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Twenty Years of Land Accounts in Europe

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Abstract: Land use and its change impact food security, carbon cycling, biodiversity, and, hence, the condition of ecosystems to mitigate and adapt to climate change, support economic prosperity, and human well-being. To support and guide policy actions between the economy and the environment, harmonized time series datasets, transparent methodologies, and easily interpretable statistics are needed. Therefore, monitoring of the function and condition of lands and their change, along with properly agreed methodologies and freely accessible data, are essential. The Copernicus Land Monitoring Service has produced over 20 years of Corine Land Cover datasets for 39 countries in Europe, which allows continental-wide harmonized and comparable monitoring and accounting of land cover and land use change at a high thematic resolution and in a long time series (2000–2018). With the upcoming 2024 update, the time series will reach a unique product worldwide in terms of time series length, spatial resolution, extent, and thematic detail, enabling policymakers and the scientific community to address the main anthropogenic drivers of land and ecosystem degradation. This paper describes a unified approach for producing continental-wide land accounts that aligns with internationally agreed-upon standards for measuring the environment and its relationship with the economy. Furthermore, the study provides a harmonized time series of geospatial data for deriving land accounts and provides statistics of land cover and land use status and changes for a twenty-year period. All geospatial data and statistics presented in this paper are freely accessible and downloadable to serve other studies.

Keywords: land accounts; Copernicus Land Monitoring Service; Corine Land Cover; geospatial database; policy support

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1. Introduction

Land is a finite resource, and its use is one of the principal drivers of environmental change, including land use and its change impact food security; carbon cycling; and water cycles, which in turn influence the integrity of ecosystems and our natural capital [1]. These changes are directly associated with a healthy environment and human well-being. In Europe, the proportion of total land use occupied by production (agriculture, forestry, etc.) is one of the highest on the planet [2], and conflicting land use demands require decisions that involve hard trade-offs. Factors driving land use in Europe include increasing demand for living space per person, the need for food, feed, and fiber, and the link between economic activity, increased mobility, and the growth of transport infrastructure. Effective land and

soil management is fundamental for sustainable resource use and the delivery of ecosystem services [3]. For policy to counteract negative impacts and to plan incentives for better land management it is essential to monitor land use and its changes using transparent, repeatable, and harmonized methods.

Land cover and land use status and change are critical to inform the development and implementation of policies, such as agriculture, forestry, biodiversity, climate policies, or regional planning. Although a binding legislative mechanism for the sustainable management of land at the level of the European Union (EU) is lacking [4], the sustainable management of land is crucial to ensure that land continues to provide its functions now and in the future. Some EU policies already frame conditions for land use, e.g., the Common Agricultural Policy or the EU regulation for land-based carbon accounting (land use, land use change, and forestry—LULUCF), as well as the EU renewable energy and climate goals. At the same time a wide range of EU environmental policies have a major stake in land management, for example the EU Biodiversity Strategy with its target to 'maintain and restore ecosystems and their services' [5]. With the adoption of the UN Sustainable Development Goals in 2016, European countries, which are party to the UNCCD, and the EU have committed themselves to implement 'Land Degradation Neutrality' (LDN) in their mandate areas in the period up to 2030. The corresponding SDG target is target 15 on land to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss".

The international System of Environmental-Economic Accounting [6] is a key reporting framework for better ecosystem management in general. It comprises, inter alia, standards on land and water accounting, published in the 'Central Framework' (SEEA CF), and guidance on ecosystem accounting. In 2021, the United Nations Statistical Commission adopted chapters 1–7 of the System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) as an international statistical standard [7]. These methods provide a systematic way to measure and report stocks and flows of natural capital and anthropogenic impacts on them [8–12]. The complex interaction between elements of natural capital calls for a coherent monitoring approach to facilitate the understanding of the coupled human–environment system [13–15]. This monitoring must be supported by quantitative, robust, reliable, and comparable methods to map the condition and degradation of ecosystems and their services, and thus supplying a standardized framework for ecosystem assessment and accounting. Therefore, land accounting based on harmonized geospatial time series is a key element of the SEEA CF.

Besides accounting for the status of land cover, another key issue is the land use transforms land cover over time, as well as the impacts these changes cause. Land use change has manifold impacts on the carbon cycle [16–22]: it accelerates climate change [23,24]; it drives soil erosion [25]; and it strongly affects biodiversity [26–30]. Land accounts support the monitoring of land use change impacts as they describe how land resources change over time in a consistent and systematic way so that the implications of change can be better understood. Land use changes and the resulting change in land cover can lead to the total elimination of ecosystem types. However, for land, it is mostly their functions that are vulnerable to depletion through human actions, and such transformations are either permanent (e.g., soil sealing) or cannot be recreated over periods relevant to most policies.

The need to manage land and ecosystem resources effectively is pressing, especially given the increasing pressures from climate change, biodiversity loss and socio-economic trends. There is a growing research effort on ecosystem and natural capital accounting both in terms of conceptual developments [31–36] and applications [37–39]. Many conceptual frameworks and methodologies have emerged on ecosystems condition accounting [40,41]. Overviews on ecosystem accounting [42] and syntheses of particular topics of ecosystem accounting [43] have been produced in the literature and in the context of the United Nations with the development of the [7,44–46]. Advances in Earth observation, particularly through the EU Copernicus Programme and its Land Monitoring Service (CLMS) enhance

our capacity to monitor natural capital trends. With the production and publication of the Corine Land Cover of the CLMS an efficient land and ecosystem accounting system could be developed and implemented for the presented work to connect policy information needs with adequate analytical tools.

While the land accounting concept is well documented in the scientific literature, according to our review continental-wide quantification of land cover change statistics with geospatial input to reproduce results do not yet exist. In our view the present paper is a first of its kind that brings several types of stakeholders close to land accounting. Accordingly, the purpose of this paper is to support the scientific and policy making community with quantitative information on land cover as well as land use status and change for a twenty-year period (2000–2018). The paper provides a sound methodology, a land accounting geospatial time series and derived statistical information using CLMS land cover data. Land accounting statistics are complemented by illustrative examples of how land accounting methods can support the analysis of environmental pressures arising from the land use sector. Besides the statistics presented in the paper to illustrate how land accounts can support various assessments, a vast amount of information is made available in interactive online dashboards. The geospatial and statistical data presented here and in interactive dashboards can be downloaded for further analytics that bring the user closer to monitoring the impact of land cover and land use change and may support further scientific and policy impact studies.

2. Materials and Methods

2.1. The Corine Land Cover Accounting Layers

The first set of Corine Land Cover (CLC) datasets of the Copernicus Land Monitoring Service was produced between 1986 and 1989, and since 2000, the CLC mapping has been performed in a harmonized manner, focusing on a single reference year for all participating European countries. Altogether, five mapping inventories have been implemented in this period, based predominantly on the visual interpretation of high-resolution (10–30 m) satellite imagery and ancillary, in situ datasets. These inventories have produced five status layers (referred to as CLC1990, CLC2000, CLC2006, CLC2012, and CLC2018, based on their nominal reference years) and four CLC-change (CLCC) layers for the corresponding periods (1990–2000, 2000–2006, 2006–2012, and 2012–2018).

The minimum mapping unit (MMU) of 25 ha was specified for CLC status products as a compromise between spatial details and feasibility, considering the intensive manual workload required to map large areas. Mapping changes with a higher spatial resolution was a user requirement, as most relevant land cover/land use changes happen on a larger scale than the 25 ha area limit. The MMU for CLCC layers was therefore defined at 5 ha. The original mapping instructions created for the CLC2000 inventory included the recommendation to create CLC1990–2000 changes as the difference in CLC1990 and CLC2000 status layers. However, due to the scale difference between CLC and CLCC data determined by varying MMUs, the simple difference between the datasets resulted in the issue that (1) the change layer included lots of noise and false changes, and (2) a significant portion of valid CLC changes between 5 and 25 ha were missing from the CLCC database. As the drawbacks of this strategy were clarified only after the CLC2000 mapping started, some countries created CLCC1990–2000 data by intersecting two status layers, while others applied the newly developed "change mapping first" approach. The consequence is that the CLCC1990–2000 data and statistics are not fully comparable between countries.

From the CLC2006 inventory onward, the only method that has been used for the derivation of CLC-Change database has been the "change mapping first" approach, producing a change database directly, by means of computer-aided visual image interpretation, comparing satellite images for the two reference years. The key steps of CLC update and CLCC mapping, according to the "change mapping first" approach [47], are as follows:

1. Revision of a previous CLC status layer (photo-interpretation);
2. Direct delineation of CLC changes (photo-interpretation);

3. Creation of a "new" CLC status layer (GIS operation automated):

$$CLC_{new} = CLC_{old,revised} + CLC_{changes} \quad (1)$$

4. Generalization (eliminating polygons smaller than 25 ha by semi-automatic GIS operations).

The step of revision of the previous CLC status layer was deemed necessary because of better reference data (higher resolution satellite images) from one inventory to the next, allowing the detection of formerly unnoticed features. The key advantage of a workflow based on change mapping first is the direct, visually controlled delineation of CLCC features, which ensures a significantly higher reliability of CLCC data than any other change derivation method could provide.

Europe-wide CLC and CLCC data are available as vector and raster products for the EEA-38 region[1] and the UK. The European vector and raster mosaics are distributed via the Copernicus Land portal[2]. Most of the modeling and statistical applications are based on the 100-m raster version of CLC data, which is also used in this study. The CORINE Land Cover Product User Manual [47] gives a detailed overview of CLC characteristics, product methodology and workflows, user requirements, and potential use cases.

Due to the technical characteristics of CLC and CLCC data, evolution of CLC update methodology and refinements in the understanding of thematic content [48], the statistics derived directly from historical CLC time series include several inconsistencies. To create a solid basis for CLC based statistical time series analysis a harmonization methodology was elaborated, resulting the so-called 'CLC accounting layers', which are the data sets recommended to be used for land or ecosystem accounting purposes and which are used in this study. The solution applied for the harmonization of CLC time series is applicable for the European CLC mosaics from 2000 onwards. It is based on combining the lower resolution CLC status and higher resolution CLC change layers to create a homogenous quality time series fulfilling the relation:

$$CLC_{change} = CLC_{accounting\ new\ status} - CLC_{accounting\ old\ status}. \quad (2)$$

Additional criteria are:

- Add more detail to the 25 ha resolution CLC status layer (CLC2018) from the higher resolution (5 ha) CLCC layers and use this "adjusted" layer as a reference.
- Create new CLC status layers by "backdating" the reference layer, realized as subtracting CLCC based information for CLC2018.

The processing steps for creating the CLC accounting layers are shown in Figure 1 and are described in detail in Appendix A with a public link to download the datasets. Harmonization leads to increased comparability in CLC time series statistics as many effects causing status layer differences are falsely evaluated as real changes are filtered out. Furthermore, the combination of the CLC change layers with the status layers also increased the spatial detail of the accounting layers. Due to this combination, the accounting layers cannot be described with an overall MMU as the status information remains on 25 ha and the land cover change information is stored on 5 ha. We consider, however, that an improved monitoring of land cover change has a much higher importance than fully confirming with cartographic conventions. The resulting data layers are known as the Corine Land Cover accounting data layers and are used by many land and ecosystem accounting systems and applications [49–53]. The reader is invited to consult Appendix A to explore the datasets as web map services.

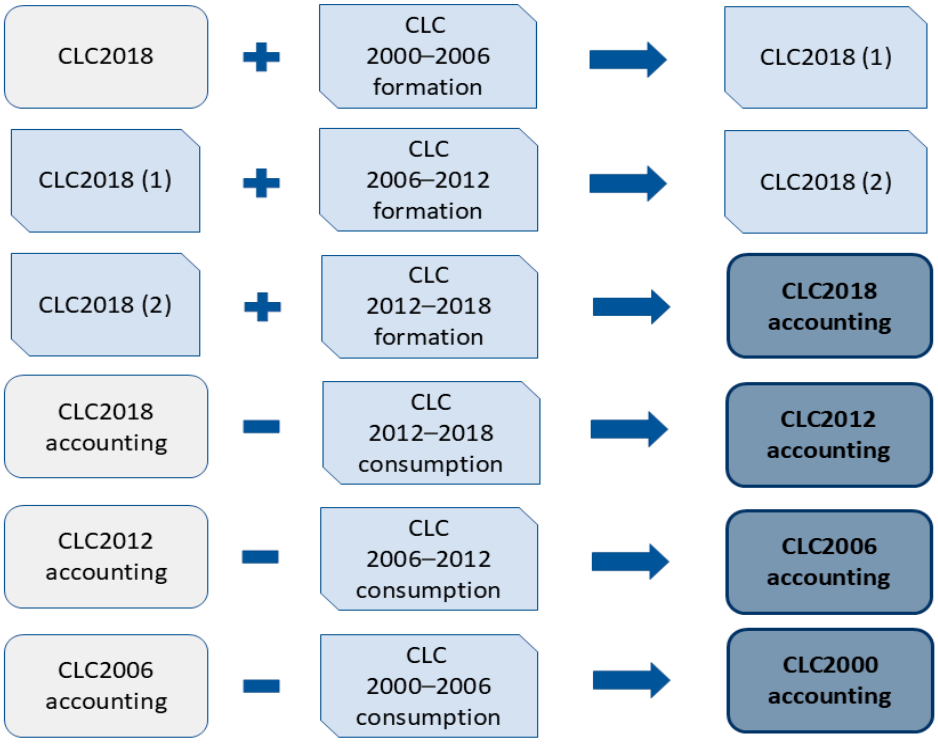


Figure 1. Processing steps for creating the CLC accounting layers.

