria. First, we differentiate between general LUC maps (Sect. 3.2), which provide information about all land uses and covers on Earth, and thematic LUC maps (Sect. 3.3), which focus on the mapping of a specific land use or cover. Second, we classify general and thematic LUC maps according to their extent, distinguishing between global and supra-national LUC maps. The general maps are classified according to the continent for which they provide information, either fully or partially, while the thematic maps are classified according to the type of land use or cover they focus on. Most of the datasets reviewed in this chapter are characterized in detail in Part IV of this book, to which this chapter acts as an introduction. This chapter includes a series of tables with all the datasets, indicating those for which a detailed description is provided in Part IV.

Keywords

Land Use • Land Cover • General maps • Thematic maps • Reference datasets

1 Introduction

Nowadays, there are many sources of Land Use Cover (LUC) data. The availability of LUC data has been increasing since the end of the last century, in line with the development of remote sensing techniques and easier access to aerial and satellite imagery. LUC data is available at all spatial scales, from local to global. Access to spatial information, including LUC datasets, has also improved in the last decade with the development of the open access culture.

Most of the LUC data being produced today refers to LUC maps, which are either single, one-off maps or form part of a time series. These maps provide layers of spatial data with LUC information for each part of the area being mapped at one (single maps) or several points in time (series of maps). Other spatial sources of LUC information include reference datasets used to validate LUC maps or train remote sensing classifiers. Although datasets of this kind have been produced since the beginning of the satellite remote sensing era, they have only recently become widely available for general purposes.

In this chapter, we review the main producers of LUC maps and the most relevant LUC datasets currently available—both LUC maps and data packages with reference data. Although this aspires to be a comprehensive review, some LUC products may be missing. We focus on the datasets that are available for download and can be used in practice. When relevant, we also mention others that are currently unavailable for download.

Many older LUC maps are not included, because they were drawn at very coarse resolution using old-fashioned production methods and therefore cannot meet the demands of modern users. Because of the scope and extent of the

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book, we focus exclusively on datasets at global and supra-national levels. A detailed description of the approach followed when carrying out this review appears in chapter “About This Book” of this book.

The most important datasets reviewed in this chapter are described in detail in Part IV of this book (chapters “Global General Land Use Cover Datasets with a Single Date”–“Supra-national Thematic Land Use Cover Datasets”), where users can find a detailed description of each dataset, including classification schemes, production methods and download options.

2 The Producers of LUC Data

We have classified LUC data producers into four main groups (Fig. 1): (i) Individual users and small actors; (ii) Research projects; (iii) Governmental and other organizations; and (iv) citizens producing LUC information through Volunteering Geographic Information (VGI) initiatives. The type of LUC data produced by each group varies.

At local and detailed scales, many organizations and users create their own LUC datasets. The fact that they have easy access to aerial/satellite imagery and to software for processing, photointerpreting and classifying these images has facilitated this process. This allows users to obtain very specific datasets that match their particular requirements. The datasets created for small projects and for specific purposes are not usually disseminated and remain the property of the communities or users that produce them. When these datasets are made available, they are often provided without the necessary technical information and general metadata.

At regional, national, supra-national and global scales, an increasing number of LUC databases are being produced for a broad range of users. Often these databases are specially designed for specific communities, such as the climate change research community. In other cases, they provide more general LUC information for a wide range of research fields and as support for policy decisions.

There are two main producers of LUC datasets. Firstly, nationally or internationally funded research projects, which

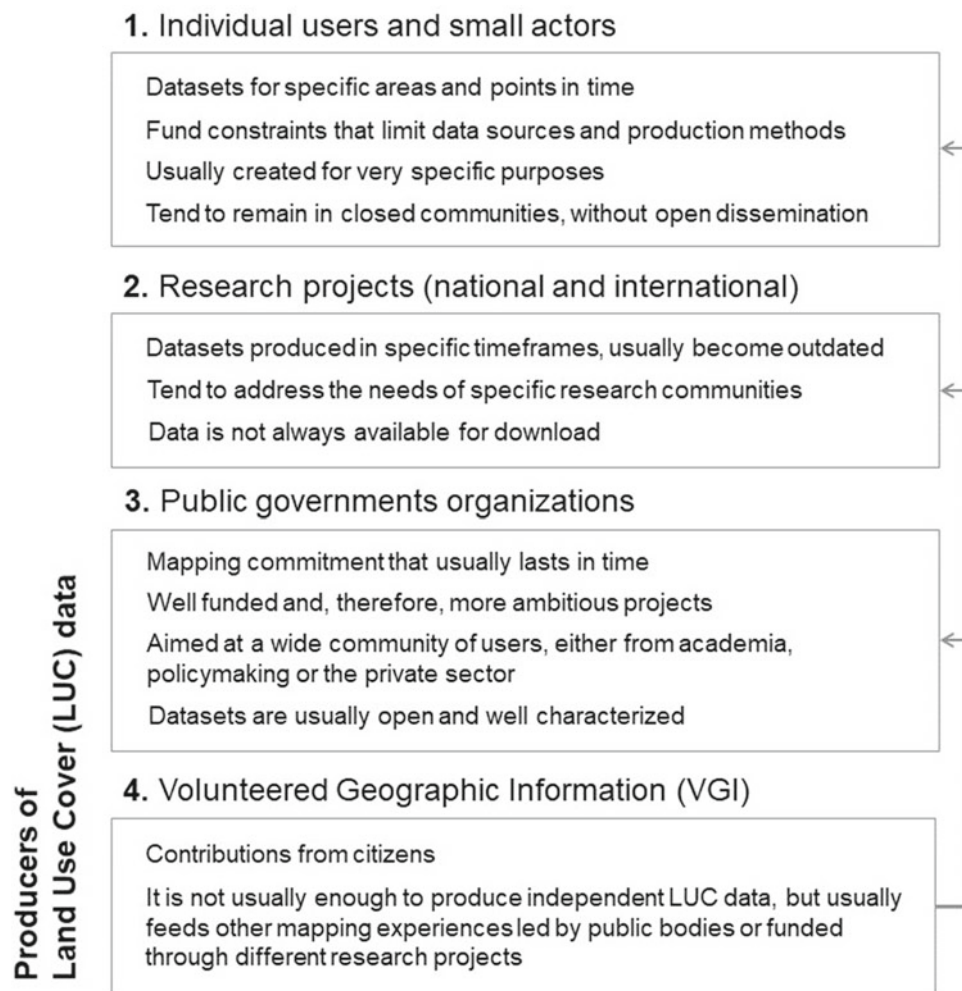


Fig. 1 Classification and characterization of LUC data producers

produce the datasets in collaboration with different universities and research institutions. The limited timeframe of these projects often affects the continuity of the mapping work they perform, and the datasets are not usually improved or updated once the project has come to an end. Dissemination of the data may also be affected by the end of funding. The Global Land Cover Facility, a reference initiative in the field of LUC research, which recently went offline,¹ is a perfect example of this problem.

Depending on the specific objectives of the projects and the institutions involved, these datasets may or may not be available for download. The quality of metadata and auxiliary information can also vary a lot from one project to the next. In some cases, a lot of technical and auxiliary information is provided, while in others users can only access the dataset itself and the research paper in which it is presented.

Governmental and other organizations are the other big producers of LUC data. In these cases, the objective is to provide information about the areas for which the organization is responsible or the areas affected by its policies and/or decisions. This data is a useful source of information for the policymaking process and is usually part of wider cartographic efforts by national and regional governments, and sometimes by international organizations, to provide geographic information of reference.

