Land Use Cover Mapping, Modelling and Validation. A Background

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Abstract

In this chapter, we offer a brief introduction to the main concepts associated with Land Use Cover (LUC) mapping, Land Use Cover Change (LUCC) modelling and the uncertainty and validation of LUC and LUCC data and model outputs. The chapter summarizes the theoretical fundamentals required to understand the rest of the book. First, we define Land Use and Land Cover concepts that have been extensively discussed and debated in the literature (Sect. 2). Second, we review the history of LUC mapping, from the first manually produced maps to the advent of aerial and satellite imagery and the production of new datasets with much greater detail and accuracy (Sect. 3). Third, we address the usefulness of LUC data and LUCC analysis for society (Sect. 4), contextualizing all these studies and efforts within the framework of Land Change Science (Sect. 5). Fourth, we offer a brief introduction to LUCC modelling, its purpose, uses and the different stages that make up a LUCC modelling exercise (Sect. 6). We also offer a brief introduction to the different types of LUCC models currently available. Finally, we present the concepts of uncertainty and validation and offer a brief introduction to the topic (Sect. 7). The chapter also includes a short list of recommendations for further reading for those who wish to explore the theory presented here in more depth.

Keywords

Land Use • Land Cover • Land Use Cover Change • Land Use Cover mapping • Land Change Science • Land Use Cover Change modelling • Uncertainty • Validation

1 Introduction

Land Use and Land Cover (LUC) data is an important source of information for a wide range of users from different backgrounds and scientific disciplines. It provides an overview of the different covers on the Earth's surface (e.g. vegetation, agricultural fields, rocks, water, artificial surfaces…) and how they evolve over time. It also traces how these covers are used (land use) and how this use changes.

LUC data can be very useful in an array of different fields. It is especially valuable for understanding the impact that many natural and human-induced processes, such as climate change, deforestation and urbanization, can have on the Earth's surface. As a result, LUC research has been receiving increasing attention over recent decades, and the number of fields making use of this data is on the rise.

Researchers have been proposing new methods and techniques for producing LUC maps. This has increased the number of LUC datasets available at global, continental, regional and local scales. This has also led to an increase in the number of users who decide to make their own LUC maps. The validation of LUC data has also been the subject of specific research and new methods, strategies and techniques have been proposed for validating and analysing LUC maps.

Despite all these advances, many users are still unaware of the wide range of datasets available, while others lack a clear understanding of the methods or techniques that can be

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used to validate LUC data. Thus, in addition to producing more LUC datasets, more information is required. Users must be able to find out more about the most appropriate datasets for their field of study, and the general uncertainties and limitations of each one. They should also be informed about the methods that can be used to assess the specific utility and uncertainties of this data for their line of research.

2 Land Use versus Land Cover

Although Land Use and Land Cover are often combined, for example, in references to LUC maps and information, they in fact have quite separate meanings. Many authors have proposed complementary definitions (Di Gregorio and Jansen 1998; Campbell and Wynne 2011; Giri 2016a; Wulder et al. 2018) and the European directive INSPIRE, which establishes an Infrastructure for Spatial Information in the European Community, also includes a definition of each term (see text box below). On the basis of these various sources, we have opted for the following definitions.

Directive INSPIRE (2007/2/EC)

Land Cover: Physical and biological cover of the earth's surface including artificial surfaces, agricultural areas, forests, (semi-)natural areas, wetlands, water bodies.

Land Use: Territory characterised according to its current and future planned functional dimension or socio-economic purpose (e.g. residential, industrial, commercial, agricultural, forestry, recreational).

Land cover refers to the Earth's biophysical covers. Areas without a specific cover, such as areas of bare rock or bare soil, are also regarded as land covers. By contrast, land use refers to the activities that humans carry out on the Earth's surface or on a specific land cover.

A land cover can have one or multiple uses, or even none. An artificial surface could be used to host people (e.g. residential area), production (e.g. industrial area) or leisure activities (e.g. sports facilities). In maps at coarser scales, this artificial surface can host all these uses together. For example, an urban area is an artificial cover which has multiple uses. Bare rock, on the other hand, often hosts no land use of any kind.

A specific land use can also be associated with multiple land covers at the same time. An airport is a land use that is usually associated with several artificial covers, such as buildings, roads and runways, and also with vegetation covers, like grassland.