2.2. Administrative Reference Layers

A detailed understanding of European land cover and use dynamics is facilitated by the inclusion of thematic or geographical dimensions, such as the political subdivisions of countries, regions, and municipalities. Within the land accounting system, a standard administrative boundaries layer that covers the whole EEA-38 region is key for identifying regional trends to support national policy objectives.

The administrative boundaries layer is a harmonized dataset that combines boundaries represented by the Nomenclature of Territorial Units for Statistics (NUTS) relative to the EU-28 Member States (in 2019), with the equivalent administrative units relative to the five non-EU EEA member countries (Iceland, Liechtenstein, Norway, Switzerland, and Turkey) and the six cooperating countries (Albania, Bosnia and Herzegovina, Kosovo [12], Montenegro, North Macedonia, and Serbia). In addition to the official release of Eurostat GISCO [13], the administrative boundary layer has been combined with the Economic Exclusive Zone dataset [14] to assign a country code to the coastal area of the CLC accounting layers not covered by the NUTS. This way, a perfect match between the CLC coverage and administrative boundaries was achieved[3].

The dataset is produced in raster format (GeoTiff) at the same resolution as the accounting layers (100 m) and contains the aggregation level by Country (NUTS0 + coastal areas. It is freely accessible from the datahub of the European Environment Agency[4]. Although the present study only explores regional land cover and use change patterns, note that analytics of any other spatial aggregations are possible as long as the scale, spatial resolution, and grid size of the various new layers match those of the CLC accounting layers. Such an application was produced, for example, for the Natura2000 areas [54].

2.3. Land and Ecosystem Accounting Nomenclature

The hierarchical nomenclature of the CLC datasets is shown in [48]. CLC level 3 has the most detailed nomenclature with 44 classes, which are aggregated to fifteen level 2 classes and five broad classes at level 1. Accounting for land cover change can in principle be implemented for individual level 3 land cover classes, but for ease of interpretation due to the numerous possible combinations of the 44 classes, a more concise class combination

was developed. CLC level 1 and 2 classes are combined into 8 new groups, the so-called LEAC (Land and Ecosystems Accounting) categories. The combinations and cross-walks between the LEAC and CLC classes are shown in Table 1.

Table 1. Aggregation used for land and ecosystem accounting (LEAC classes).

LEAC Groups		CLC Classes
1	Artificial surfaces	1
2A	Arable land and permanent crops	2.1 + 2.2 + 2.4.1
2B	Pastures and mosaic farmland	2.3 + 2.4.2 + 2.4.3 + 2.4.4
2B1	Pastures	2.3
2B2	Mosaic farmland	2.4.2 + 2.4.3 + 2.4.4
3A	Forests and transitional woodland shrub	3.1 + 3.2.4
3A1	Standing forests	3.1
3A2	Transitional woodland and shrub	3.2.4
3B	Natural grassland, heathland, sclerophyllous vegetation	3.2.1 + 3.2.2 + 3.2.3
3C	Open space with little or no vegetation	3.3
4	Wetlands	4
5	Water bodies	5

These LEAC categories are defined for describing land cover changes that group CLC classes with similar land use and/or environmental characteristics. The agriculture class, for example, is split into 'Arable land and permanent crops' and 'Pastures and mosaic farmland'. Forests are also split into two classes: 'Standing forests' and 'Transitional woodland and shrub'. The latter mainly maps areas that have been recently felled or new plantations. By treating them as part of a more general class of forested land, normal forest rotations are not confused with the losses or gains of woodland that come about through deforestation or afforestation [49].

2.4. Land Cover Flows

While the extent of various land cover types is of high importance for policies and research, it is the land cover change that is of indicative value for the condition of ecosystems. This is because the change in a given land cover to another one is indicative for various anthropogenic and environmental pressures where policies can be developed to counteract negative impacts. Land-take, for example, is the conversion of non-urban areas to artificial urban surfaces, a process which destroys habitats and hence impacts biodiversity and increases pollution. Soil sealing, which is part of land-take, is an irreversible process where land is covered with impermeable material and as a result land loses several functions, such as flood protection, carbon sequestration, or the cooling effect in case of heatwaves. Another example for land cover change of high policy importance is the drainage of wetlands for agriculture use with important biodiversity hotspots being destroyed and where the emerging aerobic condition in soils causes the oxidation of organic matter releasing CO_2 into the atmosphere.

When it comes to land cover changes between two observation periods, the concept of land cover flows (LCFs) has been developed to facilitate transparent accounting. The Corine Land Cover has 44 classes; hence, the number of potential unique land cover change combinations could be large ($44 \times 43 = 1892$), although many combinations are impossible or at least improbable in practice. Therefore, they are grouped into meaningful change categories, i.e., flows, as a practical solution for transparent assessments and statistical analytics. LCFs are defined using a hierarchical structure up to three levels, describing different processes of land cover or land use changes. Several LCF matrices may be derived

depending on user needs. Below is an example of a possible grouping of land cover flows at level 1 hierarchy, which is used in the present paper for land accounts:

- LCF1—Urban land management: internal transformation of urban areas.
- LCF2—Urban residential expansion: land uptake by residential buildings altogether with associated services and urban infrastructure (classified in CLC111 and 112) from non-urban land (extension over sea may happen).
- LCF3—Expansion of economic sites and infrastructure: land uptake by new economic sites and infrastructure (including sport and leisure facilities) from non-urban land (extension over sea may happen).
- LCF4—Agriculture internal conversions: conversion between farming types. Rotation between annual crops is not monitored by CLC.
- LCF5—Conversion from other land cover to agriculture: expansion of agriculture land use.
- LCF6—Increase in forest land cover and other semi-natural areas: farmland abandonment and other conversions from agriculture activity or others in favor of forests or semi-natural land.
- LCF7—Forest internal land cover changes: conversions between forest classes or between transitional woodland and shrubs and forest.
- LCF8—Water body and wetland creation and management: creation of dams, reservoirs and wetlands, and possible consequences of the management of the water resource on the water surface area.
- LCF9—Changes in land cover due to natural and multiple causes: changes in land cover resulting from natural phenomena with or without any human influence, plus rare or not applicable changes.

For understanding level 2 and level 3 flows in more depth, with contextual description and the formation and consumption codes building a certain LCF, the reader may consult Appendices 1 and 2 in [52]. It is important to note that any groupings of land cover flows are possible based on the objectives of the research needs (e.g., [54,55]).

2.5. Reference Grid and Data Cube for Data Integration

The use of reference grids has been long recognized as key tool for the integration of heterogeneous sources of data. The standard codification of grid cells makes the reference grids suitable for splitting the territory into several regular pieces that can be used as reference units.

The 1 km^2 European Reference Grid (ERG) was adopted by several European stakeholders at the First Workshop on European Reference Grids in 2003 and it confirms with the INSPIRE geographical grid systems[5]. The coordinate reference system (CRS) of the reference grid is ETRS89-LAEA Europe, also known in the EPSG geodetic parameter dataset under the identifier "EPSG:3035". The geodetic datum is the European terrestrial reference system 1989 (EPSG:6258). The Lambert azimuthal equal area (LAEA) projection is centered at 10° E, 52° N. Coordinates are based on a false easting of 4,321,000 m, and a false northing of 3,210,000 m. Being based on an equal area projection, the accounting reference grid is suitable for generalizing data, statistical mapping and analytical work whenever a true area representation is required. Recommended grid resolutions are 100 m, 1 km, and 10 km.

In the reference grid the grid cells store the land cover information (i.e., the area of land cover classes) and complementary information to be used as reporting units or ancillary datasets for the assessments. Depending on the nature of the dataset or variable, the following additional information can be distinguished:

- Geographic dimensions: define the geographical unit that each cell belongs to (NUTS region, NUTS, UMZ, biogeographical unit, etc.)
- Thematic dimensions: define a physical characteristic of a grid cell, such as land cover type.
- Measures: numeric variables which can be aggregated by any combination of the data dimensions available in the accounting model. They can be biophysical vari-

ables (e.g., vegetation productivity), climate (precipitation and temperature) but also socioeconomic figures (e.g., population, unemployment, GDP, etc.).

The EEA-39 reference grid[6] consists of 5,885,212, 1 km cells, each of which can hold a data record in the LEAC database. The geographic and reference dimensions intersect with the 1 km^2 EEA reference grid, in order to give each grid cell a unique feature code (e.g., a NUTS3 code, a biogeographical region code, etc.).

Considering that some thematic layers have a higher resolution than 1 km^2 (e.g., Corine Land Cover is available at a resolution of 100 m^2), the combination of such information is carried out at 100 m^2 in this study. This way, it is possible to store, for instance, the different land cover classes and their surfaces for each grid cell, as well as their extent within any administrative boundary.

Land accounts in this paper were produced by creating a data cube. The system uses cloud infrastructure to integrate diverse data types in near real time. It is component based in order to accommodate flexibility and change, while new user requirements are shaped over time. The system reads spatial datasets into the reference grid where every cell has a unique identifier. These cells become the geo-reference identifier for every other spatial dataset integrated in the data cube. Through this common identifier the user can relate and calculate area statistics based on the same cell identifier. After reading the geospatial layers these are converted into a tabular format, i.e., dimension. All, or any user selected dimensions, can be then aggregated within user defined spatial units. These aggregated dimensions are then added into one database (a data cube), which can be created at a 10 × 10 m, 100 × 100 m, 1 × 1 km, or 10 × 10 km grid resolution. The data cube is stored in an SQL database that can be directly accessed by business intelligence software. Year-to-year changes or area statistics of land surface processes can then be calculated, and results plotted in a user-friendly, attractive, and interactive way.

For the present land accounting work, a so-called Land and Ecosystem Accounting (LEAC) cube was created. The cube contains the following dimensions:

- Administrative boundaries for EEA-38 and the UK;
- Biogeographical regions;
- Coastal zones;
- CLC accounting layers for the years 2000, 2006, 2012, and 2018;
- LCFs for the periods 2000–2006, 2006–2012, 2012–2018, and 2000–2018.

These dimensions can be flexibly complemented with any other thematic or stratification layers thereby enriching the accounting information to be deducted from the data cube.

3. Results

In the following sections, twenty-year land accounts are presented for Europe using the CLC accounting layers classified into the LEAC categories (see Section 2.3), and the derived land cover flows (Section 2.4) are used to explore the change between the LEAC categories. We present land cover accounts with various measurement units (km^2, ha, and % of the selected region), where statistics are given in tabular formats or visualized in interactive charts and maps. Land cover change accounts using the land cover flows present both consumption and formation statistics, which are only detailed on level 1 hierarchy in the present paper but can be accessed for all levels in the interactive dashboards. Furthermore, we go into more detail addressing possible land accounting applications: we explore land cover change density during 2000–2018, indicating the % of grid cells that changed their land cover type during a given accounting period. We present the spatial pattern of the dominant land cover flows for each region in the 39 countries, exploring local land cover change processes. To illustrate the power of land accounting, we map specific land cover flows related to agriculture area change on high spatial detail for the entire territory.

The land accounting statistics and the country fact sheets are presented in corresponding online dashboards [53,56], where all results in the following sections can be reproduced by the reader. The user is suggested to further explore the dashboard, as the vast amount

of information stored there cannot be presented here. The dashboards allow downloading all statistics in spreadsheet format for further analysis.