As these projects are part of official mapping work conducted by nations, regions and other large organizations, they are usually backed by significant long-term funding. These databases are therefore more likely to be updated or improved in the future. Another advantage is that they usually provide highly detailed, accurate information. They are also quite flexible. As a result, these databases are widely used by the whole scientific community, public and private sector professionals and many other users.

In recent years, there has been an increase in the data produced by members of the public through crowdsourcing or similar practices. This kind of information is known as Volunteered Geographic Information (VGI) and is part of a movement called ‘citizen science’, in which private citizens participate in scientific research, either by gathering or validating data or by assisting in any of the other phases of the scientific process.

Approaches of this kind allow local knowledge and expertise to be incorporated into data production. Highly detailed, up-to-date datasets can be produced easily and cheaply. Nevertheless, important issues can arise in terms of data quality and uncertainty, due to possible inconsistencies in the methods and procedures followed by the contributors, their different levels of expertise, etc.

¹ <https://spatialreserves.wordpress.com/2019/01/07/global-land-cover-facility-goes-offline/>.

3 Land Use Cover Maps

Reviewing all the LUC maps currently available is a daunting task, which perhaps explains why it has rarely been attempted. To our knowledge, the only researchers to carry out an extensive review of LUC maps at global and regional scales were Grekousis et al. (2015). They focused on general LUC products synthesizing all the land uses and land covers on Earth, so overlooking the increasing trend towards thematic LUC datasets that provide detailed mapping of a specific land use or land cover (e.g. forest, crop areas...).

The dividing line between general and thematic LUC products is not always clear. Some LUC maps, for example, provide general information on several different land covers (e.g. artificial, vegetation, water) while providing a detailed study of just one of them, thereby adopting a thematic approach. Although, in our review, we classify LUC maps as either general or thematic, readers should be aware of these possible inconsistencies.

Both types of LUC maps, general and thematic, can also be classified according to the extent they cover, differentiating between global, supranational, national, regional and local LUC maps. However, a comprehensive review of national, regional and local maps would be a huge task that is beyond the scope of this book. We will therefore be focusing exclusively on global and supranational LUC maps.

LUC maps for national and, especially, for regional and local areas, are usually only available for developed countries, or even highly developed countries, which can afford to invest in the production of spatial information and in research programmes. The most developed nations of the European Union, Australia and the United States usually have detailed LUC datasets, not only at a national level but also for specific regions. In China, the government has invested heavily in research, so enabling the production of national and regional LUC products. China is, together with the USA, the country producing most research on LUC mapping today (Yu et al. 2014).

3.1 Platforms and Repositories

A few online platforms and repositories provide an overview of the LUC datasets available. The Geo-Wiki platform (www.geo-wiki.org) is one of the most recent. It was initially developed to collect reference LUC information through crowdsourcing and to create a hybrid LUC map. It now hosts both general and thematic LUC maps. The Google Earth Engine Platform, which was also recently launched, includes a repository of spatial datasets, with a specific section devoted to Land Cover data (<https://developers.google.com/earth-engine/datasets/tags/landcover>).

The FAO Geonetwork repository (www.fao.org/geonetwork/) makes a great deal of spatial datasets available to users. The repository includes a specific section on LUC data. It hosts LUC maps at all scales and is a valuable source of LUC information for developing countries. The Land Processes Distributed Active Archive Center (LPDAAC) (<https://lpdaac.usgs.gov/>) holds most of the LUC datasets produced by NASA and the United States Geological Survey (USGS), in addition to other important global datasets.

The Copernicus Land Monitoring System website (<https://land.copernicus.eu/>) is the main source of LUC products created through the Copernicus programme, and is of particular interest for those working with European LUC information. All Copernicus layers are also available through the WEKEO Copernicus DIAS service (<https://wekeo.eu/>), a cloud-based platform that provides access to Copernicus datasets and to various tools for processing them, including all the land monitoring data.

3.2 General Land Use Cover Maps

3.2.1 Global LUC Maps

The production of global LUC datasets started at the end of the twentieth century. By then, coarse-resolution satellite imagery was available for producing consistent global LUC datasets at a low cost. A previous attempt had been made to create a global LUC map through photointerpretation of aerial imagery (Campbell 1983). Some authors also mention the maps developed by Matthews (1983), Olson et al. (1983) and Wilson and Henderson-Sellers (1985), when reviewing the first global LUC datasets. However, these datasets are

quite thematic, focusing particularly on vegetation. They were created by combining existing maps with data obtained in the field and via interpretation of aerial imagery (Giri 2005).

The first global general LUC map of which we have record dates from 1994 (Table 1) (Defries and Townshend 1994). It was a global LUC map obtained after classification of AVHRR imagery data at a very coarse resolution: one degree (≈ 111 km at the Equator). This project was led by the Laboratory for Global Remote Sensing of the University of Maryland.

The next global LUC maps were also produced by the team from Maryland. These were an improvement on their original map. Two maps were produced at spatial resolutions of 8 km and 1 km, respectively (DeFries et al. 1995; Hansen et al. 2000). For years, they were distributed through the Global Land Cover Facility. However, since this repository went online, only the map at 1 km has been available. The other two maps are now outdated, both due to their very coarse resolution, of little use for most of today's applications, and because of the methods employed in their production.

A lot of new maps have been produced since these first global general LUC maps appeared, especially since 2010. Tables 1 and 2 provide a synthetic overview of these efforts. When available, the tables include a reference to the section of this book where these datasets are described in detail. For the datasets providing a time series of maps, we also specify to what extent LUC changes can be studied over the series of maps without important sources of uncertainty.

As in the case of the pioneering maps from the University of Maryland, all the datasets reviewed here have been

Table 1 List of available global general LUC maps with a single date

LUC map	Spatial resolution	Timeframe	Number of classes	Description note
Mathews Global Vegetation/Land Use	≈ 111 km	1983	32	-
UMD LC Classification	1 km	1992/93	14	Sect. 1 in chapter “Global General Land Use Cover Datasets with a Single Date”
GLCC 2.0 Global	1 km	1992/93	17 (IGBP)	Sect. 2 in chapter “Global General Land Use Cover Datasets with a Single Date”
GLC2000	1 km	1999/2000	22	Sect. 3 in chapter “Global General Land Use Cover Datasets with a Single Date”
GMRCA LULC	10 km	2000	10	-
Geo-Wiki Hybrid	300 m	2000/05	10	Sect. 4 in chapter “Global General Land Use Cover Datasets with a Single Date”
LADA LUC map	≈ 8.3 km	2007	40	Sect. 5 in chapter “Global General Land Use Cover Datasets with a Single Date”
GLC-SHARE	1 km	2014 and before	11	Sect. 6 in chapter “Global General Land Use Cover Datasets with a Single Date”
OSM Landuse/Landcover	10 m	2017 and before	14	Sect. 7 in chapter “Global General Land Use Cover Datasets with a Single Date”

Table 2 List of available global general LUC datasets with a time series of maps

LUC map	Spatial resolution	Timeframe	Number of classes	Does it support change detection?	Description note
GLASS-GLC	5 km	1982–2015	8	Yes	Sect. 1 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
LC-CCI	300 m	1992–2018	37	Yes	Sect. 2 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
GLC30	30 m	2000, 2010, 2020	10	Yes	Sect. 3 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
GLC250	250 m	2001, 2010	25	Not recommended	Sect. 4 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
MCD12Q1	500 m	2001–2020	18	Not recommended	Sect. 5 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
GLCNMO	1 km 500 m	2003 (1 km) 2008 (500 m) 2013 (500 m)	20	No	Sect. 6 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
GlobCover	300 m	2005, 2009	23	No	Sect. 7 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
FROM-GLC	30 m 10 m	2010 (30 m) 2015 (30 m) 2017 (30, 10 m)	11	Not recommended	Sect. 8 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”
CGLS-LC100	100 m	2015–2019	23	Yes	Sect. 9 in chapter “Global General Land Use Cover Datasets with a Time Series of Maps”

developed by research groups from different universities across the world, above all from China, Europe and the USA. The Joint Research Centre (JRC) of the European Commission and the USGS of USA have also been actively involved in many of these projects.

