LAMASUS
Land Management for Sustainability

D2.1 The LUM Geodatabase and Area Estimates of Land Use Change to 2018

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Abstract

Deliverable 2.1 is the LUM geodatabase, where this report provides information on the development and validation of the different data sets and the availability of the data. Hence, this report accompanies this data deliverable.

Keywords

Land cover and land use, land use management, spatially explicit data, high-resolution data

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Nature of the deliverable *	R

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Abbreviations

CLC	Corine Land Cover
EEA	European Environment Agency
EC	European Commission
EU	European Union
FADN	Farm Accountancy Data Network
FAO	Food and Agriculture Organization of the United Nations
LUCAS	Land Use/Cover Area frame Survey
LUM	Land use management
NFI	National Forest Inventory
NWFP	Non-woody forest products

Executive summary

This report describes the land use management (LUM) geodatabase, which is comprised of a series of spatial data sets that make up Deliverable 2.1. The LUM geodatabase has been developed to support the modelling work in LAMASUS. This report documents the methodologies that were used to develop the data sets, their validation (where relevant) and their availability.

The first component of the LUM geodatabase is the Corine land cover time series from 2000 to 2018. The Corine accounting layers for 2000, 2006, 2012 and 2018 produced by the European Environment Agency (EEA) were used as inputs along with the high-resolution land cover time series produced by OpenGeoHub. The latter time series was used to determine the year of change. Where the year could not be determined, the BFAST algorithm was applied to MODIS data. Any remaining changes were assigned randomly to a year. The year of change was then used to create Corine layers for the years in between 2000 and 2006, 2006 and 2012 and 2012 and 2018. A transition matrix was applied to ensure smooth transitions between land cover/land use types.

The second component of the LUM geodatabase is the land use management layers for 2000, 2010 and 2018. The forest, cropland, grassland and urban land use management classes are described, along with the input data sets and the rule-based methodologies for allocating the LUM classes to Corine. Different methods of validation and verification have been undertaken, including consultation with experts, who provided qualitative information to help improve the layers. The data sets were then aggregated from 100 m to 1 km and NUTS2 levels using a procedure that first involved fitting Corine land cover to official statistics on forest, cropland and grassland from FAO and Eurostat.

Finally, the LUM geodatabase contains area estimates of changes in major land cover/land use types between 2000 and 2018 with uncertainty estimates. The uncertainties were calculated from a validated sample using Geo-Wiki and visual interpretation of satellite imagery and time series to verify if changes in Corine had occurred.

The data sets can be viewed on Geo-Wiki (https://www.geo-wiki.org), the LUM Geodatabase Data Explorer and downloaded from the LAMASUS Community on Zenodo.

The report concludes with a summary of the next steps for WP2 and the LUM geodatabase in the LAMASUS project. These include (i) monitoring the release of new data sets, in particular Corine land cover for 2024 and new Copernicus High Resolution Layers on crop types and mowing events; and (ii) the completion of deliverables D2.2 and D2.4, which will outline how the LUM geodatabase can be used in monitoring land use management, the roadmap for updating the LUM geodatabase in the future, and the planned updates with new data sets to be undertaken within the timeframe of the LAMASUS project.

1. Introduction

Deliverable 2.1 is the land use management (LUM) geodatabase, which is a series of data sets that have been developed as inputs to the various LAMASUS models. This document is intended to provide a description of the data sets, including details of the methodologies that have been used to develop the data sets, including their validation (where relevant) and their availability.

The LUM geodatabase consists of the following data sets:

- Corine land cover time series (section 2)
- The land use management maps for 2000, 2010 and 2018 (section 3)
- The area estimates of land cover/land use change (section 4)

The final section of this document (section 5) provides a conclusion and outlines the next steps for the LUM geodatabase in the LAMASUS project.

1. Corine Land Cover Time Series

Corine land cover is a product provided by the European Environment Agency (EEA) (Büttner and Eiselt, 2013). It was produced for the years 1990, 2000, 2006, 2012 and 2018. A new product for 2024 is currently planned, but will not appear until 2026.

In addition to the original layers, the EEA has also produced a set of accounting layers for 2000, 2006, 2012 and 2018 (EEA, 2019). These layers take the manually digitized changes between years into account, producing a set of layers that are both spatially and temporally consistent. These accounting layers form the basis for the development of the annual time series.

1.1. METHODOLOGY

Figure 1 provides an overview of the methodology used to produce the annual time series, which essentially involved filling in the missing years between 2000 and 2006, 2006 and 2012, and 2012 and 2018. First, the accounting layers and the change layers were downloaded. The change layers provide the type of change that has occurred, but not the year of occurrence. Three different methods were employed to determine the year of change (as outlined in the green boxes in Figure 1):

1. The European high-resolution annual land cover data set that has been developed using Landsat from 2000 to 2020 was downloaded (Witjes et al., 2022). The changes from the Corine change layer were compared to changes in this time series. Where the change matched that found in the change layer OR where a signal of change was observed, the year in which that change occurred was recorded. We were able to identify the year of change in 82.9%, 80.5% and 80.4% of cases for 2000-2006, 2006-2012 and 2012-2018, respectively.
2. For any remaining changes that could not be found in the land cover data set (Witjes et al., 2022), we used the BFAST algorithm to determine the year of change using MODIS data (Masiliūnas et al., 2021). We could identify the year of change in 7.0%, 11.2% and 7.5% of cases for 2000-2006, 2006-2012 and 2012-2018, respectively.
3. Finally, any remaining changes that could not be identified using the first two approaches were assigned randomly to a year within the six-year time period, which was 10.1%, 8.3% and 12.1% for 2000-2006, 2006-2012 and 2012-2018, respectively.

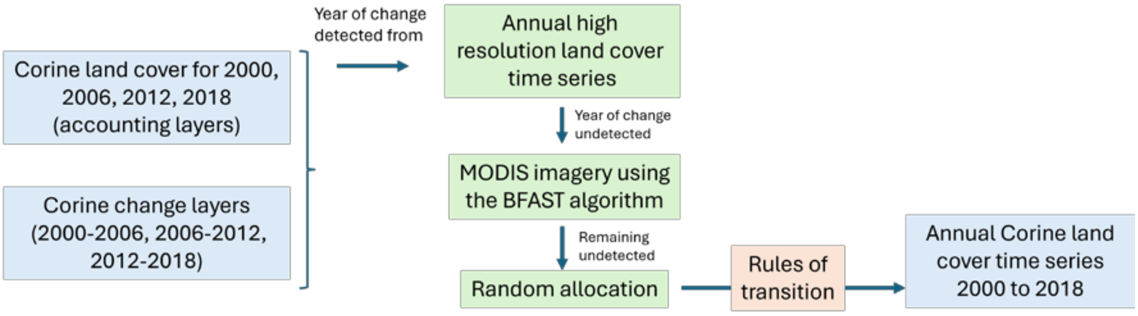

Figure 1: Overview of the methodology used to generate the Corine Time Series. (Source: LAMASUS WP2).

A set of rules governing possible land transitions was then applied to ensure that any abrupt changes (e.g., cropland transitioning to an airport over a 6-year period) had logical intermediate land use changes in the intervening years. These transition rules are provided with the annual time series (see section 2.2).

The final output of the procedure outlined in Figure 1 is the annual Corine time series from 2000 to 2018. As there was no change information available for 2018 to 2020, it was not possible to produce layers for 2019 and 2020 that would be spatially and temporally consistent with previous years. These maps were provided to support modelling efforts in WP4, and the layers for 2000, 2010 and 2018 were then used as the basis for the development of land use management layers outlined in the next section.

1.2. AVAILABILITY OF THE CORINE ANNUAL TIME SERIES

The Corine annual time series from 2000 to 2018 are available from the following locations:

- The layers can be visualized in the LAMASUS LUM Geodatabase branch of the Geo-Wiki application (https://www.geo-wiki.org) or via the LAMASUS LUM Data Explorer.
- The original accounting layers for 2000, 2006, 2012 and 2018 can be downloaded from the EEA website: https://www.eea.europa.eu/data-and-maps/data/corine-land-cover-accounting-layers.
- The annual time series from 2000 to 2018 can be downloaded from the LAMASUS Zenodo Community along with a legend file (for QGIS) and the transitional classes used in the development of the time series (doi: 10.5281/zenodo.12696960).

2. The Land Use Management (LUM) Geodatabase

This section of the report provides the methodologies used in the development of the forest, cropland, grassland and urban management classes, as well as any validation undertaken and the availability of the data. The final part of section 3 presents the methodology for fitting Corine to official statistics and the production of shares at 1 km and NUTS2 levels that match these statistics for use by the LAMASUS models.

2.1. FOREST MANAGEMENT

The first version of the forest management classes, with their definitions, is provided in Table 1. The methodology for the first version of the map was developed and implemented by LAMASUS partner VUA at a 1 km resolution for around the year 2018. The map was presented at the Forest Navigator annual meeting (end of year 1 of the project – version 1) and then modified slightly (version 2), and then further presented at the Second LAMASUS Stakeholder Workshop.