3.1. Land Cover Status Accounts

Figure 2 presents the 2018 land cover extent accounts for the EEA-39 region using the eight main LEAC categories. Statistics are given in % of the study area and in absolute values (km^2). Around 34% of all ecosystems in Europe are forested, covering approximately 2 million km^2. Forests have a major role in many ecosystem services, which include, among others, major carbon sinks and supply food, feed, and fiber for many economic activities; thus, their monitoring is of major importance. The second largest LEAC category in Europe are arable lands and permanent crops, ensuring Europe's food security, economic prosperity, and supporting farmland biodiversity. These agricultural areas cover almost 1.5 million km^2, which is around 25% of the area. Pastures and mosaic farmlands cover approximately 17% of the region, which is almost 973,000 km^2. Europe's natural grasslands, heathlands, and sclerophyllous vegetation, supporting biodiversity and other ecosystem services, cover only 8% of the area, approximately 495,000 km^2. Artificial surfaces, which affect ecosystem conditions, increase flood risk, and affect human health impacts, cover 4% of Europe.

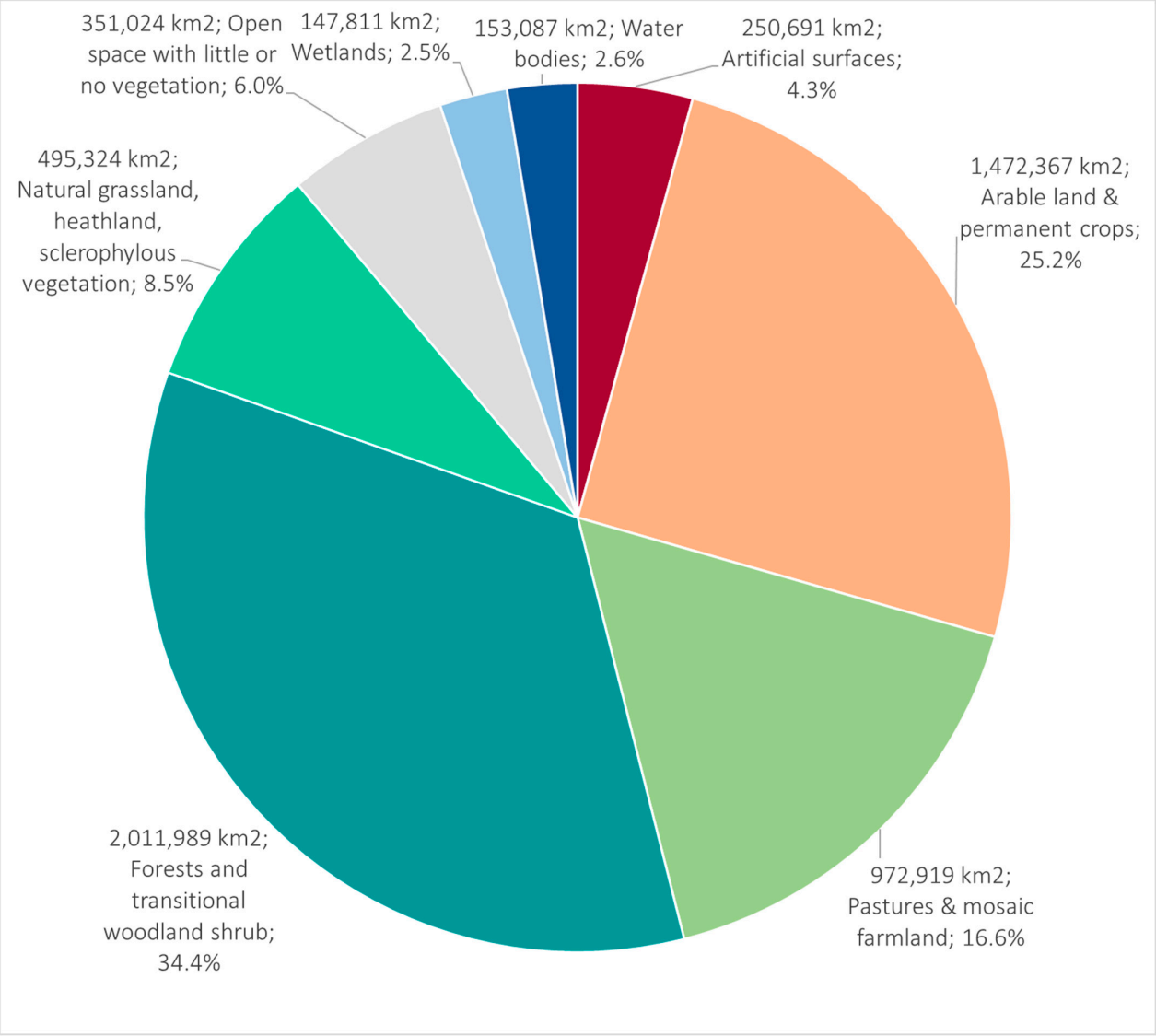


Figure 2. Distribution of LEAC classes in the study area for the year 2018, in km^2 and in % of the total study area.

Figure 3 displays the distribution of the four major LEAC categories in Europe by countries expressed in % of the country's area and Appendix B gives statistics by Europe's biogeographical regions. The Boreal region has the largest forested areas in both absolute values (612.000 km^2) as well as in % of the territory (69%). Forests, transitional woodlands, and shrubs mostly cover the Scandinavian region, reaching 72% of Finland and 66% of Sweden. A total of 62% of Montenegro's territory is covered by forests and transitional woodland, leading the Balkan and southern European countries. Local highly forested regions with more than 50% forest cover are, for example, the Landes forest in southwestern France, south-east Austria, Slovenia, and Northern Turkey. Most agricultural area (arable lands and permanent crops) are in the continental region, Hungary and Poland being in the lead with 52% and 43% of their area, respectively. Greece and Albania lead the countries with the largest natural grassland, heathland, and sclerophyllous vegetation areas with over 25% and 21% of their area, respectively. Ireland stands out among the European countries with its pastures and mosaic farmland area as 62% of the country has this category, and the next highest area in the proportion of the country is in Malta (49%) and the Netherlands (41%).

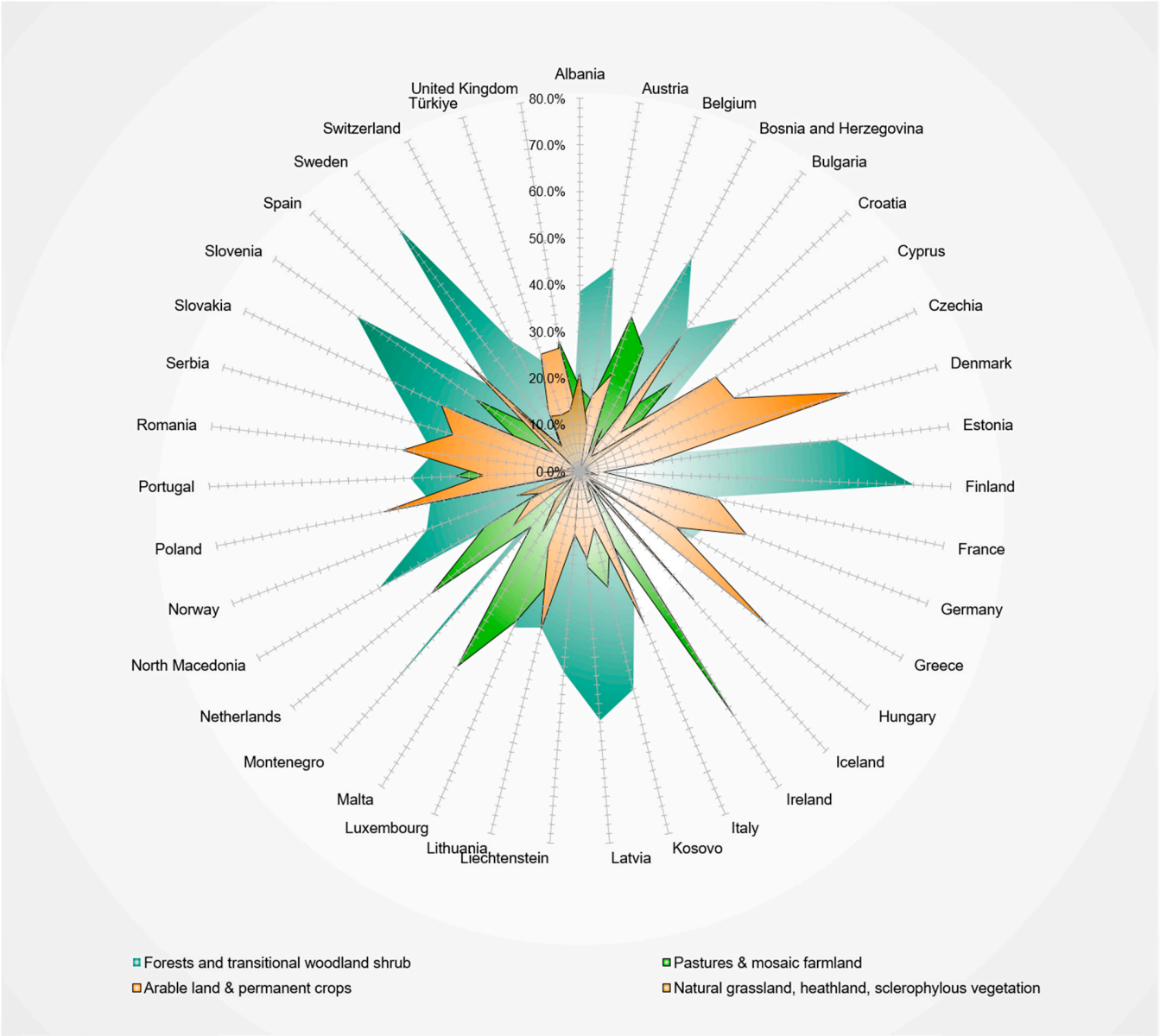
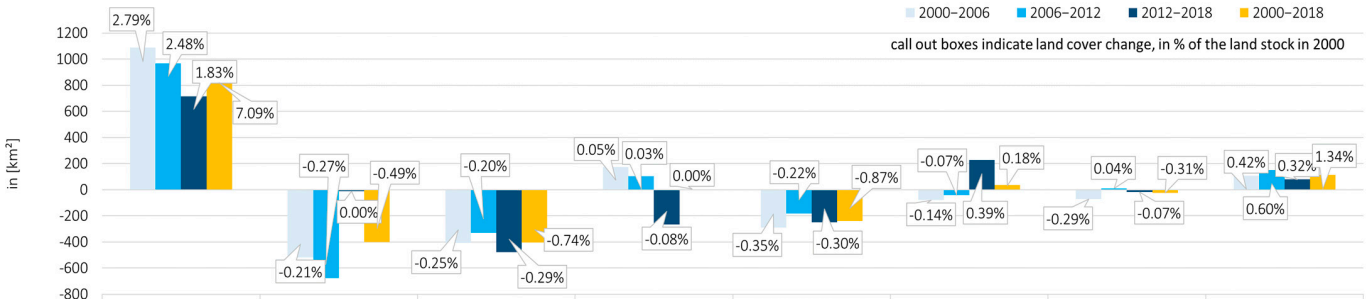


Figure 3. Distribution of the four main LEAC classes in the study area in % of the country's area.

3.2. Land Cover Status Accounts

The CLC accounting datasets, the reference layers, the reference grid and the accounting cube together allow the fast, transparent and efficient production of land accounting statistics and maps for the various accounting periods and for any spatial subset.

Figure 4 displays net change in each LEAC category in annual km^2 for the total period 2000–2018 (in yellow color) and within the three consecutive monitoring periods: 2000–2006, 2006–2012, and 2012–2018 (shown in different shades of blue). Positive numbers indicate that formation processes predominate, negative numbers indicate that consumption processes prevail. The main trends of net change per land cover type over the three periods are as follows: The formation within 'Artificial surfaces' is slowing down (1086 km^2/year, 966 km^2/year, and 715 km^2/year). The consumption of 'Arable land & permanent crops' decreases (517 km^2/year, 677 km^2/year, and 10 km^2/year). The net change within 'Forests and transitional woodland shrub' changed from formation during the first two periods (174 km^2/year and 103 km^2/year) to consumption during the last period (265 km^2/year). The consumption of grasslands and other herbaceous vegetation types fluctuated between 250 km^2/year and 290 km^2/year and the net change within 'Open space with little or no vegetation' changed from consumption during the first two periods (79.57 km^2/year and 42 km^2/year) to formation during the last period (226 km^2/year). The net of the land cover formations and consumptions indicate that Europe's land cover is under a dynamic change with the exception of forests and transitional woodlands where the net change is well below 0.1%. The net surface of natural grassland, heathland, and sclerophyllous vegetation and of pastures and mosaic farmland have decreased the most, with around 1% of these land covers available for use in 2018. Arable land and permanent crops has decreased by 0.5%. The largest gain was artificial surfaces with a 7% increase compared to artificial surfaces in the year 2000.