Most of these datasets are intended for use in climate change modelling, for which coherent global LUC maps at coarse resolutions are required. However, these databases are becoming increasingly popular and are used for many other purposes, a lot of them related with land change. This has been one of the drivers promoting the creation of new maps, with better quality and higher detail.

Below, we characterize the global LUC datasets produced in the last decades according to their method of production, level of accuracy and spatial, temporal and thematic resolutions. Over this period, map production methods have become increasingly complex in order to create more accurate maps that provide better spatial, temporal and thematic information.

The Production Methods

Nowadays, global LUC maps are created using improved and innovative production methods, involving advanced classifiers, such as those based on machine learning, as well as a lot of auxiliary data. In many cases, specific LUC categories are mapped through several specific procedures due to their particular patterns, reflectance behaviour, etc. Additional post-classification treatments have also become

common in a bid to avoid some of the uncertainties and errors associated with the production of these maps.

In recent years, due to the increasing availability of LUC datasets, more and more global LUC maps are being produced by data fusion, in which new maps are created by combining existing datasets using a range of different algorithms and approaches. The aim of these projects is to create datasets with higher levels of accuracy and, therefore, less uncertainty. To this end, they usually combine the most accurate or highest quality LUC information from each dataset.

FAO-GLCShare is perhaps the best-known example of an attempt to build a new global LUC map from data fusion. It was created in 2014 by merging high-quality detailed national and regional LUC databases (Latham et al. 2014). In many cases, the new maps were obtained from the fusion of existing LUC datasets at global scales. Geo-Wiki Hybrid (See et al. 2015) is one of the most famous examples of maps created using this approach.

LUC maps obtained from data fusion do not have a single specific date of reference for the mapped area. When first produced, they are considered as up-to-date LUC databases. However, if they are not updated frequently, they eventually become obsolete and can no longer be regarded as useful sources for LUC change analysis.

The maps obtained through crowdsourcing, i.e. by aggregating a large number of individual inputs supplied by a community of people, could undergo the same problems.

Although still relatively rare, they could play an important role in the future. OSM-LULC, released in 2017 (Schultz et al. 2017), is the only example of a global general LUC map made with crowdsourced data.

These projects are usually updated on a regular basis. However, problems of coverage arise. In OSM-LULC, most of the world (except for specific test areas in Europe) is only partially mapped. Moreover, as they rely on volunteers to provide the information they require, the mapping and updating work is dependent on the volunteers' availability and willingness to participate. These may vary greatly from one country to the next and also over time. This is an inevitable source of uncertainty.

The recent advent of the Google Earth Engine (GEE) platform has encouraged the production of new global LUC maps, some general and others thematic. GEE provides a powerful cloud computing service, giving users the chance to process and classify tons of satellite imagery. This is particularly important when users do not have the necessary computer power to do this themselves. The availability of cloud-computing services will lead to an increase, in the near future, in the number of highly detailed LUC products being created using complex computer production methods. Many of these will be produced at global scales.

Accuracy

The development and application of new methods and techniques to produce LUC maps has not improved the accuracy of these datasets. Although some global LUC maps are more accurate than others, there is no correlation between time, the introduction of new methods and techniques and the achievement of higher levels of accuracy (Yu et al. 2014).

Global LUC datasets usually have accuracy levels of over 60%. In the best cases, they are around 80%. They are therefore still subject to high degrees of uncertainty. This is to be expected given the high level of abstraction they require. The entire surface of the Earth is being mapped according to the same method and must fit into the same legend. This means there is little room for local or regional specificities, which inevitably introduces a degree of uncertainty.

Spatial Resolution

LUC mapping has evolved over time, with the result that global LUC maps are produced at an increasing number of spatial resolutions. Initially, the AVHRR and VEGETATION sensors, with a spatial resolution of 1 km, were the main source of imagery for global LUC mapping. Later, imagery from MODIS (500 m) and MERIS (300 m) became the standard source of information. In recent years, it has

become increasingly common to use the huge stock of Landsat imagery to produce global LUC maps at 30 m. Some projects have gone even further, producing global LUC maps at even finer resolutions. One example is the 2017 edition of FROM-GLC (10 m) (Chen et al. 2019), which was based on Sentinel-2 imagery.

Sentinel satellites will be providing free, long-term, high-quality imagery over the coming years. This may boost the production of global LUC maps at increasingly high levels of detail.

Temporal Resolution

The temporal resolution of LUC maps has also increased over time, especially in recent years. Historical time series of LUC maps are becoming more common (Table 2). When MODIS Land Cover (MCD12Q1) was launched in 2002, it was the first global LUC dataset to provide a series of LUC maps for different years (Friedl et al. 2002). It was later joined by GLCNMO, GlobCover, FROM-GLC and GLC30, which all provided new series of LUC maps for at least two different points in time.

However, in most of these series, LUC change cannot be reliably detected by cross-tabulating the different maps that make up the dataset. Different methods of production for each year, changes in the source of imagery, differences in the reflectance of the images, etc., introduce a lot of noise in the comparison. This makes it impossible to obtain meaningful results from LUC change analyses.

The latest version of the MODIS Land Cover (Collection 6) incorporated important changes in the product algorithm and workflow to account for these sources of uncertainty (Sulla-Menashe et al. 2019). However, change detection is still not supported and is therefore not recommended.

New time series of LUC maps have been produced recently with the specific purpose of enabling change detection. These include the LC-CCI (ESA 2017) and GLASS-GLC maps (Liu et al. 2020). They provide a long record of LUC information: with yearly maps for the period 1992–2018 in the case of the LC-CCI, and for the period 1982–2015 in the case of GLASS-GLC. The latter dataset has the longest, most frequent time series currently available. However, it uses a very coarse spatial resolution (5 km) and change detection using the GLASS-GLC map series is limited by various sources of uncertainty (Liu et al. 2020).

Classification Schemes

Unlike the spatial and temporal resolutions, there are no important variations over time in the thematic resolution of most global LUC products. In fact, standard LUC classification systems are now widely used so as to ensure that the different databases are comparable. One of the most common is the International Geosphere-Biosphere Programme

(IGBP) legend, which was used in one of the first LUC global maps ever released: the IGBP-Dis. Maps based on the IGBP legend usually distinguish around 17 categories.

The Land Cover Classification System (LCCS) proposed by the FAO in 1998 (Di Gregorio and Jansen 1998) has become the standard LUC classification method today. It is a flexible classification system that can be adapted to LUC maps at different scales and for different areas of the world. It first distinguishes between 8 broad land cover categories, each of which is later disaggregated into a varying number of subcategories based on a series of classifiers, which define the attributes or characteristics of each land cover. This enables users to adapt the classification detail to the required level of analysis. The resulting categories are mutually exclusive, as they are defined by different sets of classifiers. LCCS-based legends are hierarchical and comparable, so facilitating the comparison and analysis of global LUC maps by checking for agreements and differences.

3.2.2 Supra-national LUC Maps

A lot of international institutions and organizations need comprehensive and coherent worldwide data to support their activities. Global datasets are also required by research communities that study the whole Earth as a system. For their part, national governments and organizations require large amounts of data to support policymaking at a national level. Many other institutions, associations, professionals and researchers need very detailed data that is only available at regional and local scales.