Whereas land covers are usually visible in aerial or satellite images, land uses are more difficult to distinguish. For instance, a building could have multiple uses: apartments, offices, industrial plants, sports facilities, etc. Sometimes the land use can be deduced from contextual information in the image, but, in most cases, additional information is required. This makes map production more difficult and expensive. As a result, most maps only provide information about land covers. In other cases, they focus on the land use of certain specific covers, such as artificial or agricultural areas, so providing both Land Use and Land Cover (LUC) data. This is why in LUC science, we generally talk about Land Use and Land Cover information, as the two aspects tend to be combined within the same datasets.

3 Land Use and Land Cover Mapping: A History

Some information on Land Use and Land Cover was available prior to the advent of remote sensing instruments (Campbell 1983). However, it was the appearance of aerial and, above all, satellite images that promoted the production of systematic LUC maps at regional, continental and global scales (Loveland 2016).

Before the emergence of aeroplanes and satellites, the main method for map production was ground survey (Wallis 1981; Fuller et al. 1994; Crone 2000). This was a time-consuming, laborious process that made systematic mapping of vast territories a difficult task. However, various important projects to map national territories were carried out in the eighteenth and nineteenth centuries without the use of aerial imagery (Collier 2009a). Most of these projects involved topographic or cadastral maps, like the first French topographic survey finished in 1793, the French Napoleonic cadastre which began in 1807 or the Austrian cadastral survey launched in 1762 (Collier 2009a; Rochel et al. 2017). There are also striking examples of systematic exercises to map LUC information, such as the Land Utilization Survey of Great Britain, conducted from 1931 to 1938 (Campbell 1983). Nonetheless, the general rule was for land use information to be presented as part of other maps with more general purposes (e.g. topographic, cadastral maps) or a very thematic approach (e.g. agricultural uses and production) (Campbell 1983).

With the advent of aerial imagery and, later, satellite imagery, mappers obtained a view of the Earth's surface from the top of the atmosphere or from space. Mapping became easier and cheaper (Fuller et al. 1994). Instead of going out to the field to collect information, mappers could photointerpret and extract most of the features on the Earth's surface from the imagery, including land uses and covers.

Information collected in the field was still required to validate what was photointerpreted and to include some extra information that was not discernible in the image (Steiner 1965; Campbell 1983). However, these tasks were less time-consuming and demanding than the original ground survey activities.

Aerial images became increasingly common from the beginning of the twentieth century, with the development of the aeroplane industry within the context of the two World Wars (Collier 2009b). Most nations started or boosted ambitious national mapping programmes for strategic or economic purposes. Many national topographic or cadastral mapping projects were completed during this period (Collier 2009a). Some pioneer land use mapping projects were also launched at that time, such as the Michigan Land Economic Survey in the early 1920s and the Rural Land Classification Survey conducted by the Tennessee Valley Authority, which began in the 1930s (Steiner 1965). There was even a plan to create the first global land use map, with the foundation of a World Land Use Commission in 1949 and the mapping of different test areas in the 1950s and 1960s (Campbell 1983). However, mapping was still costly and very time-consuming. Although much easier than before, photointerpretation was a manual task carried out using rudimentary tools that required a great deal of time and effort (Steiner 1965; Campbell 1983).

The launch of the first satellite into space in 1957 proved a turning point in the history of LUC mapping (Emery and Camps 2017). Satellites provide a periodic imagery coverage of the Earth's surface. Once satellites started to provide images of the Earth, a homogeneous, cheap mosaic of the entire surface of the Earth soon became available (Morain 1998; Chuvieco 2016).

Satellites record the reflectance of the Earth's surface in different regions of the electromagnetic spectrum. The reflectance curve for each land cover can be independently characterized and defined (Chuvieco 2016; Emery and Camps 2017). In this way, satellite imagery gives mappers the information they need to draw the land covers on the Earth's surface automatically, so reducing the need for photointerpretation or human intervention in the process (Campbell and Wynne 2011; Chuvieco 2016). Nonetheless, the mapping of LUC covers from imagery reflectance has various important issues that can result in uncertainty and errors. One land cover can present several different spectral responses due to variations in vegetation density and phenology. Different land covers can also present a similar spectral response. This problem, known as spectral confusion, is critical in diverse and complex landscapes and can lead to large numbers of classification errors.