	Artificial surfaces (4.3% of EEA39 in 2018) Change 2000-2018: 16577 km2	Arable land & permanent crops (25.1% of EEA39 in 2018) Change 2000-2018: -7228 km2	Pastures & mosaic farmland (16.6% of EEA39 in 2018) Change 2000-2018: -7289 km2	Forests and transitional woodland shrub (34.4% of EEA39 in 2018) Change 2000-2018: 69 km2	Natural grassland, heathland, sclerophylous vegetation (8.5% of EEA39 in 2018) Change 2000-2018: -467 km2	Open space with little or no vegetation (6.0% of EEA39 in 2018) Change 2000-2018: 611 km2	Wetlands (2.5% of EEA39 in 2018) Change 2000-2018: -4335 km2	Water bodies (2.6% of EEA39 in 2018) Change 2000-2018: 2062 km2
2000–2006	1,086.7	-517.1	-407.6	173.6	-290.3	-79.6	-71.7	105.9
2006–2012	966.2	-677.1	-328.9	102.6	-181.9	-42.0	10.9	150.3
2012–2018	714.8	-10.4	-478.4	-265.0	-250.5	226.2	-17.0	80.3
2000–2018	922.6	-401.5	-405.0	3.7	-240.9	34.9	-25.9	112.2

Figure 4. Net change in the various land cover categories in the various accounting periods in the EEA-38 plus UK region, in km^2 and in % of the 2000 land cover extent.

Figure 5 top shows the spatial pattern of the 2000–2018 land cover change density over Europe and Figure 5 bottom displays a subset for France and Sweden selecting all three-land accounting sub-periods (2000–2006, 2006–2012, and 2012–2018). Each grid cell where any change occurred within the selected time period is colored based on the percentage of changes within the that grid cell, from light blue to red as follows: changes between 1 and 25% of the total grid area in blue, changes of 26–50% in green, changes of 51–75% in orange, and changes of 76–100% of the grid area in red. Figure 5 shows that during 2000–2018 hotspots of land cover changes in Europe were located in Portugal, France, and Sweden

(top), and that both in France and Sweden the most intense period was during 2006–2012 (Figure 5 bottom). In other areas in Europe the land cover remained fairly stable during the 20-year period. Note, Figure 5 intends to show all changes that happen in a land cover, not only land use change. This is an important detail because in the case of forestry, the land use remains the same, but forest management practices are the largest in Europe. These practices do not change the land use type, i.e., forest remains forest, but the land cover changes from trees to clear cut, transitional woodland, shrubland, etc. This is what the land cover change density map reflects and, for example, as Sweden has a large proportion of forests, forest management practices show up in a land cover change density map with a higher percentage of change. The same reasoning is valid for the Foret des Landes region in France (see the subset of France in Figure 5).

Table 2 displays the comprehensive summary of land cover change accounts for the EEA-39 region for the period 2000–2018 (Appendix C displays the summary table for the period 2000–2006, 2006–2012, and 2012–2018). It gives area statistics for the main land cover types at the beginning and at the end of the period, as well as the net changes disaggregated for their formation and consumption statistics. The consumption and formation codes are reported as the area sum of the whole period ("per period [km^2]"), as the annual change ("per year [km^2]"), in proportion of all land cover changes (row "% of LC change"), and in proportion of change in the given land cover (row "% of given LC"). Note, the total net area changes are always zero because land is finite and apart from land reclamation, the process of creating new land from oceans, seas, riverbeds or lake beds, is not addressed in this study.

Table 2. Land cover change accounts for the period 2000–2018 with formation and consumption accounts (see Appendix C for the other periods).

		Artificial Surfaces	Arable Land & Permanent Crops	Pastures & Mosaic Farmland	Forests and Transitional Woodland Shrub	Natural Grassland Heathland Sclerophyllous Vegetation	Open Space with Little or No Vegetation	Wetlands	Water Bodies	Total
beginning of the period	LC (km^2)	234,085	1,479,595	980,209	2,011,922	499,660	350,396	148,277	151,068	5,855,212
consumption	per period (km^2)	4286.29	24,388.46	15,265.19	156,795.24	6995.19	4812.87	1136.11	841.79	214,521.14
	per year (km^2)	238.13	1354.91	848.07	8710.85	388.62	267.38	63.12	46.77	11,917.84
	% of LC change	2.00%	11.37%	7.12%	73.09%	3.26%	2.24%	0.53%	0.39%	100.00%
	% of given LC	1.83%	1.65%	1.56%	7.79%	1.40%	1.37%	0.77%	0.56%	3.66%
formation	per period (km^2)	20,892.81	17,160.73	7975.50	156,862.50	2659.01	5440.30	669.56	2860.73	214,521.14
	per year (km^2)	1160.71	953.37	443.08	8714.58	147.72	302.24	37.20	158.93	11,917.84
	% of LC change	9.74%	8.00%	3.72%	73.12%	1.24%	2.54%	0.31%	1.33%	100.00%
	% of given LC	8.33%	1.16%	0.81%	7.80%	0.53%	1.55%	0.45%	1.89%	3.66%
net change	per period (km^2)	16,606.52	−7227.73	−7289.69	67.26	−4336.18	627.43	−466.55	2018.94	0.00
	per year (km^2)	922.58	−401.54	−404.98	3.74	−240.90	34.86	−25.92	112.16	0.00
	% of given LC	7.09%	−0.49%	−0.49%	0.00%	−0.87%	0.18%	−0.31%	1.34%	0.00%
end of period	LC (km2)	250,691	1,472,367	972,919	2,011,989	495,324	351,024	147,811	153,087	5,855,212

During 2000–2018, both the largest consumption processes of a given land cover and the largest proportion of changes within all consumption processes occurred in 'Forests and transitional woodland shrub' (consumption of 8711 km^2/year, which represents 73% of the total consumptions in Europe). However, the largest formation processes, and also the largest proportion of changes within all formation processes, also occurred in the 'Forests and transitional woodland shrub' LC type (formation of 8715 km^2/year), which represents 73.1% of the total formations in Europe. Therefore, the forest land cover in Europe in fact remained fairly constant (see beginning of period and end of period rows in Table 2), and these numbers indicate that it is the forest management practices within the forest land use category that dominate European forest land use and, in fact, all land use in Europe.

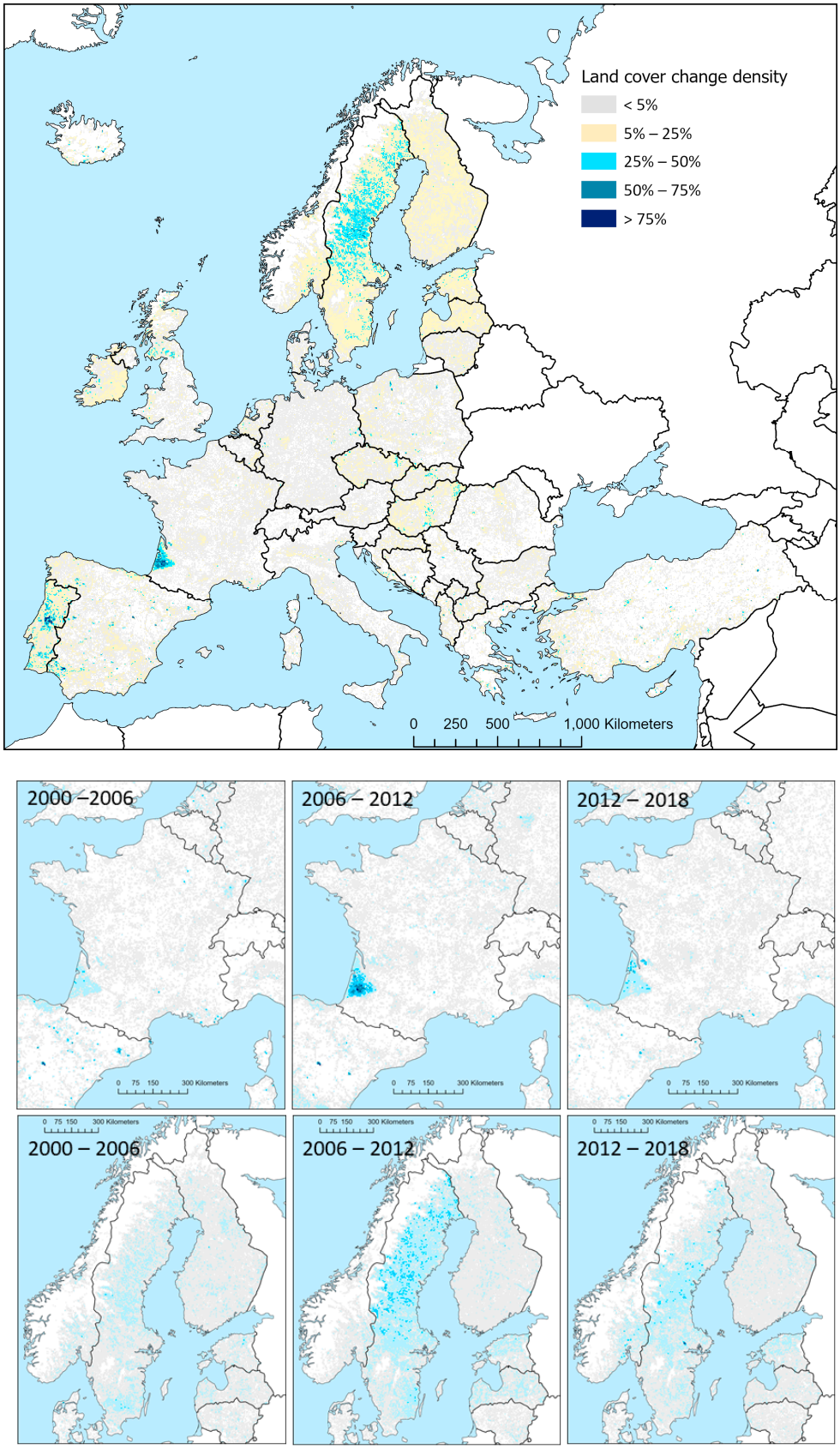


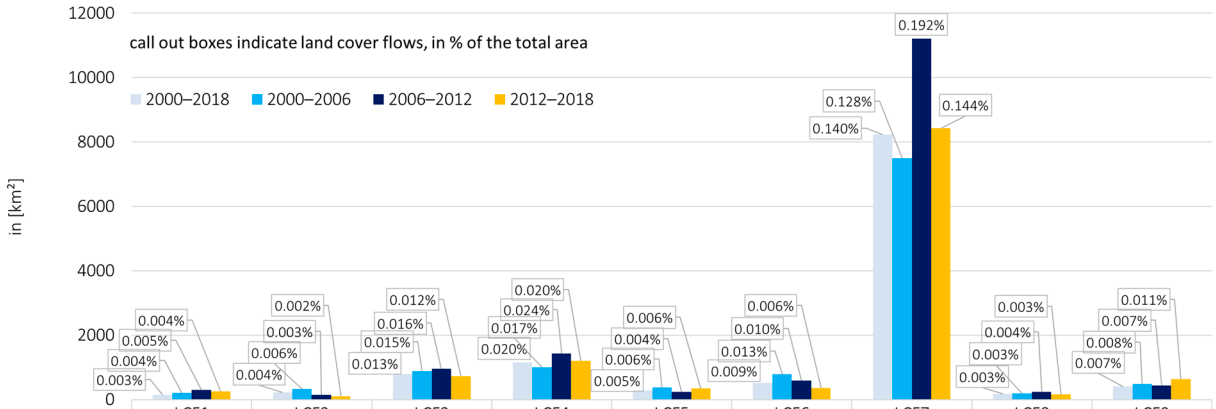
Figure 5. Land cover change density during 2000–2018. The 100 m accounting layers are aggregated within 5 km grids for better visibility. The % of grid cells that changed their land cover type during the accounting period is expressed in proportion of each 1 km accounting grid cell.

The largest positive change (i.e., formation) during 2000–2018 occurred within the 'Artificial surfaces' LC type (1160.7 km^2/year), which represents 8.3% of the total area of this land cover type and almost 10% of all land cover changes in this period. Artificial surfaces also decreased in some parts of Europe (see consumption) amounting to 238 km^2/year, but it was only 2% of all land cover changes. Still, the net change in artificial areas, i.e., the sum of the formations and consumptions amounted to 923 km^2/year increase. This means that during the 18 years period artificial areas in Europe increased from 234,085 km^2 to 250,691 km^2, thus 16,606 km^2 land was converted to artificial surfaces, which is roughly six times the area of Luxembourg. This increase in artificial surfaces was by far the highest in Europe, amounting to a 7% increase compared to the 2000 artificial areas, more than five times the second largest increase, which was creating more water bodies.

The largest negative net change occurred within 'Arable land & permanent crops' and 'Pastures & mosaic farmland', both decreasing roughly 400 km^2 annually due to consumption processes dominating formation processes. In fact, of all consumption processes, 11% happened on arable lands and permanent crops and 7% on pastures and mosaic farmlands, which together resulted in an approximately 14,500 km^2 net decrease in these important land cover types.