Within this context, supra-national datasets do not provide much detail and work at a different scale to that at which most institutions and organizations implement their policies. They therefore do not meet the requirements of the research and policy-making communities working at global scales. This means that there is less interest and consequently less funding for datasets at these scales, hence the relative lack of supra-national LUC maps.

Supra-national LUC maps have been developed by the European institutions to assist policymaking and environmental monitoring in Europe. In other continents, supra-national LUC maps are usually developed within the context of different projects funded by international institutions, such as the FAO and various different US and European institutions. The latter include the European Space Agency (ESA) and the Joint Research Centre (JRC) of the European Commission, which have been actively involved in the production of supra-national LUC maps for many developing areas with important biodiversity values.

Europe

Europe is the continent with the widest range of supra-national LUC maps. The European Union (EU) has

certain powers over the European environment and is therefore interested in monitoring any changes in land use. To this end, the EU has invested in the production of EU-wide reference data as a reliable source of information on which to base their policy decisions. As a consequence, plenty of detailed, high-quality datasets are now available providing LUC information for the European continent (Table 3). The quality and detail of these datasets reveal the large amount of resources that the EU has invested in land monitoring, especially in recent years via the Copernicus programme.

Of all the European LUC datasets, CORINE Land Cover (CLC) is by far the best known. It is one of the oldest and most successful programmes on land monitoring, offering very high levels of accuracy and detail. All these qualities have made CLC a reference in LUC mapping worldwide. It is the only cross-country initiative working at similar scales that provides detailed, temporally rich LUC data, which can be used effectively for change detection. CLC is one of the best examples of decentralized, coordinated LUC mapping. CLC is produced at a national level, which allows European countries to develop their own national datasets while taking advantage of the work and the resources invested to create CLC.

A few non-European countries have mapped the land uses and covers in their entire nations or in certain specific areas following the CLC model. Some of them have done so with the help of the European institutions and other European research groups. These include Palestine, Morocco, Tunisia, San Salvador, Guatemala, Honduras, Haiti, Dominican Republic, Colombia, Burkina Faso and Gabon (Jaffrain 2011). Nevertheless, these maps are one-off, single-date LUC maps which do not provide the monitoring capacity provided by CLC in Europe.

Through the Copernicus programme, the EU has also developed coherent and consistent LUC mapping products aimed at monitoring the LUC dynamics of specific areas (e.g. coastal and metropolitan areas, riparian zones, Natura 2000 network...). These are very detailed products in both spatial and thematic terms, which have been designed to meet the needs of their potential community of users or to provide information in support of a range of different policies. Their production is centralized, so avoiding the inconsistencies that might result from a coordinated, decentralized production method. Although they were only recently launched, the EU has assured their long-term continuity, so providing consistent time series of data.

Two other series of LUC maps, which are complementary to CLC, are also available for Europe. Annual Land Cover is a recently launched product that provides annual LUC maps, so overcoming the temporal resolution limitations of CLC, which is only updated once every 6 years. Annual Land

Table 3 List of available general LUC datasets for Europe

LUC map	Extent	Spatial resolution/Scale	Timeframe	Number of classes	Does it support change detection?	Description note
HILDA	Europe (EU)	1 km	1900–2010 (every 10 years)	6	Yes	Sect. 1 in chapter “Global General Land Use Cover Datasets for Europe”
CLC	Europe (EU)	1:100,000 MMU: 25 ha	1990, 2000, 2006, 2012, 2018	44	Yes, through layer of changes	Sect. 2 in chapter “Global General Land Use Cover Datasets for Europe”
PELCOM	Europe (EU)	1 km	1997	16	One-date map	Sect. 3 in chapter “Global General Land Use Cover Datasets for Europe”
Annual Land Cover	Europe (EU)	30 m	2000–2019	33	No	Sect. 4 in chapter “Global General Land Use Cover Datasets for Europe”
GlobCorine	Europe	300 m	2005, 2009	17	No	Sect. 5 in chapter “Global General Land Use Cover Datasets for Europe”
Urban Atlas	Functional urban areas of Europe (EU)	1:10,000 MMU: 0.25-1 ha	2006, 2012, 2018	29	Yes, through layer of changes	Sect. 6 in chapter “Global General Land Use Cover Datasets for Europe”
N2K	Natura 2000 reserves of Europe (EU)	1:5000–1:10,000 MMU: 0.5 ha	2006, 2012, 2018	11	Yes	Sect. 7 in chapter “Global General Land Use Cover Datasets for Europe”
Riparian Zones	Riparian areas of Europe (EU)	1:10,000 MMU: 0.5 ha	2012, 2018	56	One-date map	Sect. 8 in chapter “Global General Land Use Cover Datasets for Europe”
Coastal Zones	Coastal regions of Europe (EU)	1:10,000 MMU: 0.5 ha	2012, 2018	71	Yes, through layer of changes	Sect. 9 in chapter “Global General Land Use Cover Datasets for Europe”
S2GLC 2017	Europe (EU)	10 m	2017	13	One-date map	Sect. 10 in chapter “Global General Land Use Cover Datasets for Europe”

Cover is produced as part of a project funded by the European Commission, which aims to create harmonized spatial datasets for Europe. However, it is not recommended for change detection, as there is a lot of inter-annual variability between LUC covers.

HILDA is another LUC dataset providing a long time series of LUC maps for Europe. Although it has a coarser resolution, it provides the longest time series of maps reviewed here: 1900–2010. It was produced by a research project team, who combined various different datasets and applied complex modelling techniques (Fuchs et al. 2013).

Africa

A large number of supra-national LUC maps have also been found for Africa (Table 4). Most of the datasets cover specific regions of the continent, such as Eastern, Western or Southern Africa. Areas that are particularly relevant for

environmental research, such as the Congo Basin, have also been mapped.

Only a few projects tried to offer an overview of the LUC covers for the entire African continent. The FAO mapped the covers for many African countries as part of the AFRI-COVER project, but did not encompass the whole continent. The first comprehensive, Africa-specific, general LUC dataset only appeared quite recently. It was produced by EU research and earth-observation organizations. No similar initiatives have been found for America, Asia and Oceania. They are also quite rare for Europe as a whole, where continental LUC data usually covers the EU and associated countries.

There are three datasets providing a time series of LUC maps for different African countries. However, only one of these (West Africa Land Use Land Cover) was obtained by applying a common mapping approach which provides LUC information for all mapped areas at the same dates. In the

Table 4 List of available general LUC datasets for Africa

LUC map	Extent	Spatial resolution/Scale	Timeframe	Number of classes	Does it support change detection?	Description note
West Africa Land Use Land Cover	West Africa	2 km	1975, 2000, 2013	26	Yes	Sect. 1 in chapter “General Land Use Cover Datasets for Africa”
SERVIR-ESA	Eastern and Southern Africa	30 m	Different dates depending on the country (1990–2015)	7	Yes	Sect. 2 in chapter “General Land Use Cover Datasets for Africa”
SADC Land Cover Database	Southern African Development Community	1:250,000	Different dates depending on the country (1990/99)	13	One-date map	Sect. 3 in chapter “General Land Use Cover Datasets for Africa”
AFRICOVER	Burundi, DR Congo, Egypt, Eritrea, Kenya, Rwanda, Sudan, Tanzania, Uganda, Lybia, Malawi	1:200,000	Different dates depending on the country (1994/01)	8	One-date map	Sect. 4 in chapter “General Land Use Cover Datasets for Africa”
CCI LAND COVER—S2 PROTOTYPE	Africa	20 m	2016	10	One-date map	Sect. 5 in chapter “General Land Use Cover Datasets for Africa”
Congo Basin Vegetation Types	Congo Basin region	300 m	2000/07	20	One-date map	Sect. 6 in chapter “General Land Use Cover Datasets for Africa”

other two, the time series is made up of national or regional LUC maps produced for different years of reference, so hampering cross-country LUC change analyses.