Despite these limitations, the availability of satellite imagery and the ease with which land cover information could be obtained from them boosted the production of land cover maps, which until then had been relatively rare (Comber 2008). Whereas most of the LUC information available in the pre-satellite era had been focused above all on land use, from then onwards, maps focusing on land cover or on a mixture of land cover and land use became predominant (Fisher and Unwin 2005; Comber 2008).

Manual photointerpretation was still common in the early years of satellite remote sensing (Campbell 1983). It benefited from computer-assisted procedures, such as on-screen digitalization. However, it was progressively replaced by digital procedures with the development of powerful computers and the improvement of classification and image treatment methods (Loveland 2016). Nonetheless, even today manual photointerpretation still plays an important role in the production of LUC maps. Recent examples of Land Use Cover mapping over large areas using visual interpretation include maps of Europe (CORINE Land Cover; see Feranec et al. (2007)), Africa (AFRICOVER; see Di Gregorio and Latham (2003); Fritz et al. (2015)) and China (Zhang et al. 2014).

As LUC mapping became easier, cheaper and quicker, many institutions, scientists and other users began producing LUC datasets at all the different scales (Grekousis et al. 2015; Loveland 2016). Initial efforts were mainly focused on regional and national scales (Loveland 2016). However, the appearance of the first satellites with sensors providing free imagery covering the whole Earth at coarse resolutions allowed the first global LUC datasets to be developed (Congalton et al. 2014; Mora et al. 2014; Grekousis et al. 2015).

The AVHRR sensor on board the NOAA weather satellites launched in 1978 (Campbell and Wynne 2011), and the VEGETATION sensor, installed in the SPOT satellite in 1998 (Gutman et al. 2012a), provided the first sources of satellite imagery for global mapping exercises (Congalton et al. 2014; Gong et al. 2016). Landsat, which was first launched in 1972, provided the first source of satellite imagery at medium spatial resolutions, which could be used for LUC mapping at regional and local scales (Belward and Skøien 2015).

Since then, LUC mapping practice has been developed in parallel with the launch of new satellites and the increasing improvement in their spatial and spectral resolutions (Belward and Skøien 2015). This process has also been spurred by the appearance and consolidation of public and private initiatives focusing on Earth Observation and LUC monitoring (Herold et al. 2016; Wulder et al. 2018). Although many such organizations now exist, perhaps the most important are the United States Geological Survey (USGS) and the European Space Agency (ESA).

The key role played by the USGS is undeniable. It authored the first research laying down the foundations of modern LUC mapping (Anderson et al. 1976; Gutman et al.

2008) and is also responsible for some of the most important Earth-monitoring projects today (Barber 2019; Szantoi et al. 2020). The ESA has also played an important role, especially recently after the launch of the Copernicus programme with the support of the European Commission (Szantoi et al. 2020). The constellation of Sentinel satellites and the Copernicus land monitoring products, produced by the European Environmental Agency (EEA) and the Joint Research Centre (JRC), have enabled important advances in the production of detailed, high-quality LUC information that is updated periodically (Manakos and Braun 2014; Grekousis et al. 2015; Herold et al. 2016).

Users now have more information available than ever (Belward and Skøien 2015; Grekousis et al. 2015; Giri 2016a). Many LUC products have been developed and are ready to use, with abundant, detailed documentation about their characteristics (Grekousis et al. 2015; Diogo and Koomen 2016). There are numerous sources of satellite imagery, some of which are pre-treated and are available free of charge (Belward and Skøien 2015). Many methods have been developed for image processing and LUC mapping, such as classification algorithms (Bruzzone and Demir 2014; Yu et al. 2014; Khatami et al. 2016). Many methods and techniques have also been proposed for assessing the validly of LUC information (Strahler et al. 2006; Stehman and Foody 2019). Most of these methods and techniques are available on widely used software and are readily accessible to any user (Bastin et al. 2013; Mas et al. 2014b; Brovelli et al. 2018). All this has encouraged research into the production of LUC information and has widely extended its use, which has also led to an increase in published research on the topic, especially in the last 25 years (Yu et al. 2014).

4 Uses of LUC Data

The importance and utility of Land Use and Land Cover information is beyond doubt. LUC data is a valuable source of information for scientists (Bontemps et al. 2012; Manakos and Braun 2014). It gives them a better understanding of the interactions between societies and the environment (Lu et al. 2004), an aspect of special interest for many social sciences such as geography or economics (Geoghegan 1998; Green et al. 2005). LUC data can also be used to monitor a range of different natural and environmental processes (e.g. hydrological, meteorological…), a question of great interest for many natural sciences (Rindfuss et al. 2004).