Table 1. Version 1 of the forest management classes and their definitions.

CLASS	DEFINITION
Primary forest	Barely disturbed forest with a nature function. None to barely any management in place.
Close to nature management	Forests with a nature function, which have been disturbed in the past. Management actions are applied to ecosystem functioning.
Multifunctional management	Mixed objective forests, where no single objective is dominant in the management strategy. Functions may include protection, recreation, non-woody forest production (pine nuts, mushrooms, cork) or other functions.
Intensive forestry	Forests managed primarily for wood production. Rotation length is based on maximum profit. Large patches of forests are cut down for wood production either in one period or over a longer period of time.
Plantation/short rotation forestry	Forests which are intensely used for wood production. The trees are cut down in a short time period of time (i.e., shorter or equal to maximum profit), cut in large patches (i.e., big clear-cuts) and/or consist of fast-growing species only.

2.1.1. Methodology

The details of the methodology that was implemented and the 1 km forest management map (version 2) are available from this repository (Oostdijk et al., 2023): A forest management map for Europe - VU - Faculty of Science (dataverse.nl). The input data sets used in the methodology are listed in Table 2 while the decision tree for allocating the forest classes based on a set of rules is provided in Figure 2.

Table 2: Input data sets to the forest management map

DATA SET	SOURCE
Forest mask	Copernicus High Resolution Layer on forest cover, aggregated to 1 km and > 50% forest coverage
Primary forests	European Primary Forests Database (EPFD) v.2 from Sabatini et al. (2021), vector data set converted to 1 km raster
Plantation species	Plantation tree species (Eucalyptus, Populus and Robinia) were selected from the tree species data set of Brus et al. (2012).
Disturbance and frequency	Forest disturbances have been mapped by Senf and Seidl (2020). Using a window of 3 x 3 km, the average size and frequency of disturbances were measured. Disturbance size was classified into small (<0.27 ha), medium (0.27 to 3.6 ha) and large (> 3.6 ha) and disturbance frequency into few (< 1 patch/year), some (1 to 2 patches/year) and many (> 2 patches / year).
Forest age and evenness	Forest age was provided by Pucher et al. (2022) at an 8 km resolution. The data set was reclassified to young (dominant age < 20 years), medium (20 to 40 years) and old (> 40 years) and even aged if > 70% of the forest belonged to a single 20 year age bin. The data were resampled to a 1 km resolution.

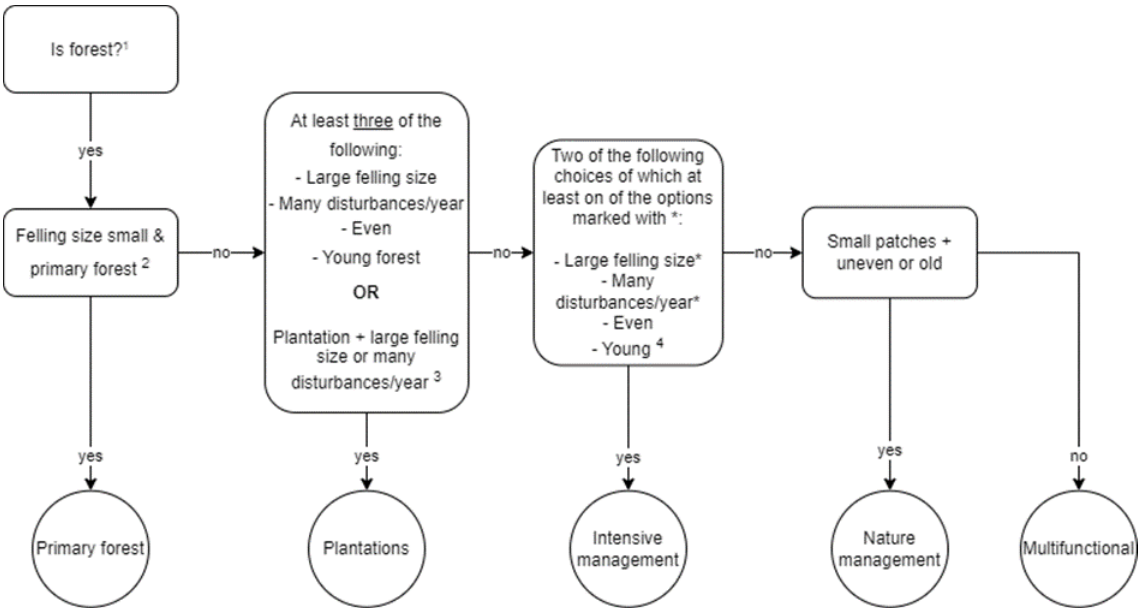

Figure 2: Allocation of forest management classes based on this decision tree. Source: Oostdijk et al. (2023)

The decision tree (Figure 2) uses the layers and classes as inputs to the decision, starting first with primary forest and allocating any remaining forest to the multifunctional class. Validation of the map is taking place within the Forest Navigator project.

The 2018 map, originally provided by VUA at 1 km resolution, was then resampled to the Corine 100 m grid and applied to the forest classes. The same operation was applied to the

2000 and 2010 Corine layers. The disadvantage of this approach is that the only factor that is changing over time is the area under forest cover. However, forest management has long cycles for wood production so the management would not necessarily change over this relatively short time period.

2.1.2. Availability of the maps of forest management

The original 1 km map and the layers containing the forest management classes for 2000, 2010 and 2018 can be visualized in the LAMASUS LUM Geodatabase branch of the Geo-Wiki application (https://www.geo-wiki.org) and the LUM Data Explorer. The forest management classes have been integrated into the complete land use management layers for 2000, 2010 and 2018; further details of availability are provided in section 3.6.

2.2. CROPLAND MANAGEMENT

Cropland management is first divided into arable and permanent cropland based on the Corine land cover classes and then further disaggregated into management intensities. Corine land cover also has a set of 4 heterogeneous cropland classes, which are dealt with separately as outlined below.

2.2.1. Methodology

Table 3 lists the cropland management classes in the LUM layer, including the inputs used in their development and the rules for allocation of Corine land cover classes to the cropland management classes. The main limitation to the development of these classes at a high resolution is the lack of availability of relevant data. Although some data are available from agricultural censuses and surveys, due to confidentiality regulations, these data are only released at NUTS 2 or coarser resolutions. For this reason, two main data sets were selected as inputs, both of which are at 1 km resolution for the year 2010, and have been produced by the Joint Research Centre (JRC) of the European Commission (EC):

- An irrigation layer: described in Wriedt et al. (2009), but updated by the JRC for 2010. Although irrigated arable cropland is a class in Corine land cover, it was used for determining if permanent cropland is irrigated.
- An energy input layer: described in Rega et al. (2020), which has been produced using the CAPRI model. This layer takes the combined energy from mineral fertilizers, the application of manure, planting/seeding, irrigation (energy used for pumping and distributing water), pesticides (manufacturing and spreading), the energy used to produce seeds, the use of machinery (including fuel consumption) and the direct consumption of electricity for building maintenance into account.

Although these layers are only available for 2010, they were applied to Corine land cover for 2000, 2010 and 2018, which assumes that neither irrigation nor energy inputs change over time. This is another limitation of the data.

A third limitation is that the energy input layer from CAPRI is not available for all European countries, such as Norway, Switzerland, the Balkans so this means that cropland management classes are not currently available for these countries.

Table 3: The cropland LUM classes and the rules for allocating the Corine land cover classes to the LUM classes.

TYPE OF CROPLAND	CROPLAND LUM CLASS	RULES FOR ALLOCATION
Arable cropland	Irrigated arable cropland (A1)	Irrigated class in Corine land cover
	Rainfed intensive arable cropland (A2)	Very high, high and medium energy inputs
	Rainfed extensive arable cropland (A3)	Low and very low energy inputs
Permanent cropland	Irrigated permanent cropland (P1)	Irrigated or very high energy inputs
	Rainfed intensive permanent cropland (P2)	High and medium energy inputs
	Rainfed extensive permanent cropland (P3)	Low and very low energy inputs
Heterogeneous cropland	Intensive heterogeneous cropland classes	Very high, high and medium energy inputs
	Extensive heterogeneous cropland classes	Low and very low energy inputs
	Agroforestry	Agroforestry class in Corine with no livestock

2.2.2. Checking against other sources/validation

The first type of exercise undertaken has been to provide the 2018 cropland management map to the EPIC modelling team from IIASA to see how well they can be used to match observed production and yield. An example is shown in Figure 3 with selected countries and various crops for the estimation of production.