The Americas

In the Americas, there is a clear distinction between the datasets covering North America and those covering South America and the Caribbean (Table 5). For North America, the North American Land Change Monitoring System (NALCMS) is of particular interest. It provides LUC maps for Canada, Mexico and the USA at three points in time. It is the only LUC supra-national American dataset with a time series of LUC maps. The NALCMS maps are created by merging datasets produced individually for each participating country following a similar approach.

Three different maps have been produced for South America, including in some cases the Caribbean. These were the result of various different research projects and activities and two of them (SERENA and South America 30 m) are no longer accessible for use.

South America 30 m, developed by Giri and Long (2014), provides the most up-to-date, detailed data. The SERENA map was designed to ensure its consistency with the NALCMS map (Blanco et al. 2013) so that together they could offer an overview of both North and South America. However, they had different spatial resolutions and were produced for different years of reference.

Asia and Antarctica

We only found one supra-national dataset for Asia, which covered the LUC of the Himalayan region (Table 6). It is possible that other supra-national datasets are available, although language barriers would prevent us from reviewing them properly. In any case, China is the most advanced country in Asia in terms of LUC mapping, and its research is focused above all on global and national mapping projects.

No supra-national maps are available for Oceania, due to its particular characteristics in which continental areas and islands are usually separate individual nations. These countries have no shared continental or inland regions for which a supra-national LUC dataset might be useful. As a result, no datasets of this kind have been produced.

Finally, a specific LUC map for Antarctica was produced recently by Chinese researchers (Hui et al. 2017). It is a vector LUC dataset for the reference year 2000, which differentiates between three land cover types. It is available online for any interested user.²

² <https://zenodo.org/record/826032>.

Table 5 List of available general LUC datasets for America

LUC map	Extent	Spatial resolution	Timeframe	Number of categories	Does it support change detection?	Description note
LBA-ECO LC-08	South America	1 km	1987/91	41	One-date map	Sect. 1 in chapter “ General Land Use Cover Datasets for America and Asia ”
NALCMS	North America	30 m 250 m	2005 (250 m) 2010 (250, 30 m) 2015 (30 m)	19	Partially	Sect. 2 in chapter “ General Land Use Cover Datasets for America and Asia ”
SERENA	South America	500 m	2008	22	One-date map	–
MERISAM2009	South America	300 m	2008/10	11	One-date map	Sect. 3 in chapter “ General Land Use Cover Datasets for America and Asia ”
South America 30 m	South America	30 m	2010	5	One-date map	–

Table 6 List of available general LUC datasets for Asia and Antarctica

LUC map	Scale	Timeframe	Number of categories	Does it support change detection?	Description note
The Himalaya Regional Land Cover database	1:350,000	2000	35	Yes, through layer of changes (1970/80–2007)	Sect. 4 in chapter “ General Land Use Cover Datasets for America and Asia ”
AntarcticaLC2000	1:100,000	2000	3	One-date map	–

3.3 Thematic Land Use Cover Datasets

Thematic Land Use Cover (LUC) datasets map parts of the Earth’s surface as a specific land cover, considering not just its extent but also its intensity of distribution. They normally focus on land covers and provide very little information about land use. Thematic LUC maps are usually produced using automatic remote sensing techniques that find accurate land use characterization difficult.

Thematic LUC maps usually represent land covers in greater detail than general LUC maps. Some provide information about the proportion of the study area occupied by a particular land cover on the ground. In other cases, they delineate the extent of a specific cover with great detail and accuracy. Other thematic LUC maps share certain features with general LUC maps, in that they map the Earth according to a set of predefined categories, which are usually subclasses of a specific type of cover (e.g. vegetation). Many maps charting vegetation in its various different forms can therefore be regarded as thematic sources of LUC information in that they characterize a specific cover.

Some maps may provide thematic information about specific land covers together with other relevant data. This was especially true in the twentieth century, when many different maps combining biogeographic and climate

information were produced for the climate and other research communities. These maps were usually produced by merging different techniques and datasets. Examples include the maps produced by Matthews (1983) and Olson et al. (1983). As these maps are now outdated and were not focused exclusively on land cover, we decided not to include them in this review.

Prior to the advent of satellite remote sensing, there were also a large number of traditional maps obtained through photointerpretation of aerial imagery and field surveys that provided information on certain specific land covers. These maps charted vegetation above all and, to a lesser extent, agricultural areas. These can be useful sources of information for historical LUC change analysis. However, as they are usually only available for national or more detailed areas and in many cases have not been digitalized, they are not reviewed here either.

There are also plenty of other spatial datasets that provide useful information for studying specific land covers. One example for vegetation covers are maps of live biomass (Kindermann et al. 2008; Thurner et al. 2014). Accordingly, there is a huge supply of information that can be used to study and characterize land covers, which comes in datasets of many different kinds. In this review, however, we will only be analysing datasets with a pure land cover approach.

The fact that thematic LUC maps focus on a single, specific cover normally means they are more accurate than general LUC maps. They are often more detailed too. This makes them especially useful for uncertainty analysis and validation exercises. As a general rule, they are a good source of reference data for studying land covers in a particular study area. However, they may not be as easy to use or to process as general LUC maps. If they provide too much information, users will have to process it to meet the specific needs of their studies.

The progress made in recent decades in the production of general LUC maps has also been achieved in thematic LUC mapping, with increasing levels of detail and more innovative, more complex methods. Some of the newest products have been produced using the cloud-computing capabilities of Google Earth Engine, which seems likely to play a key role in thematic LUC mapping in the future, and will allow more thematic datasets to be produced. Until now, the Landsat archive has been the most detailed source of imagery for LUC thematic mapping, although the imagery provided by the Sentinel constellation of satellites will soon enable users to expand the catalogue of thematic LUC datasets at highly detailed spatial resolutions of less than 30 m.

3.3.1 Global Thematic LUC Maps Focusing on Vegetation Covers

One of the most common features mapped by thematic LUC products is natural vegetation and tree and forest covers in particular. In fact, forest monitoring is one of the main applications of Landsat data, as reviewed by Hansen and Loveland (2012). This is because of widespread scientific interest in the study of vegetation dynamics and the fact that remote sensing techniques have made it much easier to characterize vegetation covers.

LUC maps focusing on vegetation covers usually offer coherent time series of LUC data that support change detection (Table 7). The most popular include the Vegetation Continuous Fields (VCF) datasets produced by NASA. These were first produced at the beginning of the 2000s and were obtained from AVHRR data at 1 km (Hansen et al. 2017). Since then, more VCF datasets have been produced at increasing levels of spatial detail, based above all on imagery from MODIS and Landsat (Hansen et al. 2003; Sexton et al. 2013). The temporal resolution of these products has also improved, with FCover providing information every 10 days for the period 1999–2020.

VCF datasets provide information about the vegetation cover fraction for each pixel in the analysed area. FCover is the only dataset that provides information on the percentage of vegetation cover, whereas all the others focus on tree or

forest covers. Whereas FCover considers all kinds of natural vegetation, MEaSURES VCF (VCF5KYR), MODIS VCF (MOD44B), Landsat VCF (GFCC) and the Hansen Forest Map focus exclusively on tree covers. In addition, GFCC and Hansen Forest Map include specific layers of forest change. Forests are mapped as such when a minimum fraction of their area is covered by trees. Therefore, changes in tree cover changes do not necessarily mean forest changes.