Policymakers also need LUC data for proper resource management and to help them deal with many of the challenges facing society today (Szantoi et al. 2020). It allows them to understand where land resources are located and how and when they change (Strand 2013; Thackway et al. 2013).

Campbell (1983) reviewed some of the applications of LUC data in policymaking in the USA at different scales. He found that “almost all governmental units have a continuing requirement to create and implement laws and policies that directly or indirectly involve existing or future land use”. Local administrations need land use information for spatial planning. Regional and national governments may require LUC information for water management, flood control or in the design and assessment of environmental policies. At the international level, LUC data provides important evidence on which to base decisions regarding many of the global challenges facing society today.

Most of the current global agendas refer to policy objectives involving Land Use and Land Cover. They play a direct role in 7 out of 17 UN Sustainable Development Goals (SDGs), and in the UN Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity, the UN Convention to Combat Desertification (UNCCD) and the Ramsar Convention on Wetlands (Szantoi et al. 2020). LUC data is required to monitor many of the targets or actions proposed in these agreements, so emphasizing the need for global LUC maps (Diogo and Koomen 2016).

The Group on Earth Observations (GEO) has defined eight Social Benefit Areas (SBAs) in which Earth observations, including LUC data, provide useful evidence in support of policymaking.[1] They are biodiversity and ecosystem sustainability, disaster resilience, energy and mineral resource management, food security and sustainable agriculture, infrastructure and transportation management, public health surveillance, sustainable urban development and water resources management. Specifically, LUC data can help, among other things, to characterize the land for disease control; monitor fires; assess the potential of land for biofuel production and wind or hydropower generation; and assess the role of LUC changes in the dynamics of hydrological systems and vegetation (Giri 2016b).

Among scientists, LUC maps are frequently used as a basis for modelling exercises (Tsendbazar et al. 2015; Herold et al. 2016). At a global scale, climate change models require global LUC maps (Sophie et al. 2011). At regional and local scales, land use and cover change models have emerged as valuable tools for policy support (Van Delden et al. 2011; White et al. 2015). These models are built on LUC datasets (Sohl and Sleeter 2012).

LUC information is also used for many other research activities, most of them related to the different policy fields mentioned above. In recent years, it has been applied, for example, in studies analysing habitat distribution and ecosystem services (Jacob et al. 2003; Brown 2013), spatial

[1] https://earthobservations.org/geo_wwd.php#.

patterns of biodiversity (Zimmermann et al. 2010; Tuanmu and Jetz 2014), and ecosystem status and biogeochemical cycling (Johnson and Patil 1998; Lawrence et al. 2012), etc. A wide variety of processes are also studied using LUC data. Bielecka (2019) review some of the most common processes analysed through the CORINE Land Cover database. These include agricultural abandonment, urbanization, afforestation, deforestation, landscape fragmentation, etc.

5 Land Change Science

Although LUC information is employed for manifold purposes, the field taking most advantage of this data is Land Use and Land Cover Change (LUCC) analysis (Feranec et al. 2007; Verburg et al. 2009; Bielecka 2019). LUCC analysis is the study of the changes in the land uses and covers on the Earth's surface, and their causes and consequences (Moran et al. 2012). LUCC is not usually studied as an end in itself, and the focus is normally on understanding its impact on a range of other natural or human-induced processes (Gutman et al. 2012a). Many of them have already been mentioned when explaining the general utility of LUC data.

LUC change analyses are widely used in climate change studies (Sophie et al. 2011), the study of hydrological systems (Carlson and Traci Arthur 2000; Cuo et al. 2009), weather conditions (Marshall et al. 2004), soil erosion (Cebecauer and Hofierka 2008), loss of biodiversity (Cebecauer and Hofierka 2008), as well as in research into ecosystem services (Hu et al. 2008) or animal habitats (Lawler et al. 2004). The utility of LUC data increases when historical information is available, as it allows us to track LUC changes over time (Verburg et al. 2011; García-Álvarez and Camacho Olmedo 2017).