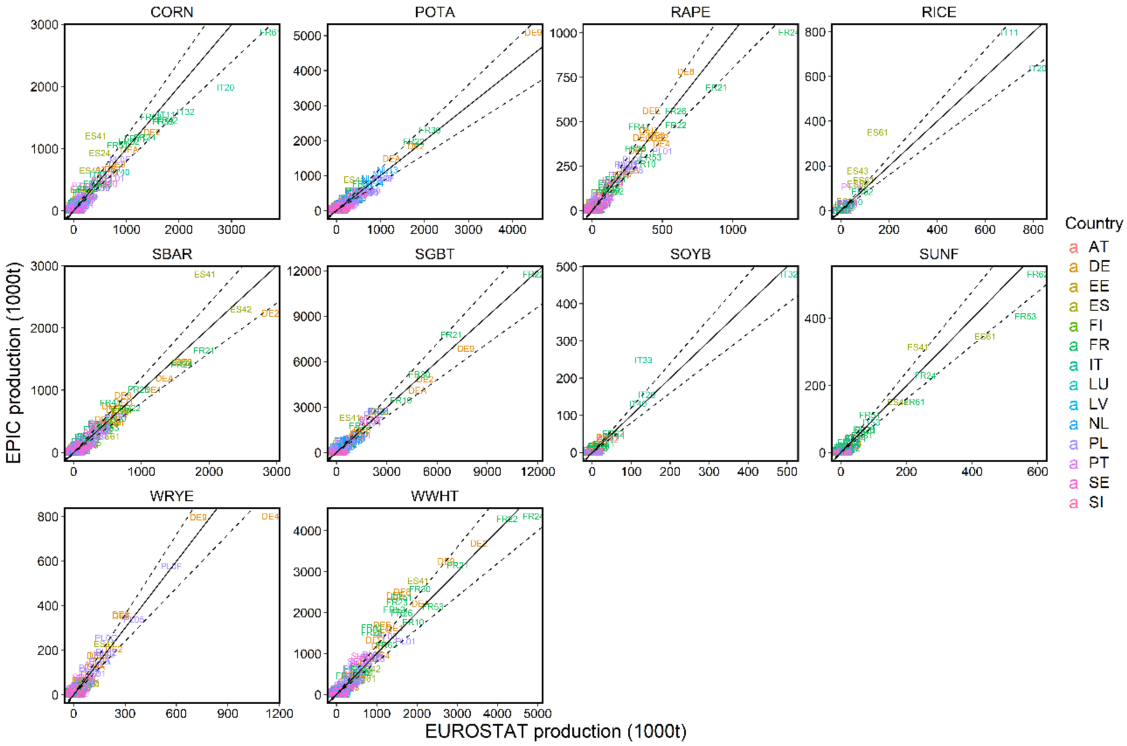

Figure 3. Estimates of production for various EU countries and crops using the EPIC model and the cropland management classes.

The results showed that for some crop types, the management classes were suitable for the prediction of both production and yield, while for other types, there were over- or underestimations, indicating that a single value of management intensity at a 1 km resolution may not be suitable for all crop types. This inconsistency is a limitation of the data, but understandable given the task of trying to match NUTS2-level yield data for every single major crop based on a single management value.

Different approaches can be taken to subsequently use the data for modelling in LAMASUS. One such approach may be to modify the intensity levels on a country-by-country basis. Figure 4 provides a comparison of the intensive and extensive cropland intensities from the cropland management map with the farming intensity indicator (C33), which is calculated from agricultural census data as well as data from the FADN (Eurostat, 2023a).

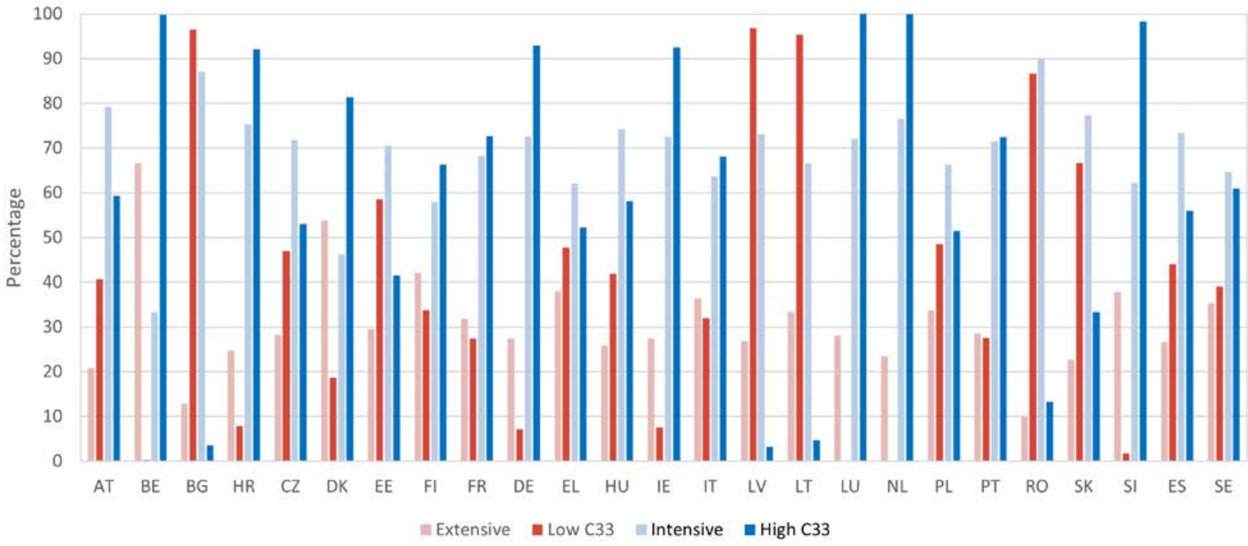

Figure 4: Comparison of intensive and extensive agriculture with the C33 farming indicator by country.

For some countries like Finland, Italy and Portugal, national values match reasonably well. However, there are other countries where the cropland management map either over or underestimates the amount of intensive versus extensive agriculture. Belgium and Slovenia are examples where there is much more intensive agriculture in the cropland management map than would be expected based on the national statistics. This comparison could form the basis for adjusting the cropland management when used by the models so that yields and production match the statistics at the NUTS2 level more closely.

An additional validation was carried out with very detailed IACS data for Austria, which are used for the CAP, keeping in mind that Figure 2 indicates that there is an overestimation in the amount of intensive agriculture based on the cropland management map. Data for 2015 to 2021 were downloaded from the Statistics Austria website, which contains parcels and around 200 different crop types. The map was overlaid on top of the Corine land cover map, and the crop type at the centroids of the Corine pixels was extracted from the seven years of data. The crop types were then reclassified into 11 major categories using the Hierarchical Crop and Agriculture Taxonomy (HCAT) classification system (Schneider et al., 2023): cereals; industrial crops; legumes/pulses, soy, vegetables, fodder crops, green plants/green manure, fallow, meadow, permanent crops and energy crops. The time series of crop types was then reclassified into crop rotations by number of rotations and type of rotation. The intensive and extensive cropland management classes were then grouped and overlaid on top of the crop rotations to determine if there was a plausible pattern emerging. For example, Figure 5 shows the percentage of intensive and extensive agriculture from the cropland management map for the 11 different crop categories when there was no rotation (or monocropping) over the seven-year period. As expected, the percentage of high intensity is very large for cereals, industrial crops, soy vegetables and energy crops, while the percentage is lower for legumes/pulses, green plants/green manure, fallow fields and meadows. The reason for any high intensity in areas with fallow fields and meadows is due to the coarse resolution of 1 km for the input energy layer and the 25 ha minimum mapping unit of Corine compared to the field scale IACS data, but nevertheless, the higher amounts of extensive agriculture make sense.

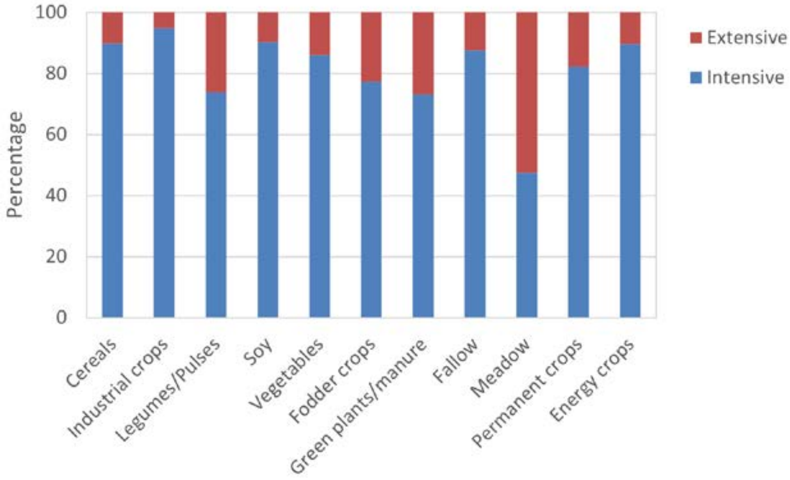

Figure 5: The percentage of intensive and extensive agriculture for different crop types for no crop rotation over a seven year period in Austria (2015-2021).

The cereals, industrial crops, soy, vegetables, permanent crops and energy crops were reclassified into cash crops, and the percentage of intensive versus extensive agriculture management was calculated for 2 to 7 crop rotations. As expected, there is a high amount of intensive agriculture across all crop rotations because they are cash crops (Figure 6).