Two recent projects have explored the potential of radar data for mapping forest extent (Shimada et al. 2014; Martone et al. 2018). One of the advantages of radar data compared to optical sensors is that it is unaffected by weather and daylight conditions. This is particularly useful when mapping certain specific forest areas, such as those located in the tropics.

3.3.2 Global Thematic LUC Maps Focusing on Agricultural Covers

Agricultural areas are also widely mapped with specific LUC products (Table 8). Thematic agricultural LUC datasets usually show the extent of croplands and pasturelands or the cover fraction per unit of analysis, i.e. per pixel. In some cases, very detailed information on different types of crops is provided. These detailed LUC datasets are obtained from a wealth of detailed auxiliary information, as it is very difficult to accurately differentiate crop covers using standard remote sensing techniques.

Unlike other LUC thematic products, those mapping agricultural areas do not usually offer a time series, which means they cannot be used for land change analysis. Mapping agricultural areas is quite complex and this has hindered the production of coherent time series of agricultural LUC maps. One exception to this general trend was the dataset by Ramankutty and Foley (1999), who used historical sources of LUC data to model cropland cover on Earth from 1992 back to 1700. Another exception was the Harvested Area and Yield for 4 Crops maps, which provided information for three different dates.

3.3.3 Global Thematic LUC Maps Focusing on Artificial Covers

Built-up areas are becoming a common subject for thematic LUC products. As with the datasets focusing on vegetation covers, they provide time series of data which support change detection (Table 9). However, many of these maps are binary maps that only differentiate between urban/impervious and non-urban/non-impervious surfaces. They do not provide information about specific land uses so limiting their utility. However, people working with artificial surfaces are more interested in land use than in land cover, as artificial areas can be used for many different purposes, each of which has a different impact on the Earth.

Table 7 List of thematic LUC datasets characterizing vegetation covers

LUC map	Spatial resolution	Thematic information	Timeframe	Does it support change detection?	Description note
VCF5KYR	≈5.6 km	Percentage of tree cover, non-tree vegetation cover and bare ground	1982–1993 2001–2016	Possible	–
The World's Forests 2000	1 km	3 forest classes	1995/96	One-date map	Sect. 1 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
Global mangrove distribution	30 m	Mangrove extent	1997/00	One-date map	–
FCover	300 m 1 km	Percentage of vegetation cover	Every 10 days from: 1999–2020 (1 km) and 2014 to the present (300 m)	Yes, through specific layers of change	Sect. 2 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
Hybrid Forest Mask 2000	1 km	Percentage of forest cover	2000	One-date map	Sect. 3 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
SYNMAP	1 km	26 vegetation classes	2000	One-date map	Sect. 4 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
GFCC	30 m	Percentage of tree cover and forest gains/losses	2000, 2005, 2010, 2015 (tree cover) 1990–2000/2000–2005 (forest change)	Yes	Sect. 5 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
Hansen Forest Map	30 m	Percentage of tree cover and forest gains/losses	2000–2019	Yes, through specific layers of forest gains and losses	Sect. 6 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
MOD44B	250 m	Percentage of tree cover	2000–2019	Yes	Sect. 7 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
PTC Global version	500 m 1 km	Percentage of tree cover	2003 (1 km) 2008 (500 m)	Possible	Sect. 8 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
FNF	25 m	Forest extent	2007–2010 2015–2017	Possible	Sect. 9 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
Forests of the World 2010	250 m	Percentage of tree cover	2010	One-date map	Sect. 10 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”
TanDEM-X Forest/Non-Forest Map	50 m	Forest/Non forest	2011/16	One-date map	Sect. 11 in chapter “ Global Thematic Land Use Cover Datasets Characterizing Vegetation Covers ”

Table 8 List of thematic LUC datasets characterizing agricultural covers

LUC map	Spatial resolution	Thematic information	Temporal frame	Does it support change detection?	Description note
Historic Croplands Dataset	0.5 degrees	Cropland proportion	1700–1992	Yes	–
1992 Croplands Dataset	10 km (5 min)	Cropland proportion	1992	One-date map	–
Harvested Area and Yield for 4 Crops (1995–2005)	10 km (5 min)	Map proportion for 4 crops	1995–2005	Not for assessments at the cell level	–
GMRC	10 km	66 categories grouped into 9 Rainfed cropland	2000	One-date map	–
GIAM	10 km	28 categories Irrigated cropland	2000	One-date map	–
Cropland and Pasture Area in 2000	10 km (5 min)	Cropland proportion Pastureland proportion	2000	One-date map	–
Harvested Area and Yield for 175 Crops	10 km (5 min)	Map proportion for 175 crops	2000	One-date map	–
Global Agricultural Lands	10 km	Cropland proportion Pastureland proportion	2000	One-date map	–
Global Cropland Extent	250 m	Cropland extent	2000/08	One-date map	Sect. 1 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
IIASA-IFPRI Cropland Map	1 km	Percentage of cropland cover	2005	One-date map	Sect. 2 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
GRIPC	500 m	3 cropland classes	2005	One-date map	Sect. 3 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
FROM-GC	30 m	Cropland extent	2010	One-date map	–
GFSAD1KCD	1 km	8 cropland classes	2010	One-date map	Sect. 4 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
GFSAD1KCM	1 km	5 cropland classes	2010	One-date map	Sect. 4 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
Global Synergy Cropland Map	500 m	Percentage of cropland cover	2010	One-date map	Sect. 5 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
UCL	250 m	Percentage of cropland cover	2014	One-date map	Sect. 6 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
GFSAD30	30 m	Cropland extent	2015	One-date map	Sect. 7 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”
LADA Dominant crops	8.3 km	Up to 534 categories	Data fusion	One-date map	–
ASAP Land Cover Masks	1 km	Percentage of cropland/rangeland covers	2019	One-date map	Sect. 8 in chapter “Global Thematic Land Use Cover Datasets Global Thematic Land Use Cover Datasets”

Table 9 List of thematic LUC datasets characterizing artificial covers

LUC map	Spatial resolution	Thematic information	Timeframe	Does it support change detection?	Description note
Global Urban Land	30 m	Artificial areas extent	1980, 1990, 1995, 2000, 2005, 2010, 2015	Yes	Sect. 1 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
GHSL	10 m (2018) 20 m (2016) 30 m, 250 m, 1 km (1975–2014)	Built-up areas extent Percentage of built-up areas (2014)	1975, 1990, 2000, 2014, 2016, 2018	Yes, except for the 2016 layer	Sect. 2 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
GAIA	30 m	Artificial areas extent	1985–2018	Yes	Sect. 3 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
GUB	30 m	Urban boundaries	1990, 1995, 2000, 2005, 2010, 2015, 2018	Yes	Sect. 3 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
Global Urban Expansion 1992–2016	1 km	Urban areas extent	1992, 1996, 2000, 2006, 2010, 2016	Yes	Sect. 4 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
ISA	1 km	Impervious area density	2000/01, 2010	Unknown	Sect. 5 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
URB_MAP	500 m	Urban extent	2001/05	One-date product	–
HBASE	30 m 250 m 1 km	Urban areas extent	2010	One-date product	Sect. 6 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
GMIS	30 m	Percentage of impervious areas	2010	One-date product	Sect. 6 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
GUF	≈12 m ≈84 m	Built-up areas extent	2011	One-date product	Sect. 7 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
WSF	10 m, 100 m, 250 m, 500 m, 1 km, 10 km	Settlement areas extent	1985–2015, 2014/15, 2019	In the future	Sect. 8 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”
GISM	30 m	Impervious areas extent	2015	One-date product	Sect. 9 in “Global Thematic Land Use Cover Datasets Characterizing Artificial Covers”

3.3.4 Global Thematic LUC Maps Focusing on Water and Other Covers

Some thematic LUC products focus specifically on water covers, two of which provide information on their change over time (Table 10). Other products offer a hybrid between general and thematic LUC datasets. These include the Global 1-km Consensus Land Cover, which provides a LUC thematic map for 12 different land covers (Tuanmu and Jetz 2014). It has 12 layers, each of which contains information about the fraction of the pixel occupied by the cover being mapped. A thematic LUC dataset with a similar approach

was obtained for 13 different covers as part of the ClimAfrica project for the period 1901–2017 (Churkina et al. 2009). Like other similar datasets already reviewed, it was obtained by a model based on different sources of historical LUC information.