The importance of LUCC studies has led to the emergence of a specialist field called Land Change Science (Gutman et al. 2012a; Turner 2017), which is also referred to as Land Use Science or Land System Science (Müller and Munroe 2014). This is defined as a "transdisciplinary field" that "seeks to understand the dynamics of land cover and land use as a coupled human–environment system to address theory, concepts, models, and applications relevant to environmental and societal problems, including the intersection of the two" (Turner et al. 2007). One of its hallmarks is the integration of natural and social sciences via a holistic approach (Rindfuss et al. 2004; Gutman et al. 2012a). Land Change Science now has its own specialists, who work at the confluence between these fields of knowledge (Moran et al. 2012; Müller and Munroe 2014).

Land Change scientists are responsible for monitoring LUC change, understanding it and modelling for the future, so obtaining knowledge and evidence that may be useful for policymaking (Turner et al. 2007). Land Change is part of the wider field of research addressing Global Environmental Change, for which historical series of LUC data are required (Turner et al. 2007; Janetos 2012). This is why Land Change Science has emerged in parallel to the growth in remote sensing observation and the appearance of the first time series of Earth observation data (Moran et al. 2012; Turner 2017).

Many international programmes and organizations have stressed the importance of LUCC and Land Change Science (Giri 2016b). Turner (2017) claims that the science first originated in the joint programme on LUCC funded by the International Geosphere Biosphere Program (IGBP) and the International Human Dimensions Programme (IHDP). Other programmes that have emphasized the importance of LUCC studies include the U.S. Climate Change Science Program, the Global Land Project and the Group on Earth Observations (GEO) and the United States Global Change Research Program (USGCRP) (Gutman et al. 2012b; Moran et al. 2012). Some of these programmes are specifically focused on LUCC as a specialist interest, lying at the heart of their activities. These include the Land Cover and Land Use Change (LCLUC) programme run by NASA and the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) programme (Gutman et al. 2012b).

6 Land Use and Land Cover Change Modelling

As previously noted, Land Change Science is not only a question of analysing and understanding LUC changes, but it also seeks to model them in the near future (Gutman et al. 2012a; Turner 2017). Once we have understood what has changed, where it has changed, why it has changed (drivers or causes), how it has changed and what the consequences are, we can then take a step further and try to understand how different change trends can affect human-natural ecosystems. This is especially useful for policymaking. By evaluating different change scenarios, we can understand what the future may look like and what we can do to put the policy objectives we are seeking into practice (Oxley et al. 2002; Soares-Filho et al. 2006; Escobar et al. 2018).

Land Use and Land Cover Change Modelling (LUCCM) is about understanding the LUC dynamics at work within a given Earth system and modelling their future evolution (Verburg et al. 2004; Paegelow and Camacho Olmedo 2008). To understand these dynamics, we need to study how the system has changed in the past and analyse the processes that gave rise to these changes (Plata Rocha 2010; Toro Balbotín 2014). By studying these processes in detail, we can identify the drivers behind the changes taking place (Bürgi et al. 2005; Kolb et al. 2013). Once we know what changes are occurring and why, we can conceptualize this information and translate it into modelling terms.

Models allow us to play around with the system we are studying so as to predict how different policies affect LUC and the changes they may cause (Van Delden et al. 2011). Models also help us understand how these changes may evolve in the future under different socio-economic conditions (Antoni et al. 2018). At a more modest level, LUCC models also enable us to study and analyse these systems in detail, so as to obtain a more in-depth understanding of them (Hewitt et al. 2014).

LUC maps are the main input for LUCC models (Sohl and Sleeter 2012; Grinblat et al. 2016), forming the base on which all processes are conceptualized (García-Álvarez et al. 2019b). LUC maps conceptualize the landscape to be modelled: they present the LUC categories into which the landscape is divided and determine the spatial detail of the model (Conway 2009; García-Álvarez et al. 2019a). They are also often used as a reference for studying LUC changes in the past (Burnicki et al. 2010) and for validating LUCC models (Van Vliet et al. 2016).

Many types of LUCC models are available today (National Research Council 2014). Although there is no standard, globally accepted classification, we can broadly distinguish between process and pattern-based LUCC models (Brown et al. 2013). The latter assume that changes in the landscape pattern are the result of the processes and dynamics taking place, and that each pattern is a consequence of a specific process (Mas et al. 2014a). These models simulate the pattern and its changes. They are therefore heavily reliant on time series of LUC maps and the changes they show.