3.3. Land Cover Flows

Figure 6 compares the trends in the land cover flows between the accounting periods 2000–2006, 2006–2012, and 2012–2018 and the entire period 2000–2018 for the EEA38 + UK area in [km^2/year]. The trends in the LCFs over the three mentioned periods are relatively stable. Visible changes occur in 'LCF2: Urban residential expansion' where the values halved between the first two periods and keep decreasing (323.1 km^2/year, 147.2 km^2/year, and 106 km^2/year during the three periods, respectively) and in 'LCF6: Increase in forest land cover and other semi-natural areas', where the values nearly halved between the two periods 2000–2006 and 2012–2018, decreasing from 786.6 km^2/year to 356.8 km^2/year. There is an increase in 'LCF9: Changes of land cover due to natural and multiple causes' between the last two periods (435.43 km^2/year in 2006–2012, and 636.93 km^2/year in 2012–2018), which in most cases indicates the impact of wildfires. Within 'LCF7: Forest internal land cover changes' which represents changes covering the largest total area there was a sudden increase during the middle period (7502.44 km^2/year in 2000–2006, 11,213.66 km^2/year in 2006–2012, and 8428.31 km^2/year in 2012–2018).



	LCF1	LCF2	LCF3	LCF4	LCF5	LCF6	LCF7	LCF8	LCF9
2000–2018	152.2	225.2	783.3	1154.3	283.0	518.7	8223.3	179.8	398.1
2000–2006	206.2	323.1	884.4	1006.0	377.6	786.6	7502.4	188.0	487.9
2006–2012	294.5	147.2	949.0	1431.4	242.0	591.5	11213.7	238.2	435.4
2012–2018	250.6	106.0	731.3	1195.9	337.0	356.8	8428.3	165.7	636.9

Figure 6. Comparison of the land cover flows between the accounting periods 2000–2006, 2006–2012, 2012–2018, and the entire period 2000–2018 for the EEA39 area [in km^2/year].

Analyzing land cover flows on a grid cell level allows the understanding of the regional impact of land cover conversions. Figure maps the dominant land cover flows for the period 2000–2018. Each grid cell where any change occurred within the selected period is colored based on the land cover flow that dominated that grid cell, i.e., the majority of the process within that grid cell. The pie charts in Figure 7 show the distribution of the main land cover flows (LCF1–LCF9) in both km^2 and percentages of all land cover flows (i.e., adding up to 100%) for the 2000–2018 accounting period. During that period the total land cover change effected 214,521 km^2, which is also shown in Table 2, detailing the land cover change accounts (see column total formation or total consumption).

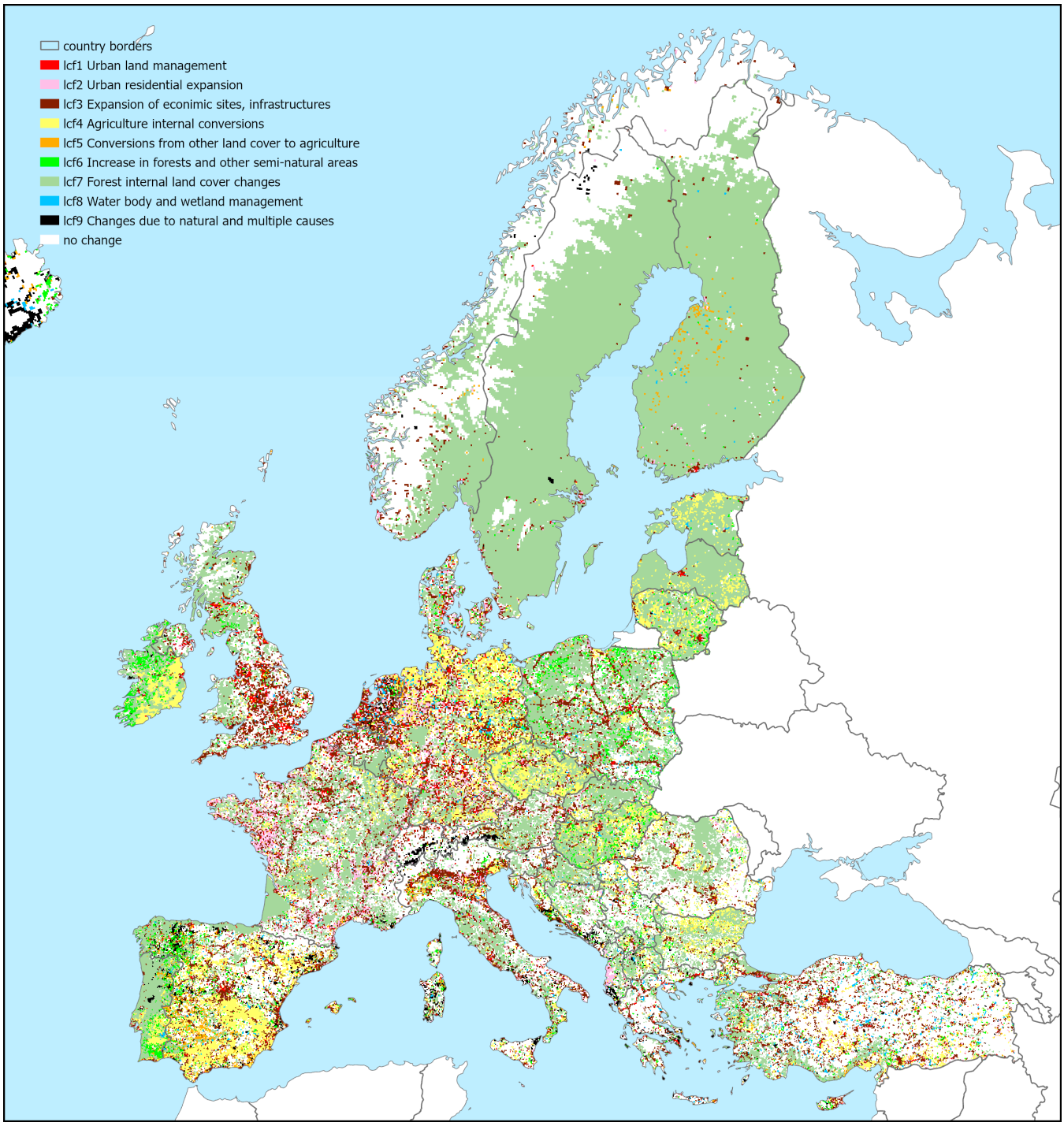


Figure 7. *Cont.*

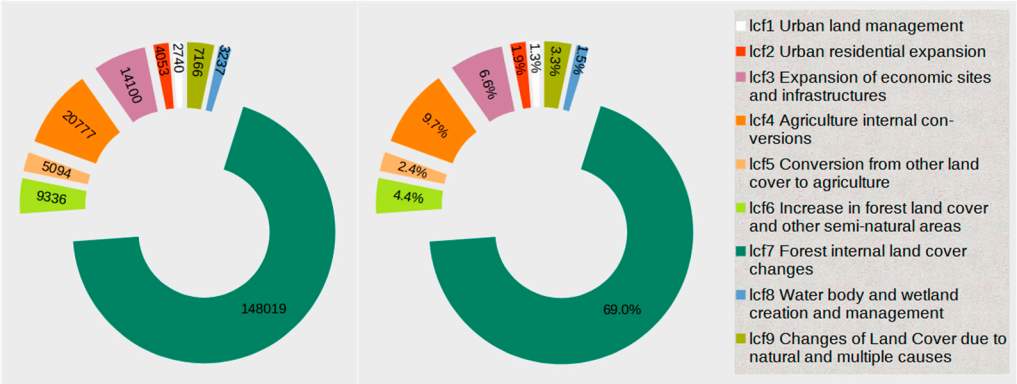


Figure 7. Top—map of dominant land cover flows (LCFs) for the period 2000–2018 in a 1 × 1 km grid. Each grid is colored based on the dominant land cover flow (i.e., the majority of the category). LCF1–LCF9 are explained in the legend as well as in chapter 2.4. Bottom—share of dominant land cover flows for the period 2000–2018 in km^2 and in % of the study area.

During 2000–2018, the land cover flow covering the largest total area was 'LCF7: Forest internal land cover changes' with 148,017 km^2 (69% of all land cover flows), mostly concentrating in the Nordic countries due to the large proportion of forests in these areas. This was mostly in Sweden, Norway, and Finland, where more than 90% of the land cover changes happened within their forests (Figure 8), whereas in Latvia and Slovakia, forest management accounted for more than 80% of the land cover changes. Other large land cover changes occurred due to agriculture internal conversions (LCF4, 20,777 km^2), and thus agriculture land management, which represented almost 10% of all changes (Figure 7). Countries where agricultural management dominated all land cover changes were Czechia (over 50% of the changes), Ireland and Germany (approximately 40% of all land cover changes).

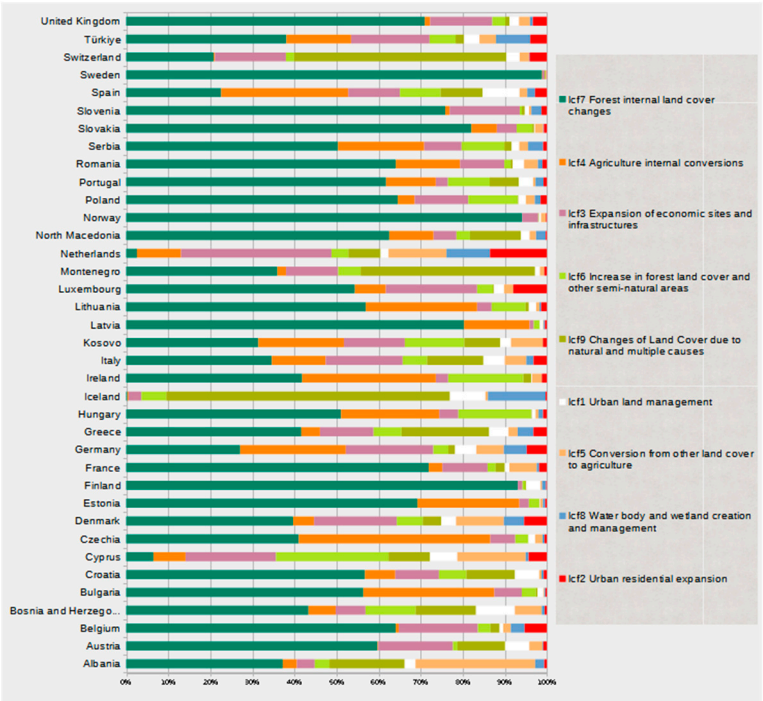


Figure 8. Proportion of the land cover flows (LCFs) in European countries, for the period 2000–2018 (in % of the country area).

The land cover flow "expansion of economic sites and infrastructures" (LCF3) was the third largest process in Europe and that took place over 14,100 km^2 (around 7% of all LCF), taking land from other land cover types (Figure 7). This land-take process mostly happened in the Netherlands (36% of all land-take processes in the country) and was around 20% of all land conversion processes in Cyprus, Denmark, Germany, and Luxembourg (Figure 8). The increase in forests and semi-natural areas (LCF6) only happened on 9336 km^2, which was slightly over 4% of all land cover changes. Cyprus led the way in creating these green areas, accounting for almost 27% of all land cover processes in the country, followed by Hungary and Ireland with 17%. However, all together, very few green areas were created in Europe, concerning the fact that urban residential expansion was over 4000 km^2, which, together with the expansion of economic sites and infrastructure, impacted over 18,000 km^2. This urban sprawl was also the greatest in the Netherlands (13% of land cover flows), followed by Denmark and Germany, where urban sprawl accounted for around 5% of all land use changes.

3.4. Land Use Drivers of Land Cover Change

Another important element is assessing the different land use processes that have caused land cover to change and analyzing which classes have gained or lost area at the expense of other classes. In other words, what is interesting is analyzing not only the quantitative figures of changes, but also the drivers behind those changes (from which classes and/or to which classes a specific transition has occurred). Combining the land cover flows with the LEAC classes allows for the understanding of the drivers behind the change in land cover. Table 3 shows the area changes (in km^2) of the LEAC classes (columns) between 2000 and 2018 and the rows of the tables break down these changes according to the various land cover flow processes. The top part of Table 3 summarizes the consumption processes, whereas the bottom part details the formation processes.

Table 3. Consumption and formation of the LEAC classes by the various land use change processes (land cover flows) during 2000–2018. Values are presented in km^2.