3.3.5 Supra-national Thematic LUC Maps

We have only reviewed a few experiences of supra-national thematic LUC mapping (Table 11). The majority of them map vegetation covers, focusing especially on areas of special biodiversity or environmental value.

Table 10 List of thematic LUC datasets characterizing water and other covers

LUC map	Spatial resolution	Thematic information	Timeframe	Does it support change detection?
Historical land use based on Synmap landcover	0.5 degrees	13 themes (Map proportion for each)	1901–2007	Yes
Global Surface Water	30 m	Water occurrence 1–100	1984–2019	Yes, through specific product
CC WB	150 m	Water/no water	2000/12	One-date product
Daily Global Surface Water Change Database	500 m	Water 3 categories	2001–2016 (Daily)	Yes
Global 1-km Consensus Land Cover	1 km	12 themes (Map proportion for each)	Data fusion	One-date product

Table 11 List of thematic supra-national LUC datasets

LUC map	Extent	Spatial resolution/Scale	Thematic information	Timeframe	Does it support change detection?	Description note
TREES Vegetation Map of Tropical South America	Amazon basin	1 km	Vegetation 14 categories	1992	One-date map	–
Circumpolar Arctic Region Vegetation	Arctic region	1:7,500,000	Vegetation 20 classes	1993/95	One-date map	–
Insular Southeast Asia—Forest Cover Map	Insular Southeast Asia	1 km	5 forest classes	1998/00	One-date map	Sect. 1 in “ Supra-national Thematic Land Use Cover Datasets ”
Continental Southeast Asia—Forest Cover Map	Continental Southeast Asia	1 km	8 forest/wood classes	1998/00	One-date map	Sect. 2 in “ Supra-national Thematic Land Use Cover Datasets ”
Central Africa—Vegetation map	Cameroon Central African Republic Republic of Congo Equatorial Guinea Gabon DR Congo	1-5 km	Vegetation	1987/93	One-date map	–
Congo Basin Monitoring Map	Congo River Basin	57 m	Forest extent Forest probability Forest cover clearing	1990/00	Information on forest clearing	Sect. 3 in “ Supra-national Thematic Land Use Cover Datasets ”
FACET	DR Congo Congo Gabon	60 m	Forest 3 cover categories + gains and losses	2000 2005 2010	Yes	–
MARS Crop Mask Over Africa	Africa	250 m	Cropland extent	One date, different depending on the mapped area	One-date map	Sect. 4 in “ Supra-national Thematic Land Use Cover Datasets ”
HRL Impervious	Europe (EU)	10 m (after 2018) 20 m, 100 m (before 2018)	Extent and percentage of impervious areas	2006, 2009, 2012, 2015, 2018	Yes, through layer of changes	Sect. 5 in “ Supra-national Thematic Land Use Cover Datasets ”

(continued)

Table 11 (continued)

LUC map	Extent	Spatial resolution/Scale	Thematic information	Timeframe	Does it support change detection?	Description note
HRL Forests	Europe (EU)	10 m (after 2018) 20 m, 100 m (before 2018)	Percentage of tree cover areas, leaf type and forest type	2012, 2015, 2018	Yes, through layer of changes	Sect. 5 in “ Supra-national Thematic Land Use Cover Datasets ”
HRL Grasslands	Europe (EU)	10 m (after 2018) 20 m, 100 m (before 2018)	Extent of grassland areas	2015, 2018	Yes, through layer of changes	Sect. 5 in “ Supra-national Thematic Land Use Cover Datasets ”
HRL Water	Europe (EU)	10 m (after 2018) 20 m, 100 m (before 2018)	5 water-wet classes	2015, 2018	Unknown	Sect. 5 in “ Supra-national Thematic Land Use Cover Datasets ”
HRL Small Woody Features	Europe (EU)	5 m	Extent of Small Woody Features	2015	Not at the moment	Sect. 5 in “ Supra-national Thematic Land Use Cover Datasets ”
ESM	Europe (EU)	2 m (2015) 2.5 m (2012) 10 m (2012)	Built-up extent (2015) Residential areas extent (2012) 13 built-up categories (2012) Percentage of built-up areas (2012)	2012, 2015	No	Sect. 6 in “ Supra-national Thematic Land Use Cover Datasets ”

They are usually produced by international institutions, such as the European Commission, or research groups from internationally renowned universities. They are interested in monitoring and understanding the land dynamism of high biodiversity areas of worldwide importance.

The European Commission, through the Copernicus programme, is behind some of the few supra-national thematic LUC datasets that focus on other covers such as artificial surfaces or agricultural areas.

4 Reference Land Use Cover Data

Reference data is required to train supervised remote sensing classifiers and to validate LUC maps. Reference LUC datasets consist of a series of geographically distributed sample points with LUC information. Each point contains information about the specific land use or cover in the pixel or polygon of the Earth’s surface represented by the point.

The reference datasets are subject to the same spatial abstraction required in LUC maps. Reference points are associated with a specific pixel or polygon. The level of abstraction required varies depending on the size of these points. The uncertainty of the reference information will also

vary accordingly. The fact that a single land use or cover is assigned to a whole pixel or polygon, even though they may contain other land uses or covers, can also produce uncertainty. In addition, there is always a degree of subjectivity in the decision to assign a pixel or polygon to a particular category, especially in borderline cases that are not clear-cut. This can create an additional source of uncertainty.

Relatively few general LUC reference datasets are currently available. This is because many reference datasets were created ad hoc every time a new LUC map was validated or reference data was required to train a remote sensing classifier, and it was therefore unnecessary to have a ready supply of general LUC reference datasets. These datasets are also affected by some degree of thematic generalization, as is any LUC map. LUC information must conform to a specific classification system or legend. Given the ad hoc nature of many reference datasets, the classification or legend used to classify the land uses and covers was normally also case-specific. However, the recent emergence of standard LUC reference datasets aimed at a wide range of users and research fields has extended the use of standard legends and classification systems, such as the FAO LCCS, when drawing up these datasets.

One of the most renowned LUC reference datasets is the Land Use Cover Area frame Sample (LUCAS), produced by EUROSTAT every 3 years since 2006. It is made up of more than 330,000 survey points across the EU.³ An increasing number of countries have taken part in every new version of the survey. Of all the LUC reference datasets available, this is the most comprehensive. For each point, experts collect information about land uses, land covers and other relevant environmental parameters. LUCAS also includes four photographs for each surveyed point. It is the only LUC reference dataset reviewed that provides a coherent time series of data for different years.