Process-based models simulate the processes taking place, rather than the pattern (O'Sullivan and Perry 2013). There are different kinds of process-based models, with agent-based LUCC models gaining increasing popularity. These models simulate the behaviour of the agents or actors that take part in the system being modelled and their interactions (Crooks and Heppenstall 2012). These agents cause the processes taking place on the ground and the changes in the landscape pattern. Although important, LUC maps do not play the same key role in these models as they do in pattern-based models, as most of the parameters used in process-based models are inferred from other sources (Mas et al. 2014a).

LUCC models can also be classified according to the scale of analysis, their stochastic or deterministic nature, the type of scenarios they can produce and the techniques and methods they apply (García-Álvarez 2018a). For example, some models include Markov chains to estimate the quantity of simulated change in the future (Sang et al. 2011; Eastman and Toledano 2018). These are usually calculated on the basis of the changes that took place between two LUC maps in the past (Sinha and Kimar 2013; Mas et al. 2014a), so increasing the importance of LUC data in the modelling exercise.

Modelling exercises normally consist of four main phases: calibration, simulation, validation and the proposal of scenarios (Camacho Olmedo et al. 2018), although other phase-based structures have also been proposed. In almost all cases, researchers differentiate between the calibration and the validation phase (Pontius Jr. et al. 2004; Gallardo 2014; Van Vliet et al. 2016). Nonetheless, some studies omit the validation stage, choosing solely to explore the modelled system and its behaviour.

Calibration refers to the setting-up and parametrization of the model (Clarke 2004; Mas et al. 2018). The users define the objectives of the exercise, and the data and model to be used. They then parametrize the model in line with their understanding of the simulated system. After the initial results are obtained, the model is adjusted to obtain the best possible results (Van Vliet et al. 2016). Once the model is fully calibrated and a simulation has been obtained, this must be validated by comparing it with reference data that were not used earlier on in the modelling exercise (Pontius Jr. and Malanson 2005; Paegelow and Camacho Olmedo 2008).

The methods and techniques used for calibration are similar to, if not the same as, those used in the validation phase (Mas et al. 2018). In the calibration phase, the results obtained from the model are compared with reference data so as to obtain a model that properly simulates the system being studied (Van Vliet et al. 2016). The model is then validated with independent data sources, not used in the calibration phase (Pontius Jr. and Malanson 2005; Van Vliet et al. 2011). Thus, whereas calibration fits the model to the reference data, validation makes sure that there is a good fit over time and not just for the date of the reference map. In this way, it ensures that the processes that explain the changes in the system being studied were correctly modelled.

7 Uncertainty and Validation

The increased availability of satellite and aerial imagery and the development of new methods and techniques for image processing and classification has enabled the production of an increasing number of LUC maps and time series of LUC maps at all scales (Yu et al. 2014; Grekousis et al. 2015; Giri 2016a). The same trend can be observed in the application of LUCC models, which has become very common as a result of easy access to LUC maps and LUCC modelling software (Sohl and Sleeter 2012; Ferchichi et al. 2017).

With the increasing production and use of LUC maps and LUCC models, more attention has been paid to the uncertainty and limitations of these data and analyses (Yeh and Li 2006; Krüger 2016; Loveland 2016; Ferchichi et al. 2017; García-Álvarez et al. 2019b). Uncertainty can be defined as "the lack or the degree of certainty about any data or geospatial analysis due to the difference between reality and its representation through geospatial data or tools" (García-Álvarez et al. 2019b). Understanding how different these maps and exercises are from real landscapes and processes and, therefore, how reliable they are is essential. This is the only way of knowing how accurate the information we obtain from these maps and analyses is and to what extent it can be used as a basis for taking policy decisions.

It is important to realize that all spatial data and analyses contain some degree of uncertainty (Longley et al. 2011). They are an abstraction and simplification of real landscapes and processes (Comber et al. 2005; Devillers and Jeansoulin 2006). This means that the maps and models are themselves just conceptualizations of different processes and features of the Earth. When we conceptualize a landscape on a map, what we are actually doing is simplifying it to obtain elements with which we can work and experiment.