	Arable Land & Permanent Crops	Artificial Surfaces	Forests and Transitional Woodland Shrub	Natural Grassland, Heathland, Sclerophylous Vegetation	Open Space with Little or No Vegetation	Pastures & Mosaic Farmland	Water Bodies	Wetlands
				Consumptions				
lcf1	−42	−2652	−5	−9	−1	−30	−2	0
lcf2	−1837	0	−283	−149	−35	−1747	−1	−2
lcf3	−6222	−197	−2587	−1172	−331	−3348	−129	−113
lcf4	−13,181	0	0	−663	0	−6933	0	0
lcf5	0	−685	−2424	−926	−612	0	−54	−392
lcf6	−2242	−422	0	−2264	−1575	−2402	−12	−419
lcf7	0	0	−148,019	0	0	0	0	0
lcf8	−834	−242	−600	−306	−387	−721	−75	−72
lcf9	−32	−88	−2878	−1505	−1872	−84	−568	−137
Total consumption	−24,388	−4286	−156,795	−6995	−4813	−15,265	−842	−1136
				Formations				
lcf1		2740						
lcf2		4053						
lcf3		14,100						
lcf4	14,928			196		5653		
lcf5	2233			983		1878		
lcf6			8843	92	39	362		
lcf7			148,019					
lcf8					75		2701	461
lcf9	1	0	1	1388	5327	82	160	208
Total formation	17,161	20,893	156,863	2659	5440	7976	2861	670
Net change	−7228	16,607	67	−4336	627	−7290	2019	−467

Lcf1 = urban land management; lcf2 = urban residential expansion; lcf3 = expansion of economic sites and infrastructure; lcf4 = agriculture internal conversions; lcf5 = conversion from other land cover to agriculture; lcf6 = increase in forest land cover and other semi-natural areas; lcf7 = forest internal land cover changes; lcf8 = water body and wetland creation and management; lcf9 = changes in land cover due to natural and multiple causes.

The net change in artificial surfaces was almost 17,000 km^2, which can also be read from Table 2. The "Formations" section of Table 3 also explains that the major part, 14,100 km^2, of the increase in artificial surfaces was due to lcf3, i.e., the expansion of economic sites and infrastructure. Table 3 also explains where these processes took place, i.e., where the sprawl of economic sites and infrastructure consumed other land cover. This can be found in the "Consumptions" part of Table 3, in row lcf3, where, summing the km^2 consumptions of all LEAC categories, we receive the same 14,100 km^2 as in the formation section of artificial surfaces due to lcf3. The land accounting statistics indicate that the majority of the sprawl of economic sites and infrastructure was on arable land and permanent crops, converting 6222 km^2 to artificial surfaces. Another large consumption due to lcf3 took place on "Pastures and mosaic farmland" where 3348 km^2 land was converted to economic infrastructure. "Forests and transitional woodland, shrub" lost 2587 km^2 to the expansion of economic infrastructure and 1172 km^2 of natural grasslands, heathland, and sclerophyllous vegetation was converted to artificial surfaces through lcf3. Urban residential expansion (lcf2) happened over 4053 km^2 and mostly impacted "Arable land and permanent crops" and "Pastures and mosaic farmlands" where a sum of approximately 3600 km^2 was converted to artificial surfaces.

During the period 2000–2018, 24,388 km^2 of arable land were transformed, and a large portion of arable land and permanent crop changes were internal conversions (lcf4), e.g., crop rotations, converting orchards or olive plantations to arable lands, or the opposite changes. The increase in forest land cover and other semi-natural areas (lcf6) happened mostly in forests and transitional woodland, with shrubs creating 8843 km^2 of these green areas. From the consumption section, we can understand that the increase in forest land cover and other semi-natural areas (lcf6) mostly used arable lands and permanent crops (2242 km^2), natural grassland, heathland, and sclerophyllous vegetation (2264 km^2), open spaces with little or no vegetation (1575 km^2), and pastures and mosaic farmland (2402 km^2).

The changes in the land cover classes in Table 3 can be further analyzed regionally by mapping the differences in the formation and consumption processes for each grid cell. In this paper, we map and analyze the spatial pattern of net changes in arable land and permanent crops between 2000 and 2018 (Figure 9) together with their main contributing processes (Figures 10 and 11). Arable land and permanent crops cover 25% of Europe (Figure 3), and during the 20-year period this land cover lost most surface area (Figure 4). Hence, analyzing the net gains and losses of this large land cover through the land cover flows gives us insight into the "to" and "from" conversion processes and the connection between changes in arable land and permanent crops and other land covers.

The largest hotspots of arable land and permanent crop losses were observed around major capitals and major cities, indicating that the drivers behind the losses were the sprawl of urban areas and of economic infrastructure. While in Scandinavia the loss of arable land and permanent crops was not significant, some countries in central, western, and southern Europe show distinct agricultural area losses. Dominant patterns with decreasing agricultural areas are apparent in Poland, the Netherlands, the UK, Ireland, Hungary, the interior and southern parts of Spain and southern Portugal. In Poland and the Netherlands, around 40% of the loss of arable land and permanent crops was due to the sprawl of economic sites and infrastructure (lcf3, Figure 10), which was responsible for little more than 70% of the loss in the UK. In Spain, Portugal, and Ireland, more than 70% of the loss was due to agriculture internal conversions (lcf4), which was a major driver in Hungary as well. In Hungary, Poland, Lithuania, and Finland, the increase in forest land cover and semi-natural areas also contributed to the loss of arable lands and permanent crops with 15% of the conversions from agriculture creating these green spaces.

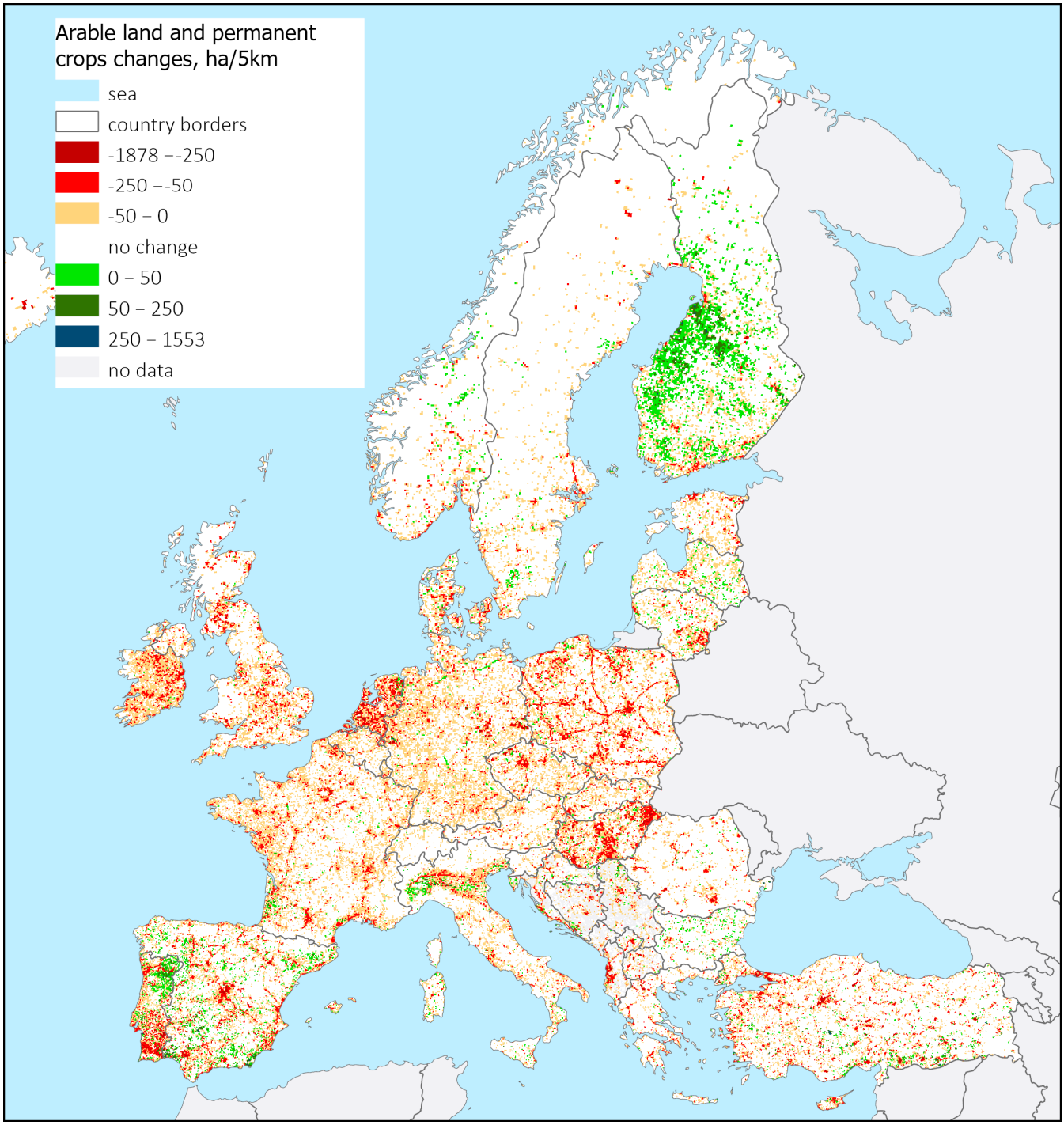


Figure 9. Arable land and permanent crops gain and losses during the period 2000−2018, EEA-39.

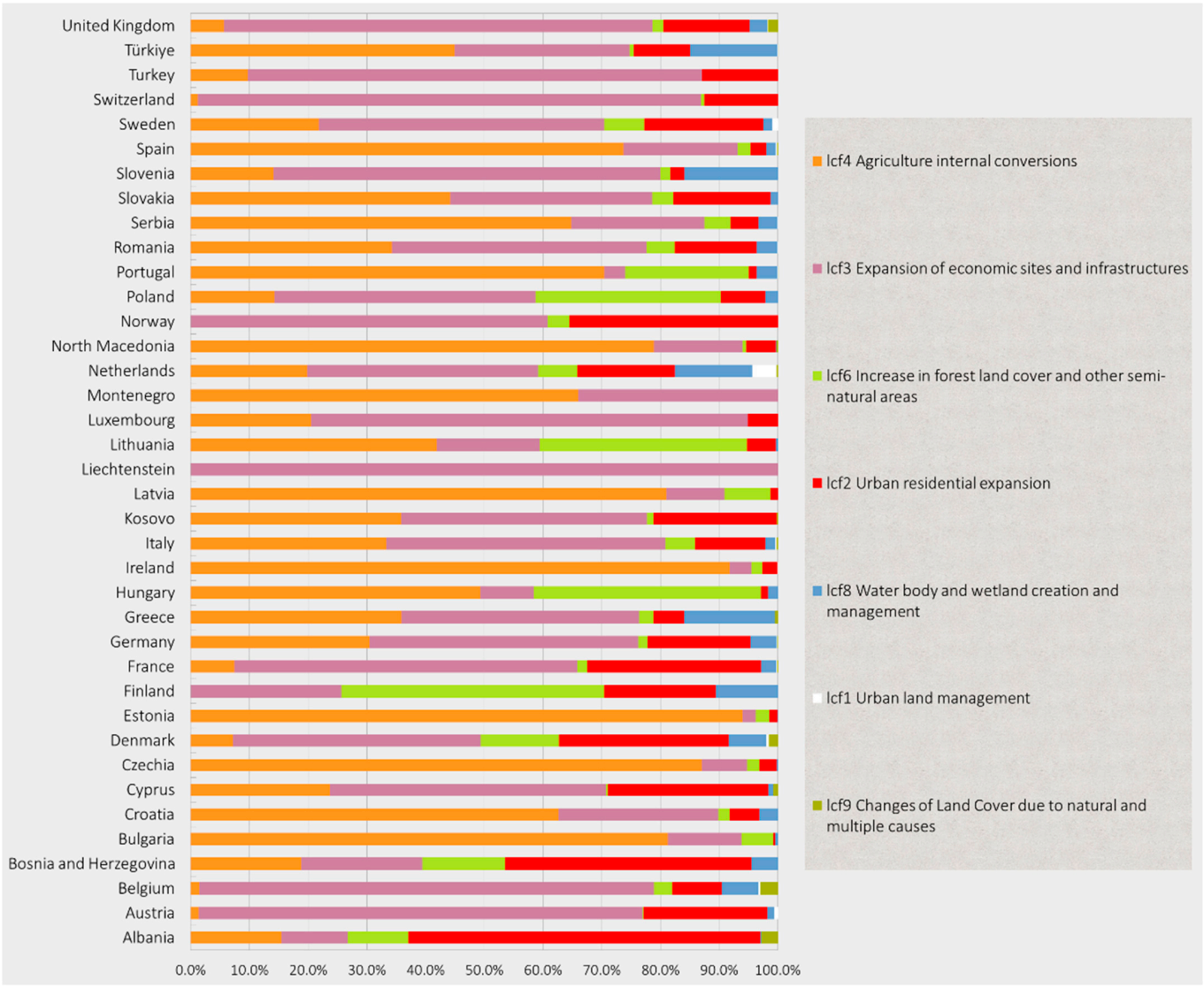


Figure 10. Consumption of arable land and permanent crops in the EEA-38 + UK region, during 2000–2018 by the various land cover flows.