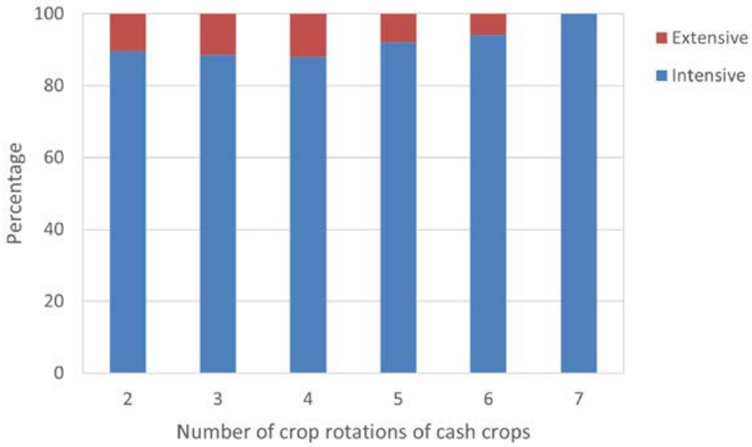

Figure 6: The percentage of intensive and extensive agriculture for different numbers of crop rotations over a seven-year period in Austria (2015-2021) for cash crops.

Figure 7 shows the amount of intensive and extensive agriculture for two crop rotations, where there are cash crops rotated with less intensively managed crop types and other combinations of two crop rotations. As expected, the amounts of extensive relative to intensive agriculture is higher for less intensively managed crop types.

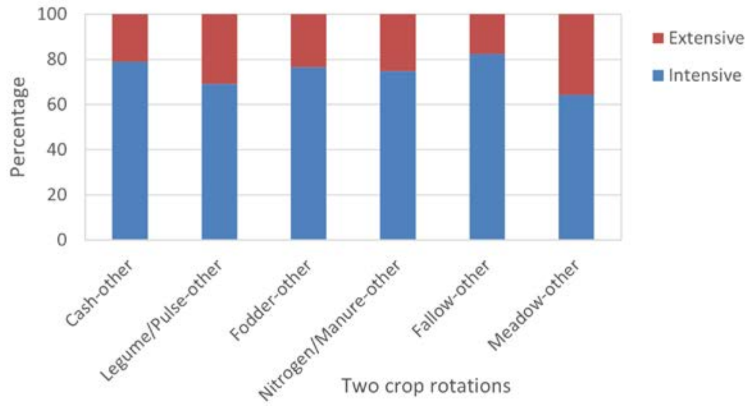

Figure 7: The percentage of intensive and extensive agriculture for two crop rotations over a seven-year period in Austria (2015-2021) for various combinations of major crop types.

Finally, Figure 8 shows the results for crop rotations of three or more types of cash crops and the other types grouped together. As expected, the amount of extensive agriculture increases with an increase in the number of crop rotations, particularly of crops in the less intensively managed category.

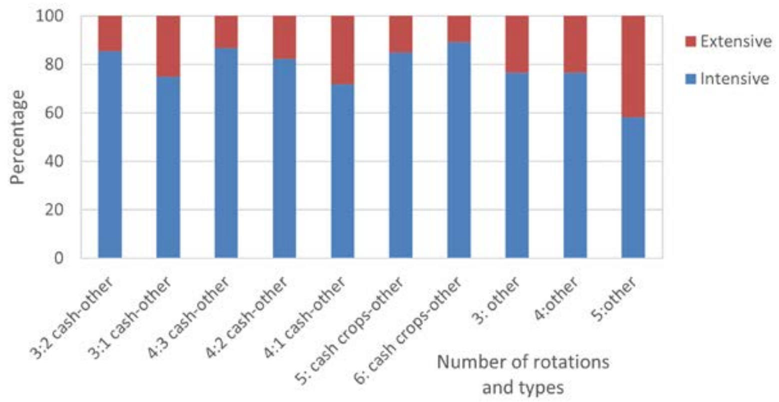

Figure 8: The percentage of intensive and extensive agriculture for three and more crop rotations over a seven year period in Austria (2015-2021) for cash crops and other categories of crop type.

Overall, for Austria, the results of the cropland management mapping seem plausible, given the differing resolutions of the data sets and the fact that different crop types could be managed differently over short geographical spaces (i.e., < 1 km), which would not be captured by the cropland management map.

A true validation process would involve having an independent data set on cropland management, e.g., from an agricultural census. However, such data are not available.

2.2.3. Comparison with other data sources

As an example of how the data set can be used, the 2018 cropland management map was overlaid with the soil organic carbon loss and gain map produced by De Rosa et al. (2024). Aggregating the results for Europe shows that 91.4% of cropland experienced a loss in soil organic carbon between 2009 and 2018, where 63% of losses occurred in areas with intensive agriculture. These losses are further broken down for a selection of European countries as shown in Figure 9. Although Austria, France and Germany show lower SOC losses in cropland compared to Italy, Poland and Spain, these losses occur in a higher percentage of intensively managed cropland.

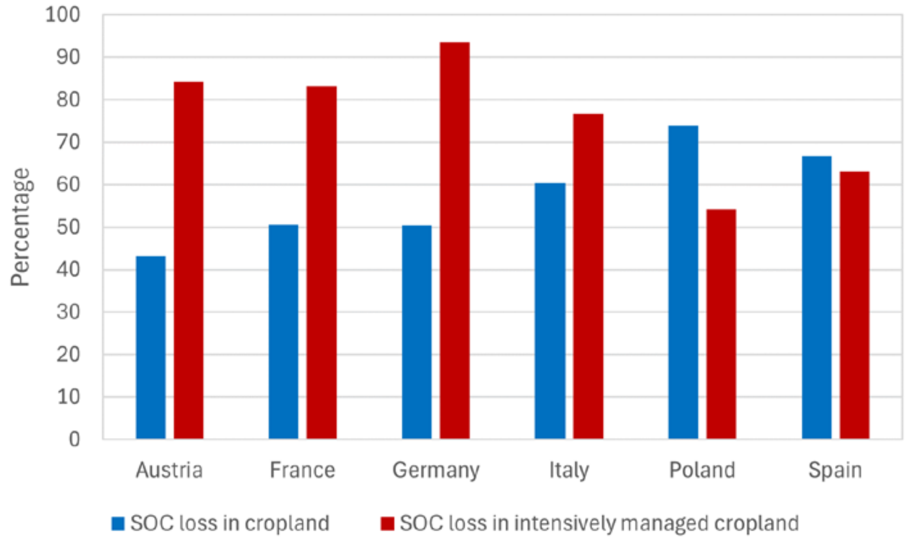

Figure 9. Losses in soil organic carbon (SOC) as a percentage of total cropland and within intensively managed cropland for a selection of European countries.

Note that there are also gains in SOC in cropland, which could have been shown here. However, this is not meant to be a comprehensive analysis but rather an example of how the data could be used.

2.2.4. Availability of the maps of cropland management

Layers containing only the cropland land use management classes for 2000, 2010 and 2018 can be visualized in the LAMASUS LUM Geodatabase branch of the Geo-Wiki application (https://www.geo-wiki.org) under the heading 'Cropland' and in the LUM Data Explorer. The cropland management classes have been integrated into the complete land use management layers for 2000, 2010 and 2018; further details of availability are provided in section 3.6.

2.3. GRASSLAND MANAGEMENT

The development of the grassland management layers builds on the semi-natural grassland mapping undertaken by Malek et al. (2024b). In this previous study, the authors calculated the probability of grazing livestock in semi-natural areas and then allocated the total amount of stock available based on the highest probabilities. Here, the method is extended to the pasture class, moors and heathlands, complex cultivation and agroforestry to map grassland management systems in Europe.

2.3.1. Methodology

The initial set of grassland management classes was developed in the early part of the LAMASUS project and is described in D2.3. The involvement of Žiga Malek, the European Environment Agency and various grassland experts via several discussions showcasing preliminary maps resulted in the final classes (and thresholds) listed in Table 4.

Table 4: The grassland LUM classes, including the input layers used and the rules for allocating the Corine land cover classes to the LUM classes.

GRASSLAND MANAGEMENT CLASS	DEFINITION
1 Very high-density managed pasture system	Grazing livestock > 2 LSU/ha in grazing areas [1.5 for Mediterranean zone]
2 High-density managed pasture system	Grazing livestock 1 to 2 LSU/ha in grazing areas [1.0 to 1.5 for Mediterranean zone]
3 Moderate-density managed pasture system	Grazing livestock 0.5 to 1.0 LSU/ha in grazing areas [0.5 to 1.0 for Med zone]
4 Low-density managed pasture system	Below 0.5 LSU/ha in grazing areas [0.5 for Mediterranean zone]
5 Very high-density managed grassland	Grazing livestock > 2 LSU/ha outside of grazing areas [1.5 for Mediterranean zone]
6 High-density managed grassland	Grazing livestock 1 to 2 LSU/ha outside of grazing areas [1.0 to 1.5 for Med zone]
7 Moderate-density managed grassland	Grazing livestock 0.5 to 1 LSU/ha outside of grazing areas [0.5 to 1.0 for Med zone]
8 Low-density managed grassland	Below 0.5 LSU/ha outside of grazing areas [0.5 for Mediterranean zone]
9 Rough grazing	Livestock present on moors, heathland, shrubland
10 Silvo-pastoral agroforestry	Grazing livestock present in agroforestry, permanent cropland, heterogenous cropland
11 Managed semi-natural and natural grassland	Grazing livestock present in natural grassland classes (not covered by rough grazing)
12 Unmanaged semi-natural and natural grassland	No livestock, natural grassland, shrubland, heathland classes, transitional woodland, sparse vegetation

One of the key inputs to the grassland management map is the input data on livestock numbers and extensive grazing. Livestock data were collected for each European country for multiple years (2000, 2010 and 2018/2020) at the highest resolution possible. Some countries release data only at the NUTS2 level, while others publish data at a much higher resolution, e.g., local authorities. Once all the data were collected, they were harmonized as livestock units (Eurostat, 2023b) and described in a data paper submitted to the journal Scientific Data (Malek et al., 2024a). An additional data set that was collected and as part of this data collection effort was on grazing shares by country (or at the sub-national level where available).