In the case of LUC maps, the complexity and variety of real landscapes is normally translated into a given set of categories (Di Gregorio and Jansen 1998; Herold and Di Gregorio 2012). Land Use and Land Covers do not always fit into a precise, clear-cut classification, as they show heterogeneous, mixed patterns that cannot be easily classified within a specific category (Di Gregorio and Jansen 1998; Villa et al. 2008). This makes it difficult to clearly define a particular land use and to distinguish it on the ground from all other land uses, establishing boundaries between them (Fassnacht et al. 2006). Some degree of uncertainty is therefore inevitable in the classification process.

Mapping the full complexity of the Earth remains beyond human capacity, and even beyond existing computer capabilities (Unwin 1995; Murayama 2012). The smaller or coarser the scale, the greater the need for abstraction or simplification (Lloyd 2014). At whatever scale we work, we are capable of assimilating similar amounts of information. This means that at larger or finer scales we can add details, while at smaller or coarser scales we can only show the essentials.

To understand the uncertainty and limitations of our data and analyses, we usually carry out uncertainty assessments (Van Asselt 2000; Jcgm 2008; Abreu and Ralha 2017; García-Álvarez et al. 2019b). In general, when we assess our data and analyses against reference data to evaluate the reliability of the information they provide, we are said to be validating the data or models (Fonte et al. 2015; Van Vliet et al. 2016). Validation can therefore be defined as the process by which we assess how certain or reliable a piece of data or result is. This is done by comparing it against other data or information that we use as a reference and consider to be true.

Although validation is already a common practice and there are many methods, strategies and reference data available for validating LUC maps and LUCC models, there is still a lot of room for improvement. In the case of LUCC maps, when Olofsson et al. (2013) carried out their review, up to 15% of the papers addressing land change with LUC maps did not include any proof of data validation. They also found that most of the reviewed papers did not include all the relevant information about the accuracy of the measured changes. The review carried out by Yu et al. (2014) produced even less hopeful results: of 6771 papers including some type of LUC mapping exercise, only 1585 reported overall accuracy measures. Morales-Barquero et al. (2019) found that only 32% of the papers they reviewed provided a reproducible accuracy assessment and recommended that more statistically rigorous accuracy assessment practices be encouraged.

In LUCCM, several authors emphasized the importance of analysing the uncertainty of the results, even when general validation exercises are carried out (Li and Wu 2006; Krüger 2016). In fact, Van Asselt (2000) criticized the widespread use of validation exercises in modelling as a tool "to sell the model as being scientifically credible", without proper discussion and analysis of the uncertainties and limitations of the modelling exercise. Sohl et al. (2016) consider the lack of information regarding uncertainty and the failure to quantify it as one of the reasons hampering the adoption of LUCC models in decision-making.

The uncertainty of most of the available LUC datasets has been assessed in a large range of research studies (Grekousis et al. 2015; Tsendbazar 2016). However, these studies do not usually address all possible sources of uncertainty. Some limitations have been reported regarding the validation of specific areas and categories, which are heterogenous and, therefore, more difficult to map (Leyk et al. 2005; Fassnacht et al. 2006). The mapping accuracy of these categories and areas is not usually well characterized, as validation exercises only assess the general uncertainty or validity of the whole dataset (Prestele et al. 2016). Moreover, the validity of a specific dataset will depend on how it is used (Castilla and Hay 2007). An LUC map considered invalid for a specific type of study could be a reliable source of information for another study at another scale and with different aims. Maps like these are often described as "fit for use" or "fit for purpose" (Chrisman 2010). In addition, users often process the datasets in some way, so introducing sources of uncertainty that need to be evaluated (Nienkemper and Menz 2016). When using a series of LUC maps, additional uncertainties may arise. As Olofsson et al. (2013) noted, even when two independent maps are both very accurate, it is possible that the accuracy of the change map obtained by post-classification comparison will be low due to error propagation.

Many users develop their own maps, given the increasing availability of free imagery and tools with which to process and classify the images easily (Belward and Skøien 2015; Yuan et al. 2020). They need to validate the maps that they produce both for general purposes and for the specific use for which they were designed (Chuvieco 2016). The LUCCM community also need to validate the results of their modelling exercises (Paegelow and Camacho Olmedo 2008). To correctly interpret these results, they also need to understand the uncertainty of the LUC databases on which LUCC models are built (Prestele et al. 2016; García-Álvarez 2018b), given that input data and, specifically, input LUC maps, are considered one of the main sources of uncertainty in LUCCM (Verburg et al. 2013; Houet et al. 2015).