The largest hot spots of arable land and permanent crop gains were observed in Spain, northern Portugal, southern Turkey, the Baltic countries (in particular Latvia), and from the south to central Finland (Figure 9). While in the Baltic countries of Estonia, Latvia, and Lithuania, arable land was created almost exclusively by agriculture internal conversions (converting pastures), in central Finland, all the gains were due to converting other land cover to agriculture. And a more in-depth investigation of land accounts (see tab 6 in [57]) shows that in Finland, 69% of the arable land and permanent crops-gained processes converted forested lands and 31% converted wetlands. In Portugal and Spain, the main reasons were the conversion of pastures, forest, and semi-natural land.

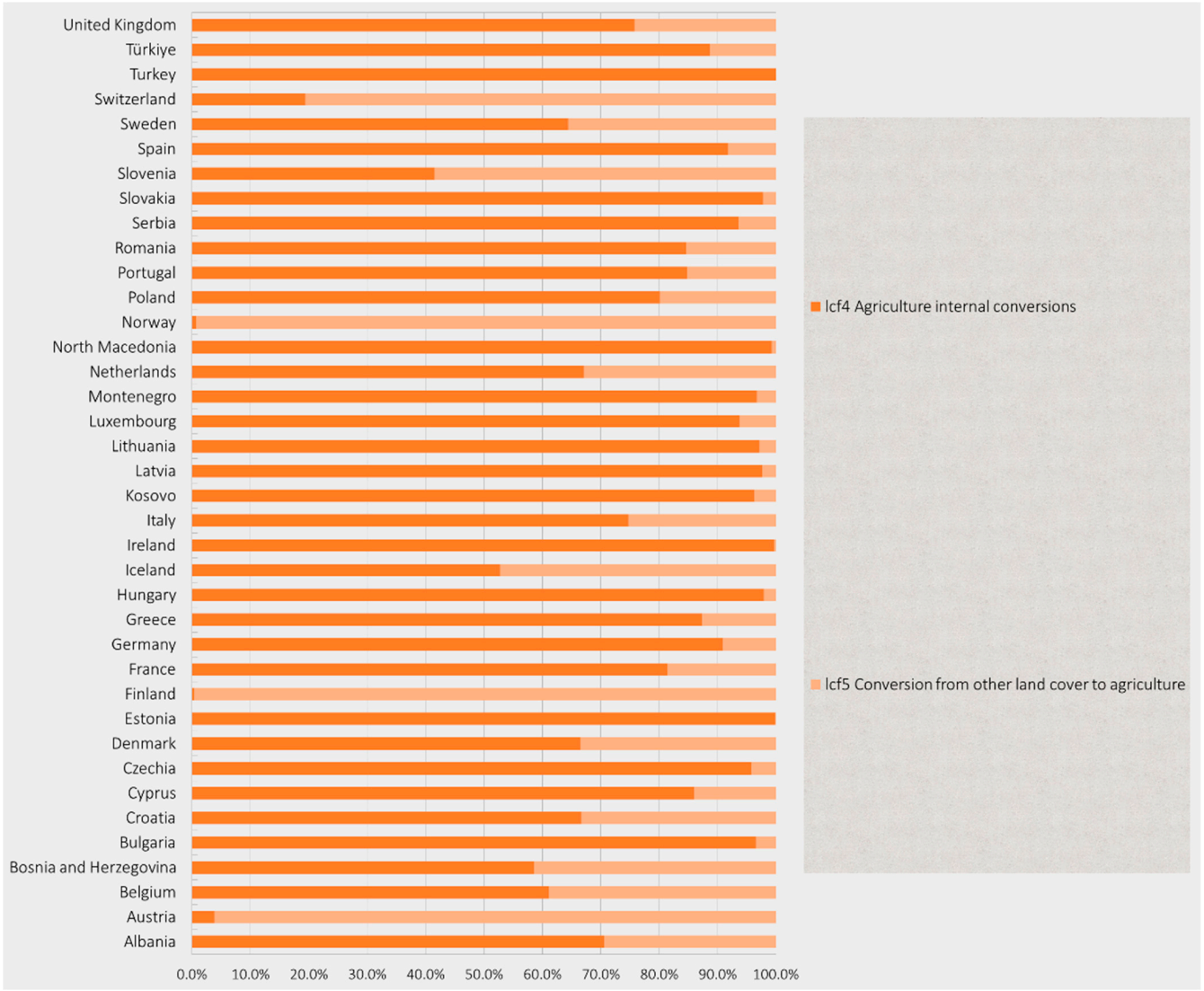


Figure 11. Formation of arable land and permanent crops in the EEA-38 + UK region, during 2000–2018 by the various land cover flows.

4. Discussion

Europe's land resources are under pressure—about 80% of Europe's land surface has been shaped by human activities, such as being covered with buildings, roads, industrial infrastructure, or used for agriculture and forestry [57]. The driving forces of change are socio-economic pressures, such as the need for land surface for industrial and economic activities, urban sprawl, and the need for food, fiber, and feed. The way we use land constitutes one of the main drivers of environmental degradation and climate change. Under sustainable conditions, land is used in a multi-functional way to satisfy economic, social, and environmental needs. When multi-functionality is interrupted by non-sustainable use, the delivery of ecosystem services is hampered. The negative impacts of intensive and non-sustainable land use may reach a level where the land starts to degrade, in some cases reaching an irreversibly degraded state.

The status and change in land and ecosystems are important elements to inform the development and implementation of policies that impact on these components of natural capital, such as water, climate, agricultural land, forest, biodiversity, and regional planning. Key EU policy documents, i.e., the Eight Environment Action Programme and the Biodiversity Strategy to 2030, set the development of natural capital accounts in the EU, with a focus on ecosystems and their services, including land, as their main objectives.

For serving the European policies especially on natural capital, climate change mitigation, adaptation, and biodiversity, the production of ecosystem and land accounts, their spatial location, and the drivers of change are important elements which inform us on the status of Europe's environment. The land and ecosystem accounting (LEAC) method presented here quantifies the land cover extent as stocks and quantifies the changes (increase and decrease in the extent) as flows between one time-step to another. The LEAC methodology and datasets align with the SEEA-CF internationally agreed-upon standards and the approach also supports the calculation of ecosystem accounts as proposed by the United Nations Statistics Department on 'Experimental Ecosystem Accounting (SEEA-EEA).

Using the described method and the geospatial time series, we have developed a vast amount of information can be derived on land cover change due to land use change. The net of the land cover formations and consumptions during 2000–2018 in Europe indicate that on the continental level, land cover extent is quite stable. The net surface of natural grassland, heathland, and sclerophyllous vegetation, of pastures and mosaic farmland, and of arable land and permanent crops have decreased the most, but only by 1% or their 2000 area. Still, this decrease together resulted in approximately 15,000 km^2 of net loss of this important land cover resulting from consumption processes dominating formation processes. In fact, of all consumption processes, 11% happened on arable lands and permanent crops, and 7% on pastures and mosaic farmlands. Next to the loss of the extent of these areas, large land cover changes occurred within these areas due to agriculture internal conversions; hence, agriculture land management, which represented almost 10% of all changes. Countries where agricultural management dominated all land cover changes included Czechia (over 50% of the changes), Ireland, and Germany (approx. 40% of all land cover changes).

The extent of forests and transitional woodlands net change during 2000–2018 was well below 0.1% in Europe, resulting from almost the same amount of formation and consumption processes of this land cover at the continental level. However, both the largest consumption processes and the largest formation processes in Europe occurred in this land cover type, with consumption and formation approximately 9000 km^2/year, representing 73% of all consumption and formation processes. Hence, while the forest land cover extent in Europe remained fairly constant (see also Table 2), the formation and consumption numbers indicate that it is the forest management practices within the forest land use category that dominates European land use. This process was predominantly in Sweden, Norway, and Finland, where more than 90% of the land cover changes happened within their forests, whereas in Latvia and Slovakia forest management, it accounted for more than 80% of the land cover changes.

The only land cover with a large, and by far the largest, change in its extent during 2000–2018 was artificial surfaces, with a 1160.7 km^2 annual increase, which is almost 10% of all land cover increases in this period. While we observed consumption of artificial surfaces as well, which can be attributed to land recycling, it was very little compared to the formation processes, resulting in a 7% net increase compared to artificial surfaces in the year 2000. The net increase in artificial areas, i.e., the sum of the formations and consumptions amounted to 923 km^2/year; hence, during the 18-year period, sealed areas in Europe increased by 16,606 km^2, which is roughly six times the area of Luxembourg. The processes that create artificial areas are urban sprawl (lcf2) and the sprawl of economic sites and infrastructure (lcf3), which were the third largest processes in Europe (after agriculture and forest internal conversions), converting 18,000 km^2 of land. Urban sprawl and the sprawl of economic sites and infrastructure mostly happened in the Netherlands (approx. 50% of all land-take processes in the country) and were around 25% of all land conversion processes in Denmark and Germany.

The major fraction of the sprawl of economic sites and infrastructure was on arable land and permanent crops converting 6222 km^2 to artificial surfaces and on "Pastures and mosaic farmland" where 3348 km^2 land was converted to economic infrastructure. Forests and transitional woodland, shrub lost 2587 km^2 to the expansion of economic infrastructure and 1172 km^2 of natural grasslands, heathland and sclerophyllous vegeta-

tion was converted to artificial surfaces through lcf3. Urban residential expansion (lcf2) happened over 4053 km^2 and mostly impacted "Arable land and permanent crops" and "Pastures and mosaic farmlands" where a sum of approximately 3600 km^2 was converted to artificial surfaces.

The core data set underpinning the presented land and ecosystem accounting system is Corine Land Cover accounting layers. The CLC accounting layers enable the consistent assessment of land accounts for the 20 years period of 2000–2018. The CLC accounting layers may be freely integrated with other datasets, such as biogeographical regions, administrative boundaries, geo-physical variables such as elevation classes, other land use information such as landscape fragmentation or socio-economic variables such as population density to understand the magnitude, the drivers and the impacts of land cover changes. The EU Copernicus Earth Observation Programme and the increasing collection of geospatial data on ecosystems and biodiversity will increase the data sets available for land and ecosystem accounting manifold. The presented land and ecosystem accounting approach can flexibly incorporate any new or updated datasets on demand.

The presented data cube approach allows the efficient, transparent, repeatable, and quality-controlled integration of geospatial datasets in accounting statistics. By converting geospatial datasets into analysis-ready formats, the workflow is faster and more effective than performing GIS analysis on raw data. If, for example, a new version of one of the input geospatial datasets becomes available, updating the accounting cubes is efficient as only the dimension in question needs to be renewed. Furthermore, as the dimensions are stored in the cloud environment, the use of the same inputs is ensured in the case of several existing versions of the same input dataset. This allows the system to deal with the increasing set of input data sets and analytical demands efficiently. With the increasing number of high-spatial and -temporal resolution Earth observation images, data are becoming bigger and bigger in size, in many cases reaching several hundreds of terabytes. The management and processing of big data is therefore a necessity in order to ensure fast, efficient, up-to-date, and state-of-the-art policy support. This is the way forward in geospatial environmental accounting systems and will allow more versatile support for a wider range of policy questions.

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Data Availability Statement: The Corine Land Cover accounting layers are publicly available via the following link: https://www.eea.europa.eu/data-and-maps/data/corine-land-cover-accounting-layers/clc-accounting-layers. Accessed on 12 August 2024.

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Conflicts of Interest: Author Erika Orlitova was employed by the company Gisat s.r.o. Authors Gergely Maucha and Barbara Kosztra were employed by the company Lechner Non-profit Ltd. Authors Mirko Gregor and Manuel Löhnertz were employed by the company Space4environment. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Processing Steps to Produce the CLC Accounting Layers

The accounting layers were produced with the following workflow:

Step 1: Include formation information from CLC-change layers into current CLC2018 status by creating CLC2018 accounting layer.

1. Overwrite CLC2018 with code_2006 from CLC-change 2000–2006. Intermediate result: A1_CLC2018.
2. Overwrite A1_CLC2018 with code_2012 from CLC-change 2006–2012. Intermediate result: A2_CLC2018.
3. Overwrite A2_CLC2018 with code_2018 from CLC-change 2012–2018. Result: CLC2018 accounting layer.