Then, using the same methodology as outlined in Malek et al. (2024b), maps of grazing and non-grazing livestock were generated using the information on grazing shares. Once generated, a rule-based allocation system was used to produce the grassland management classes from Corine using the maps of grazing and non-grazing livestock (as well as livestock grazing in semi-natural areas) and the livestock densities calculated from the harmonized livestock data (Figure 10). The environmental strata of Metzger et al. (2005) were used to divide Europe into the Northern/Alps and Mediterranean zones, so that different livestock density thresholds could be applied as listed in Table 4.

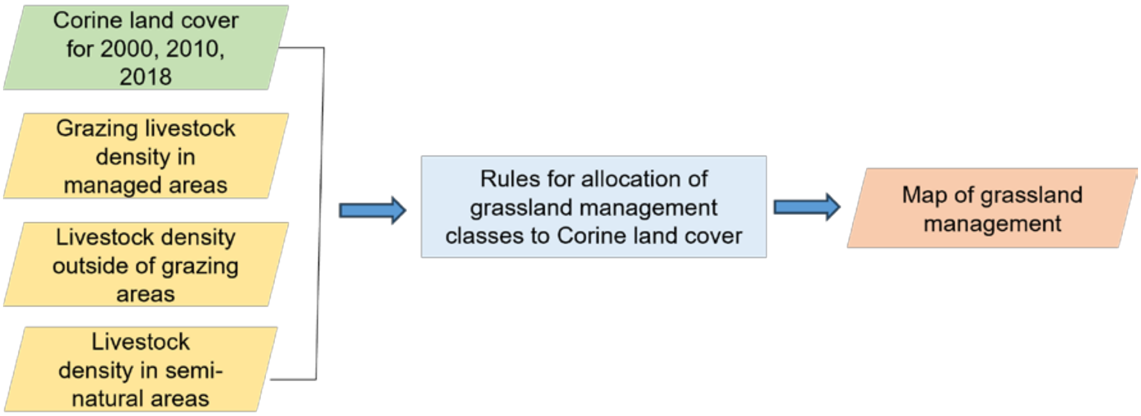

Figure 10. The methodology for mapping grassland management

The rules for the allocation of Corine land cover to grassland management are provided in Figure 11 for pasture and heterogeneous cropland classes and Figure 12 for other relevant Corine classes. Note that the thresholds shown apply to the northern and alpine zones of Europe according to Metzger et al. (2005). For the Mediterranean zones, the thresholds were modified and taken from Table 4.

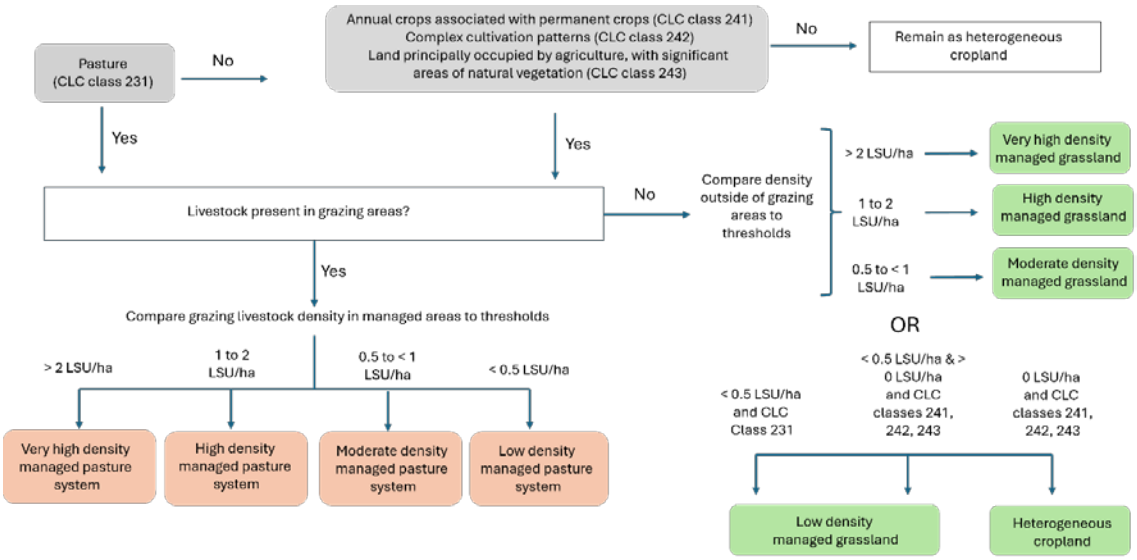

Figure 11. Allocation of pasture and heterogeneous cropland classes from Corine to grassland management classes.

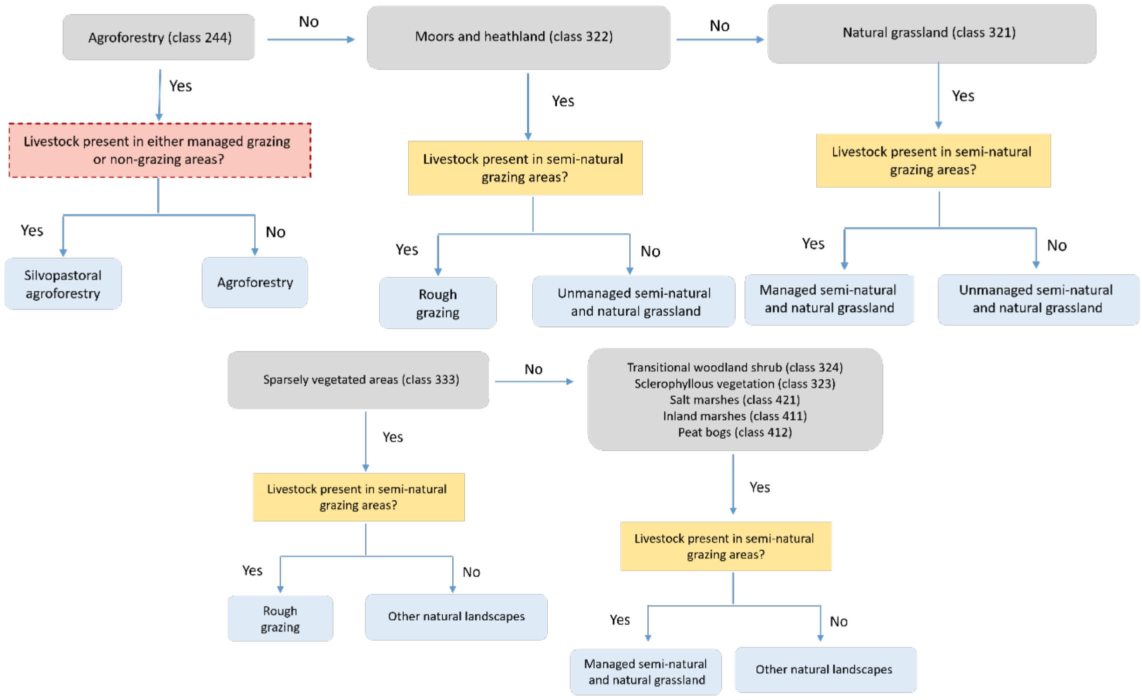

Figure 12. Allocation of other relevant Corine classes to grassland management classes

Note that classes 1 to 4 (managed pasture systems) are proxies for grazing systems, while classes 5 to 8 (managed grasslands) are proxies for grasslands that are mowed. Although grasslands can be both grazed and mowed, it is not possible to explicitly map this combination until other input data become available, such as the Copernicus mowing event data layers, which will be publicly released in 2024/2025. At that stage, the grassland management classes could be revisited for inclusion of this data set.

2.3.2. Validation with experts

To validate the 2018 map, we first collected contacts from grassland and grazing experts from all EU countries and the UK. For each country, we selected experts who have published scientific or technical reports on grasslands and grazing or are mentioned as data contacts on web pages of national statistical offices or other authorities responsible for livestock or grassland data. In addition, we included experts from organizations that have a good overview of grasslands or grazing for the whole of the EU, such as the European Environment Agency and the European Grassland and Pastoralism Society from Wales, UK. The contacts are summarized in Annex A.