In recent years, various reference datasets used to validate and train classifiers of global LUC maps have been made available online, so enabling them to be used for other purposes rather than just in the production of one specific map. The work done by the team from the GOF-C-GOLD Land Cover Office is of special note. They collected and improved the reference datasets from six different LUC products (GLC2000, GlobCover 2005, STEP, VIIRS, GLCNMO and the urban dataset from the University of Tokyo). Samples of these datasets (with up to 70% of all the available reference points) are freely available for download on the project website.⁴

There is a growing trend to gather reference data through crowdsourcing and volunteering initiatives. Information gathered in this way is often referred to as Volunteered Geographic Information (VGI) and is part of citizen science. Members of the public create reference LUC information that will later be used to train classifiers and validate final maps. The information is gathered by local volunteers across the world, so taking advantage of local expertise. It is also a good source of cheap reference information. However, production methods of this kind have many related limitations and uncertainties.

The most famous of these initiatives is Geo-Wiki, which is frequently used to collect LUC information for calibration and validation practices. Geo-Wiki provides a user-friendly online tool that makes it very easy to visualize LUC maps and to collect the reference LUC data required to validate them. Many international research projects working on LUC mapping and citizen science have based their research on Geo-Wiki. One of the most important is the H2020 LandSense Citizen Observatory.⁵ It produced a global LUC reference dataset over four campaigns (Fritz et al. 2017).

Sahariah et al. (2017) also produced a global LUC reference dataset for cropland land covers using Geo-Wiki and crowdsourcing. Both datasets are available online for any user interested in the PANGAEA repository.⁶

The Australian Terrestrial Ecosystem Research Network (TERN) has developed a specific Geo-Wiki application to validate Australian LUC maps: AusCover.⁷ Also associated with Geo-Wiki, the LACO-wiki platform provides another tool for the collection of LUC reference datasets.⁸ Users can easily validate their own LUC maps on this platform, which includes a repository of reference data created or hosted by the community. It is a very comprehensive, user-friendly tool for LUC reference data production and LUC map validation, which has outperformed the capabilities of Geo-Wiki for this specific task.

Many other tools and platforms have been developed in recent years with similar purposes: Collect Earth, GLFC LT, VIEW-IT... (Bey et al. 2016). However, although these platforms offer the tools required to create LUC reference datasets through crowdsourcing, many of these datasets are not made available online. Even in the platforms based on crowdsourced information, the LUC reference data remains very case-specific and is not disseminated, so preventing its reuse in other situations.

Although they cannot be considered LUC data as such, volunteered geo-referenced photographs may be useful for obtaining reference LUC datasets. They provide a fixed picture of a landscape at a given point in time. By analysing the picture, users can identify the dominant land cover or land use, so obtaining LUC reference data.

Several initiatives for collecting volunteered photographs of specific geographic locations are already ongoing. Flickr is one of the most famous, although its purposes and objectives have little to do with science or scientific methods. The Degree Confluent Project (DCF)⁹ aims to collect photographs and descriptions of each integer degree intersection of latitude and longitude on Earth. Geograph collects representative photographs of every single square km in England, Ireland¹⁰ and Germany.¹¹ The Field Photo Library¹² collects geo-referenced photos across the earth. Google Maps also hosts pictures and is now regarded as a successor to Panoramio, a service similar to Flickr.

³ <https://ec.europa.eu/eurostat/web/lucas>.

⁴ http://www.gofcgold.wur.nl/sites/gofcgold_refdataportal.php.

⁵ <https://landsense.eu/>.

⁶ <https://doi.pangaea.de/>.

⁷ <https://application.geo-wiki.org/branches/auscover/>.

⁸ <https://old.laco-wiki.net/en/Welcome>.

⁹ <http://confluence.org/index.php>.

¹⁰ www.geograph.org.uk/

¹¹ <https://geo-en.hlipp.de/>

¹² <http://www.eomf.ou.edu/photos/>

Further Reading

Fonte CC, Bastin L, See L, et al. (2015) Usability of VGI for validation of land cover maps. *Int J Geogr Inf Sci* 29:1269–1291. <https://doi.org/10.1080/13658816.2015.1018266>

This paper reviews the main platforms and sources available for volunteer-based collection of LUC reference data and other information that may be useful for producing datasets of this kind. It also discusses the pros and cons of this approach for obtaining reference LUC data.

Grekousis G, Mountrakis G, Kavouras M (2015) An overview of 21 global and 43 regional land-cover mapping products. *Int J Remote Sens* 36:5309–5335. <https://doi.org/10.1080/01431161.2015.1093195>

Comprehensive review of general LUC datasets available at global and continental scales. It also reflects on the progress made and the challenges that lie ahead, proposing a series of recommendations for future LUC mapping practice.

Herold M, See L, Tsendbazar NE, Fritz S (2016) Towards an integrated global land cover monitoring and mapping system. *Remote Sens* 8:1–11. <https://doi.org/10.3390/rs8121036>

This paper summarizes the state of the art on global LUC mapping. It identifies the areas where most progress has been made in the field, referring in particular to the products with greater spatial detail and more frequent temporal information; the increasing importance of validation; the progressive implementation of the FAO Land Cover Classification System (LCCS) framework as the standard LUC classification method; and the increasing interest in citizen engagement. The paper also mentions some of the specific fields that have recently been the focus of scientific attention: data fusion; uncertainty analysis by data comparison; and quantification of LUC change. Finally, the authors reflect on the work that remains to be done and the challenges that lie ahead.

Mora B, Tsendbazar N-E, Herold M, Arino O (2014) Global Land Cover Mapping: Current Status and Future Trends. In: Manakos I, Braun M (eds) *Land Use and Land Cover Mapping in Europe. Practices & Trends*. Springer, Dordrecht, Heidelberg, New York, London, pp 11–30.

Book chapter offering a short but very comprehensive state of the art on global LUC mapping. It reviews the LUC datasets available in 2014 and summarizes the progress that had been made until then. It also points out the main issues

with regard to global LUC mapping practice and objectives for the future. Many of these objectives have now been accomplished.

P. Giri C (ed) (2012) *Remote sensing of land use and land cover. Principles and applications*. CRC Press.

One of the reference books on Land Use Cover mapping and analysis. It provides an introduction to the field, tracing its history and an overview of the main concepts relating to LUC mapping and remote sensing. It also addresses the main methodological issues in relation to LUC mapping using remote sensing techniques, such as validation practices, land cover change detection and image classification methods. In Part III, the book includes examples of regional LUC mapping and LUCC monitoring.

See L, Fritz S, Perger C, et al. (2015) Harnessing the power of volunteers, the internet and Google Earth to collect and validate global spatial information using Geo-Wiki. *Technol Forecast Soc Change* 98:324–335. <https://doi.org/10.1016/j.techfore.2015.03.002>

Good description of the Geo-Wiki platform, its history, evolution and current capabilities. It also reviews some of the LUC reference datasets based on information collected through the platform.

Tsendbazar NE, de Bruin S, Herold M (2015) Assessing global land cover reference datasets for different user communities. *ISPRS J Photogramm Remote Sens* 103:93–114. <https://doi.org/10.1016/j.isprsjprs.2014.02.008>

The paper compares and analyses 12 LUC reference datasets in detail. These datasets are used in the production and validation of global LUC maps. This is one of the most comprehensive reviews of the LUC reference datasets currently available. It also assesses the potential reuse of these datasets, focusing on the data requirements imposed by different user communities. The authors try to identify the particular features that LUC reference datasets must have to enable them to be used by a wide range of users.

Wulder MA, Coops NC, Roy DP, et al. (2018) Land cover 2.0. *Int J Remote Sens* 39:4254–4284. <https://doi.org/10.1080/01431161.2018.1452075>

A long but detailed reflection on the progress that has been made and the changes in Land Cover mapping since the appearance of remote sensing.

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