8 Conclusions

Many frequent users of LUC data and LUCC models are unaware of the latest developments in validation and uncertainty analysis of LUC data. It is also possible that they have limited knowledge of many of the datasets currently available for carrying out LUC exercises.

Many of the recent advances in this field remain within closed scientific communities and are not disseminated among the wider LUC community outside the research arena. This book seeks to respond to their needs. It provides an overview of the state of the art on LUC datasets, including time series of LUC maps, and the tools and methods available for LUC map validation. It also presents and explains frequently used tools and guidelines for validating the results produced by LUCC models. As many of the tools and techniques reviewed here are used in both LUC mapping and LUCC modelling validation exercises, in this book we address these two analyses together.

A full validation exercise, characterizing all the uncertainties of a given dataset or model, is a complex task that requires a high level of expertise and a wide range of tools and strategies, each one addressing different sources of uncertainty. This is beyond the scope of this book. Here we focus on the quantitative validation of LUC maps and LUCC model results. For detailed information about qualitative analyses of uncertainty, we refer readers to more specialized bibliography, depending on the specific objectives of their research. Readers wishing to find out more about other important aspects of uncertainty and validation practice, such as uncertainty communication, are also referred to specific literature on this topic.

Further Reading

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

This is one of the main reference books on Land Use Cover mapping, focusing specifically on LUC mapping and analysis. It offers an overview of the main concepts associated with LUC mapping and remote sensing and provides an introduction to this field, tracing its history. 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 the third part, the book includes examples of regional LUC mapping and LUCC monitoring for different parts of the world.

Manakos I, Braun M (2014) Land Use and Land Cover Mapping in Europe: Practices & Trends. Springer, Dordrecht, Heidelberg, New York, London.

Focused on Europe, this book is part of the reference bibliography for LUC mapping and LUCC monitoring. It provides a state of the art of LUC mapping globally, for Europe and at a national level for some of the European countries. Several chapters focus on remote sensing practices and methods for LUC mapping and LUCC detection. The book also has several introductory chapters on the role of remote sensing in the production of LUC information. Other chapters focus on the LUCC monitoring of processes relevant for policymaking.

Camacho Olmedo MT, Paegelow M, Mas J-F, Escobar F (2018) Geomatic Approaches for Modeling Land Change Scenarios. Springer, Cham, Switzerland.

This book provides an up-to-date review of LUCCM practice. The first part describes each of the LUCCM phases: calibration, simulation, validation and proposal of scenarios. Each chapter also presents common methods and strategies, implemented in different modelling software, for setting up and running a LUCC modelling exercise. The book also includes a series of technical notes for many of these tools and techniques, as well as short presentations of standard LUCC modelling software that is currently available. Common applications of LUCC models for thematic analyses and methodological studies are also described.

García-Álvarez D, Van Delden H, Camacho Olmedo MT, Paegelow M (2019) Uncertainty Challenge in Geospatial Analysis: An Approximation from the Land Use Cover Change Modelling Perspective. In: Koutsopoulos K, de

Miguel González R, Donert K (eds) Geospatial Challenges in the 21st Century. Springer, pp 289–314.

This book chapter offers a synthetic overview of uncertainty in LUCCM. It includes a theoretical explanation of what uncertainty is and analyses its different dimensions. It also presents the different sources of uncertainty in LUCCM and reviews different strategies and methods for managing it.

Gutman G, C. Janetos A, Cochrane COJ, et al. (2012) Land Change Science. Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Springer Netherlands, Dordrecht.

Although outdated (it was initially edited in 2004), this book provides an introduction to Land Change Science and Land Use Cover Change analysis. The experience acquired with the International Land Use and Land Cover (LUCC) Research Programme of the NASA is the leitmotif of the book. It provides an overview of Land Change Science, defining its main concepts and presenting the main international initiatives in LUCC research. It also offers an overview of the main processes of change analysed within the LUCC framework and its utility for policymaking and other fields. The book has various chapters focusing on methodological issues, some of which refer to LUCCM.

Belward AS, Skøien JO (2015) Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites. ISPRS J Photogramm Remote Sens 103:115–128. https://doi.org/10.1016/j.isprsjprs.2014.03.009

This paper offers an overview of the history of civilian earth observation satellite missions that produce information that can be used in LUC mapping. It describes various different space missions and reflects on how useful they have been for the LUC community.

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