We performed the validation as follows. First, we uploaded all spatial data on livestock density and grassland management on the publicly accessible platform Geo-Wiki. We chose Geo-Wiki, as it enables easy zooming into any part of Europe, combined with very high-resolution satellite imagery and other base maps to support the validation. It also enables the provision of feedback (see bottom left pane in Figure 13), either by writing comments, or by drawing polygons of interest, for example, by marking areas where the data are incorrect.

Figure 13. Validation using Geo-Wiki feedback tools

Secondly, we prepared high-resolution (A3 300 DPI) versions of all maps and shared them in a PowerPoint or pdf format (as preferred) with the experts, so that they could also look at the maps on their computers and write comments or mark up the documents, e.g., by drawing shapes. Figure 14 shows an example of such a high-resolution map for the Iberian Peninsula. We shared both the link to the Geo-Wiki platform and the high-resolution images with our experts.

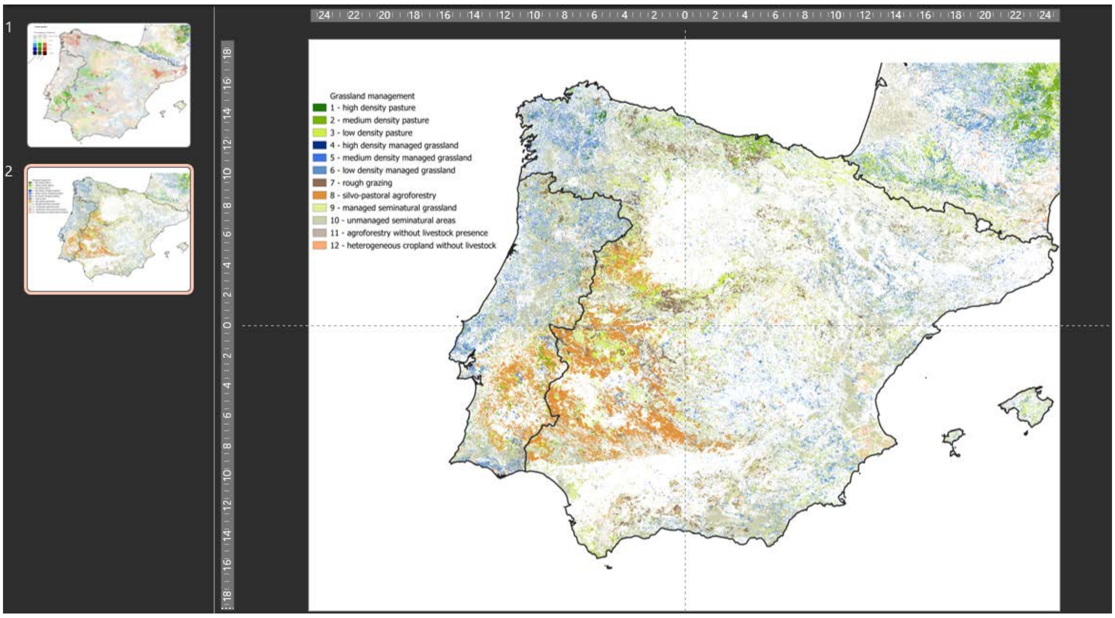

Figure 14. Validation using high-resolution presentations or PDF files, where experts could provide comments.

Finally, with the experts who indicated that they had time, we performed a more in-depth validation. We held three online workshops with experts for the whole of Europe, and experts from the United Kingdom, Denmark (European Environment Agency), Spain and the Netherlands, and the map was presented at the Second LAMASUS Stakeholder Workshop, where feedback was received. We then shared the high-resolution maps with three stakeholders from three countries, and they provided feedback via email. Finally, we pursued more detailed email exchanges with experts from France, Hungary, Portugal, Greece and Slovenia, where they were asked for additional clarification or provided more detailed feedback on the maps.

In total, 20 experts provided feedback on 12 countries and for the EU more generally. We improved our maps if the feedback was implementable. For example, if the experts indicated that better data were available on the livestock distribution, we obtained these data; we did this for Ireland, the UK, Italy and the Netherlands.

The feedback we received was related to two main categories: 1. The input data; and 2. The grassland management classification, summarized below. More detailed country-specific feedback is provided in Annex B.

Input data

All experts agreed that using Corine land cover is not entirely suitable for capturing grassland management at such a detailed scale. While Corine is regularly updated and is amongst the most widely used spatial data sets in environmental studies, it also does not match official statistics, and it has issues with mapping heterogeneous classes, many of them representing pastoral, grassy landscapes that are grazed. The experts did agree that, at the European scale, there are not many alternatives, although some suggestions have been provided, such as the Copernicus High Resolution Grassland Layer. However, there is no separation between natural and managed grassland, which is one of the advantages of using Corine.

Nearly all the experts suggested that using IACS data would be better because it maps parcels, meaning that it maps grasslands better. However, it was acknowledged that using such data could lead to inconsistencies in grassland or pasture definitions between different countries. In addition, IACS data are only openly available for a minority of European countries.

Secondly, the experts indicated that the LUCAS data used to map the spatial distribution of grazing is incomplete in many areas. LUCAS, while using trained surveyors and clear definitions of what grazing observations are, is performed at a single time, meaning that much of the grazing could be underreported, and could occur at other times than when the survey was performed. In addition, LUCAS does not indicate what type of livestock is grazing, meaning that our approach potentially overestimates grazing in areas predominantly grazed by small ruminants (e.g., in Hungary).

The third issue with the data is that in many countries, livestock statistics are only available at a coarse spatial scale (e.g., NUTS3), meaning that the map depicts regional averages and does not capture local variations. We can confirm the significant impact of detailed statistical data on the spatial distribution, as demonstrated for Ireland and the United Kingdom (see Annex B for the detailed country-specific feedback).

Grassland management classification

We first prepared a classification with six grassland classes based on livestock density (Table 5). The experts on European grazing systems then suggested two improvements. First, they suggested including lower densities for the high and very high density for the Mediterranean and Alpine environmental zones (Table 5). Secondly, they suggested splitting the moderate density into low (up to 0.5 LSU/ha) and moderate (0.5 to 1 LSU/ha) classes, which enabled grasslands with low densities to be identified.

Table 5. Initial and modified classification. The density classes were used for both grazed and managed (mown and not grazed) grasslands resulting in 6 classes in the initial, and 8 in the modified version.

VERSIONS	CLASS	LIVESTOCK DENSITY
Initial version	Moderate	Up to 1 LSU/ha
	High	1 to 2 LSU/ha
	Very high	Over 2 LSU/ha
New version	Low	Up to 0.5 LSU/ha
	Moderate	0.5 to 1 LSU/ha
	High	1 to 2 LSU/ha (1 to 1.5 LSU/ha in the Alps and the Mediterranean)
	Very high	Over 2 LSU/ha (over 1.5 LSU/ha in the Alps and the Mediterranean)

2.3.3. Validation with mowing event data for Germany

We compared the grassland management map of 2018 to two German-wide mowing event maps of 2018 generated by Schwieder et al. (2022) and Reinermann et al. (2022), which are, respectively, named *ThEO* and *DLR* in this deliverable. Both products are generated for grassland areas based on rulesets applied to a time series of satellite images. A time series of Sentinel-2 and Landsat 8 images was used to create the ThEO maps, while Sentinel-1 and Sentinel-2 images were used to generate the DLR product.

The boxplots in Figure 15 capture the relationship between the grassland management classes on the X-axis and the number of mowing events (cuts) on the Y-axis. By and large, there is an agreement between the two maps regarding the median number of cuts (red lines) for all management classes except rough grazing. Excluding the outliers (hollow dots), the range of cuts was the same for all classes except high, moderate, and low-density pastures, and unmanaged seminatural areas. Given that the two maps are mowing event maps, they could be used at best to assess the plausibility of the managed grassland classes (5, 6, 7, 8), which are strictly mowing classes. Excluding the outliers, the results of both maps were the same for all the managed grassland classes. Most of the cuts ranged from 0 to 6 for very high and high-density managed grasslands, and the cuts for moderate and low-density managed grasslands mostly ranged from 0 to 3. From each map, the median number of cuts for very high and high-density managed grasslands is 2, and the median cut for both moderate and low-density managed grasslands is 1. The more intensively managed the grassland, the higher the number of cuts, which is what would be expected.