Step 2: Create CLC2012 accounting by including consumption information (code 2012 from CLC-change 2012–2018) into CLC2018 accounting layer. Result: CLC2012 accounting layer.

Step 3: Create CLC2006 accounting by including consumption information (code 2006 from CLC-change 2006–2012) into CLC2012 accounting layer. Result: CLC2006 accounting layer.

Step 4: Create CLC2000 accounting by including consumption information (code_2000 from CLC-change 2000–2006) into CLC2006 accounting layer. Result: CLC2000 accounting layer.

The Corine Land Cover accounting layers are publicly available via the following link: https://www.eea.europa.eu/data-and-maps/data/corine-land-cover-accounting-layers/clc-accounting-layers. Accessed on 12 August 2024.

The accounting layers can be explored as web map services under the following links: Land/CLC_accounting_layer_2000 (ImageServer) (europa.eu); Land/CLC_accounting_layer_2006 (ImageServer) (europa.eu); Land/CLC_accounting_layer_2012 (ImageServer) (europa.eu); Land/CLC_accounting_layer_2018 (ImageServer) (europa.eu). Accessed on 12 August 2024.

Appendix B. Land Cover Extent Accounts for the Year 2018 Aggregated for Biogeographic Regions

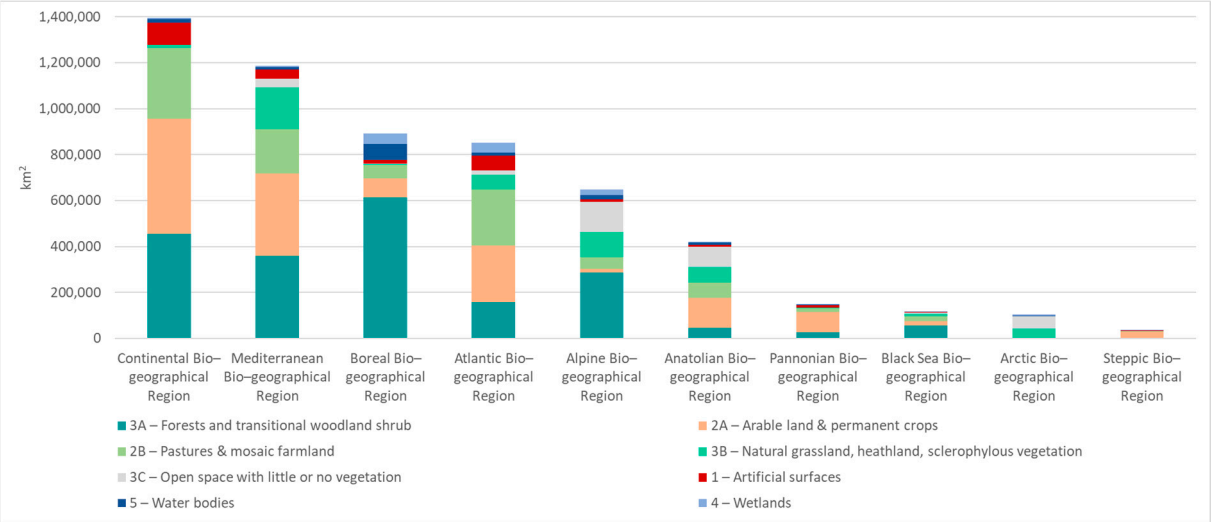


Figure A1. *Cont.*

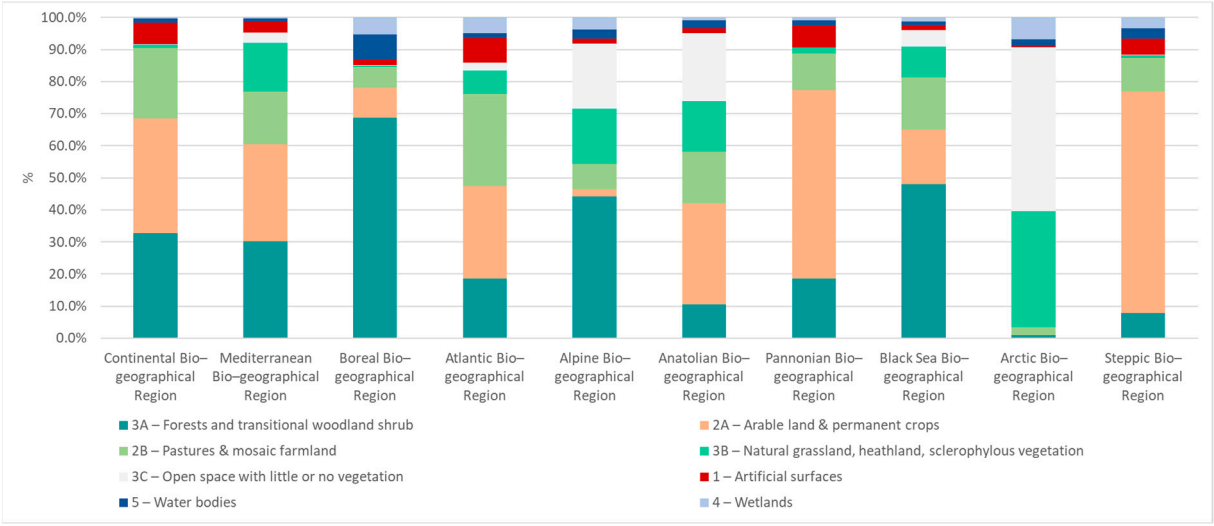


Figure A1. Distribution of LEAC classes in the study area (EEA-39 region) by biogeographic regions, for the year 2018. Top chart in km^2 of the study area, bottom chart in % of the biogeographic region.

Appendix C. Land Cover Extent Accounts for the Periods of 2000−2006, 2006−2012, and 2012−2018

begining of the period		Artificial surfaces	Arable land & permanent crops	Pastures & mosaic farmland	Forests and transitional woodland shrub	Natural grassland, heathland, sclerophylou.	Open space with little or no vegetation	Wetlands	Water bodies	Total
	LC [km²]	234,085	1,479,595	980,209	2,011,922	499,660	350,396	148,277	151,068	5,855,212
consumption	per period [km²]	1,961.60	8,527.69	5,141.29	48,540.55	2,913.89	2,461.75	655.04	370.64	70,572.45
	per year [km²]	326.93	1,421.28	856.88	8,090.09	485.65	410.29	109.17	61.77	11,762.08
	% of LC change	2.78%	12.08%	7.29%	68.78%	4.13%	3.49%	0.93%	0.53%	100.00%
	% of given LC	0.84%	0.58%	0.52%	2.41%	0.58%	0.70%	0.44%	0.25%	1.21%
formation	per period [km²]	8,482.07	5,424.95	2,695.80	49,582.15	1,172.04	1,984.36	225.11	1,005.97	70,572.45
	per year [km²]	1,413.68	904.16	449.30	8,263.69	195.34	330.73	37.52	167.66	11,762.08
	% of LC change	12.02%	7.69%	3.82%	70.26%	1.66%	2.81%	0.32%	1.43%	100.00%
	% of given LC	3.53%	0.37%	0.28%	2.46%	0.23%	0.57%	0.15%	0.67%	1.21%
net change	per period [km²]	6,520.47	-3,102.74	-2,445.49	1,041.60	-1,741.85	-477.39	-429.93	635.33	0.00
	per year [km²]	1,086.75	-517.12	-407.58	173.60	-290.31	-79.56	-71.66	105.89	0.00
	% of given LC	2.79%	-0.21%	-0.17%	0.05%	-0.35%	-0.14%	-0.29%	0.42%	0.00%
end of period	LC [km²]	240,605	1,476,492	977,764	2,012,964	497,918	349,919	147,847	151,703	5,855,212

Figure A2. Land cover extent accounts for the periods of 2000−2006.

begining of the period		Artificial surfaces	Arable land & permanent crops	Pastures & mosaic farmland	Forests and transitional woodland shrub	Natural grassland, heathland, sclerophylou.	Open space with little or no vegetation	Wetlands	Water bodies	Total
	LC [km²]	240,605	1,476,492	977,764	2,012,964	497,918	349,919	147,847	151,703	5,855,212
consumption	per period [km²]	2,546.49	10,037.77	5,744.22	69,987.22	2,200.24	2,181.98	213.51	345.15	93,256.58
	per year [km²]	424.42	1,672.96	957.37	11,664.54	366.71	363.66	35.59	57.53	15,542.76
	% of LC change	2.73%	10.76%	6.16%	75.05%	2.36%	2.34%	0.23%	0.37%	100.00%
	% of given LC	1.06%	0.68%	0.59%	3.48%	0.44%	0.44%	0.14%	0.23%	1.59%
formation	per period [km²]	8,343.93	5,974.97	3,770.69	70,602.83	1,108.86	1,929.73	278.62	1,246.95	93,256.58
	per year [km²]	1,390.66	995.83	628.45	11,767.14	184.81	321.62	46.44	207.83	15,542.76
	% of LC change	8.95%	6.41%	4.04%	75.71%	1.19%	2.07%	0.30%	1.34%	100.00%
	% of given LC	3.39%	0.40%	0.39%	3.51%	0.22%	0.39%	0.19%	0.82%	1.59%
net change	per period [km²]	5,797.44	-4,062.80	-1,973.53	615.61	-1,091.38	-252.25	65.11	901.80	0.00
	per year [km²]	966.24	-677.13	-328.92	102.60	-181.90	-42.04	10.85	150.30	0.00
	% of given LC	2.41%	-0.28%	-0.13%	0.03%	-0.22%	-0.05%	0.04%	0.59%	0.00%
end of period	LC [km²]	246,402	1,472,429	975,790	2,013,579	496,827	349,666	147,913	152,605	5,855,212

Figure A3. Land cover extent accounts for the periods of 2006−2012.

begining of the period		Artificial surfaces	Arable land & permanent crops	Pastures & mosaic farmland	Forests and transitional woodland shrub	Natural grassland, heathland, sclerophylou.	Open space with little or no vegetation	Wetlands	Water bodies	Total
	LC [km²]	246,402	1,472,429	975,790	2,013,579	496,827	349,666	147,913	152,605	5,855,212
consumption	per period [km²]	2,238.51	6,751.89	5,034.80	54,161.62	2,396.74	1,947.65	356.42	362.91	73,250.54
	per year [km²]	373.09	1,125.32	839.13	9,026.94	399.46	324.61	59.40	60.49	12,208.42
	% of LC change	3.06%	9.22%	6.87%	73.94%	3.27%	2.66%	0.49%	0.50%	100.00%
	% of given LC	0.91%	0.46%	0.52%	2.69%	0.48%	0.56%	0.24%	0.24%	1.25%
formation	per period [km²]	6,527.12	6,689.70	2,164.13	52,571.67	893.79	3,304.72	254.69	844.72	73,250.54
	per year [km²]	1,087.85	1,114.95	360.69	8,761.95	148.97	550.79	42.45	140.79	12,208.42
	% of LC change	8.91%	9.13%	2.95%	71.77%	1.22%	4.51%	0.35%	1.15%	100.00%
	% of given LC	2.60%	0.45%	0.22%	2.61%	0.18%	0.95%	0.17%	0.55%	1.25%
net change	per period [km²]	4,288.61	-62.19	-2,870.67	-1,589.95	-1,502.95	1,357.07	-101.73	481.81	0.00
	per year [km²]	714.77	-10.36	-478.44	-264.99	-250.49	226.18	-16.96	80.30	0.00
	% of given LC	1.74%	0.00%	-0.19%	-0.08%	-0.30%	0.39%	-0.07%	0.32%	0.00%
end of period	LC [km²]	250,691	1,472,367	972,919	2,011,989	495,324	351,024	147,811	153,087	5,855,212

Figure A4. Land cover extent accounts for the periods of 2012−2018.

Notes

1 https://www.eea.europa.eu/en/countries Accessed on 12 August 2024.

2 https://land.copernicus.eu/pan-european/corine-land-cover Accessed on 12 August 2024.

3 https://sdi.eea.europa.eu/catalogue/srv/api/records/8526ff78-b000-42e1-8360-a2fb3a51e4ac Accessed on 12 August 2024.

4 https://www.eea.europa.eu/en/datahub/datahubitem-view/94438969-2dd5-4ba3-b708-e4d29a8b7699 Accessed on 12 August 2024. https://sdi.eea.europa.eu/catalogue/srv/api/records/8526ff78-b000-42e1-8360-a2fb3a51e4ac Accessed on 12 August 2024.

5 https://www.eea.europa.eu/en/datahub/datahubitem-view/3c362237-daa4-45e2-8c16-aaadfb1a003b Accessed on 12 August 2024.

6 See note 5 above.

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