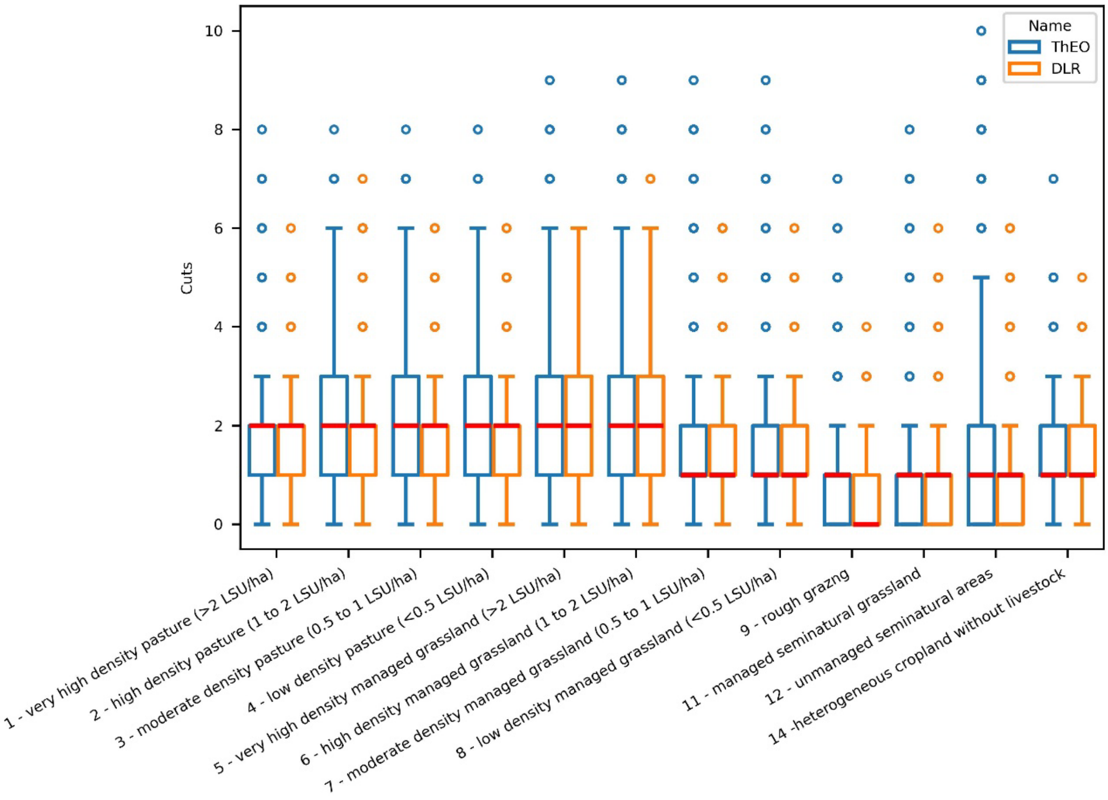

Figure 15: Boxplots showing the relationship between the grassland management classes on the X-axis and the number of mowing events (cuts) on the Y-axis. The red lines represent the median and the hollow dots represent the outliers.

Using only the ThEO map, we calculated the median number of cuts for each managed grassland class for all NUTS3 polygons in Germany (Figure 16). This enables the spatial assessment of how the median cuts at the polygon level deviate from the German-wide median cuts, as already shown in Figure 15. As shown by the polygons shaded in green (Figure 16), in most cases, the median number of cuts at the polygon level corresponds with the German-wide medians for each managed grassland class. However, there are some instances (i.e., polygons shaded in red), where there were deviations. This may be due to a combination of errors in Corine, LUCAS and/or the livestock density maps, as well as errors in the mowing event data themselves, which is a remotely sensed product.

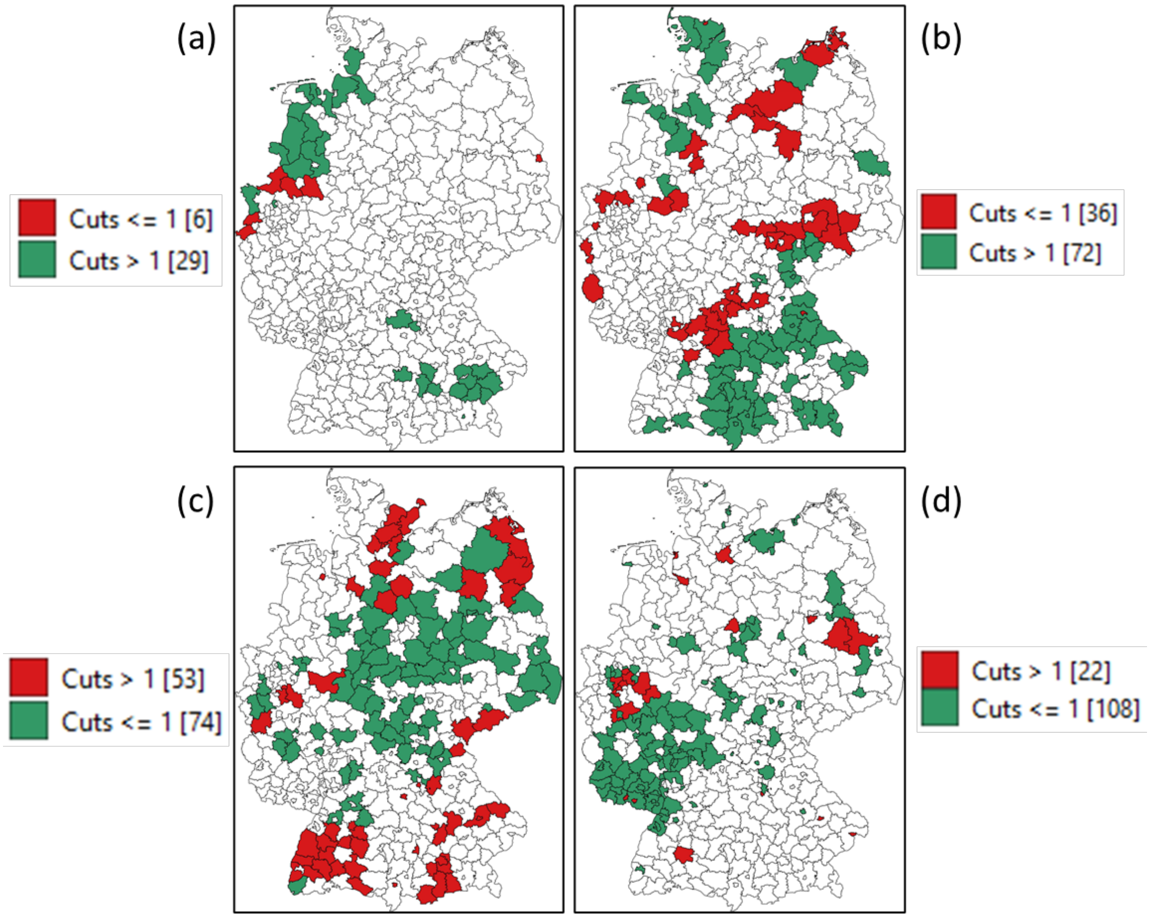

Figure 16: Median number of cuts extracted for all NUTS3 polygons in Germany for (a) very high density managed grassland, (b) high density managed grassland, (c) moderate density managed grassland, and (d) low density managed grassland. The polygons without color do not contain pixels of the respective managed grassland classes or the share of pixels of a particular class is less than 0.5% of the total area of the overlapping polygon. The numbers in the brackets of the four legends represent the number of polygons in agreement with the German-wide median (green) and those that deviate (red).

2.3.4. Validation with citizen science data

In addition to qualitative validation and validation using remote sensing and other geospatial products, a citizen science campaign was run between February and August 2025 using the Picture Pile rapid image classification tool. Photographs from the LUCAS survey that were taken in grassland areas were classified by citizens in two separate tasks:

- Presence of and type of livestock (cattle, horses, donkeys, sheep and goats)
- Evidence of grassland management (mowing, grazing)

The data collected were then compared with the grassland management part of the LUM geodatabase.

The citizen science campaign involved 65 participants in classifying 26,128 unique locations in the livestock pile and 59 participants in classifying 10,127 unique locations in the grassland management pile. Photographs were classified multiple times so that a consensus approach could be used. Not all LUCAS photographs were completely classified, which is why some countries have better coverage (e.g., Ireland, Spain), but in all countries, the sample is large enough for validation.

Table 6 shows the number of photographs classified with and without a majority consensus, while Figure 17 and Figure 18 show the photograph locations for livestock and grassland, respectively, across Europe. Table 6 shows that livestock was easier to classify, which is why the majority consensus for livestock was high. Nevertheless, in some photographs, the livestock were quite far away, which may explain why some photographs have no majority consensus. Grazing and mowing, in contrast, were much harder to identify from a photograph. Correspondingly, the number of photos without a majority consensus for grazing is higher. Although a set of marked-up photographs was provided as exemplars along with detailed instructions, there is no guarantee that these were used by the participants. Feedback from some participants also confirmed the greater difficulty in identifying grassland management.

Table 6: The number of photographs at unique locations classified in Picture Pile with and without majority consensus

LIVESTOCK	WITH MAJORITY	WITHOUT MAJORITY	GRASSLAND MANAGEMENT	WITH MAJORITY	WITHOUT MAJORITY
Cattle	524	230	Grazing	2,479	2,475
Sheep	175	129	Mowing	1,130	1,656
Goats	4	19	None	4,139	2,044
Donkeys	10	32	Can't tell	508	2,710
Horses	76	35			
None	25,084	308			
Can't tell	97	625			

The image classifications with majority agreement were then overlaid on the grassland management part of the LUM geodatabase. For livestock (Table 7), there was a higher percentage of livestock present in the grazing classes 1 to 4 compared to the managed grassland classes 5 to 8, which are meant to be more indicative of mowed fields and livestock fed indoors, and which is, therefore, expected. Higher amounts of livestock were also present in the pastoral classes (9 to 11) compared to the remaining non-livestock classes, although these are very small numbers. However, the occurrence of livestock in classes 9 to 15 is lower than that found in the pasture/managed grassland classes (1 to 8), which is also to be expected. However, it is also clear that livestock are not present in LUCAS photographs all that often, which makes validation using this source quite challenging.

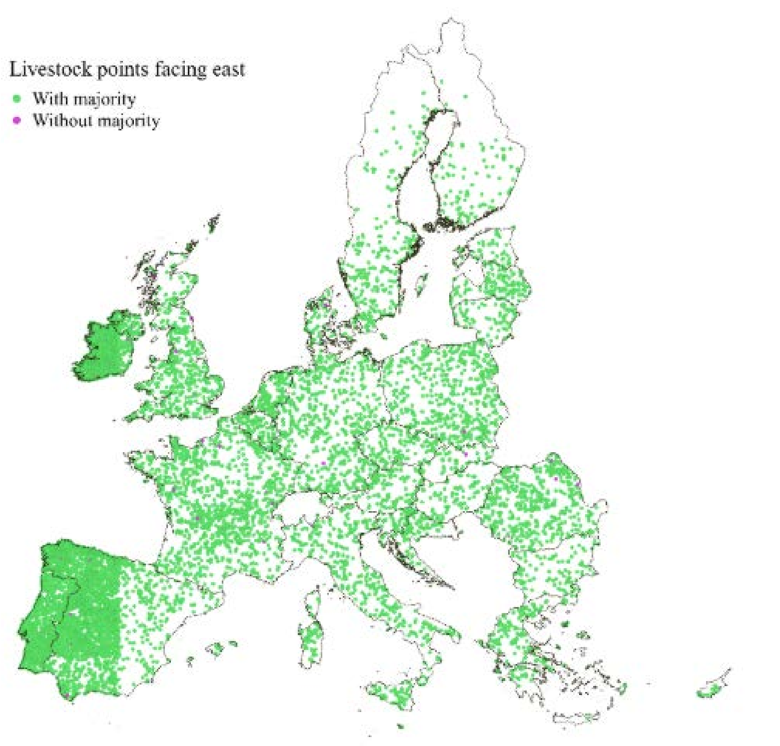

Figure 17: The location of photographs classified for livestock showing mostly majority agreement

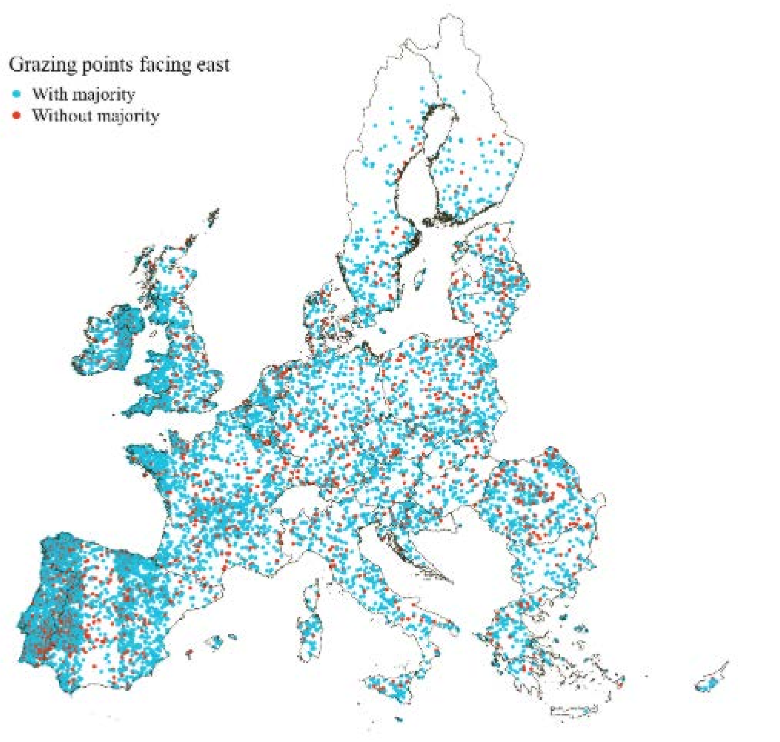

Figure 18: The location of photographs classified for grassland management showing less majority agreement than the livestock classification

Table 7: The percentage of photographs with livestock present and absent (with absolute values in square brackets) for grazing, managed, other pastoral and remaining classes (non-livestock)

LIVESTOCK	PASTURE/GRAZING CLASSES (1 TO 4)	MANAGED GRASSLAND CLASSES (5 TO 8)	OTHER PASTORAL CLASSES (9 TO 11)	REMAINING CLASSES (12 TO 15)
Present	4.66% [128]	2.12% [49]	1.94% [19]	1.66% [10]
Absent	95.24% [2617]	97.88% [2266]	98.06% [959]	98.34% [591]

Similarly, we do get some expected patterns from the classification of grassland management photographs (Table 8), i.e., there is a higher percentage of grazing in the pasture/grazing classes (1 to 4) and the other pastoral classes (9 to 11) compared to the managed grassland classes (5 to 8).

Table 8: The percentage of photographs with evidence of grazing, mowing or no evidence (with absolute values in square brackets) for grazing, managed, other pastoral and remaining classes (non-livestock)

GRASSLAND MANAGEMENT	PASTURE/GRAZING CLASSES (1 TO 4)	MANAGED GRASSLAND CLASSES (5 TO 8)	OTHER PASTORAL CLASSES (9 TO 11)	REMAINING CLASSES (12 TO 15)
Grazing	53.9% [1064]	35.43% [676]	40.77% [296]	26.34% [123]
Mowing	13.88% [274]	17.45% [333]	5.65% [41]	8.35% [39]
No evidence	32.22% [636]	47.12% [899]	53.58% [389]	65.31% [305]

Overall, there is consistency between the data from citizen science and the grassland management map, but there are also clear limitations to this validation approach. LUCAS photographs are at a very precise location, while the grassland management map is at a 100 m resolution, where the underlying Corine land cover has a minimum mapping unit of 25 ha. Hence, there will always be some mismatch between the LUCAS data and Corine. Moreover, it is clear that livestock are often not present in the photographs, while grazing and mowing were much more difficult to identify from the photographs.

For this reason, we have also been experimenting with the use of Artificial Intelligence for the automated recognition of both livestock and grassland management. To date, the results have been quite promising, but this analysis is beyond the scope of the LAMASUS project.

2.3.5. Availability of the maps of livestock, grazing and grassland management

The livestock data are available for downloading from the LAMASUS Community (https://zenodo.org/records/11058509), with full details provided in Malek et al. (2024a). The grazing layers will become available for downloading from the LAMASUS Community once the publication being prepared is submitted.

Layers containing the grassland management classes for 2000, 2010 and 2018 can be visualized in the LAMASUS LUM Geodatabase branch of the Geo-Wiki application (https://www.geo-wiki.org) under the heading 'Grassland' and in the LUM Data Explorer. The grassland management classes have been integrated into the complete land use management layers for 2000, 2010 and 2018; further details of availability are provided in section 3.6.

2.4. URBAN LAND USE MANAGEMENT/INTENSITIES

2.4.1. Methodology

There are five main urban land use management classes, as outlined in Table 9. The first three classes represent three different levels of urban intensity from low to high, which are meant to reflect the density of buildings in the city. The fourth class contains all infrastructure-related features, while the fifth class contains the remaining urban features that are mapped in Corine land cover.

Corine land cover has 11 urban classes, while the Copernicus Urban Atlas product has 17 more detailed classes. The Urban Atlas, which is only available for 2006, 2012 and 2018, was used in a rule-based mapping as outlined in the second column of Table 9. For example, when classes 11100 and 11210 were present, they were assigned to the urban land use management class: High intensity urban. This rule-based mapping procedure was undertaken for all urban areas in Corine for 2006, 2012 and 2018.

Table 9: The urban LUM classes and the corresponding classes from the Urban Atlas for 2006, 2012 and 2018.

URBAN LAND USE MANAGEMENT CLASSES	CLASSES FROM URBAN ATLAS
High intensity urban (buildings)	11100 Continuous urban fabric 11210 Discontinuous dense urban fabric
Medium intensity urban (buildings)	11220 Discontinuous medium density urban fabric
Low intensity urban (buildings)	11230 Discontinuous low density urban fabric 11240 Discontinuous very low density urban fabric 11300 Isolated structures 13400 Land without current use 14100 Green urban areas 14200 Sports and leisure facilities
Infrastructure	12100 Industrial, commercial, public, military and private units 12210 Fast transit roads and associated land 12220 Other roads and associated land 12230 Railways and associated land 12300 Port areas 12400 Airports
Other urban	13100 Mineral extraction and dump sites

For the year 2000 and for urban areas in 2006, 2012 and 2018, where no Urban Atlas data were available, the classes from Corine land cover were assigned to the urban land use management classes as outlined in Table 10. The only exception was class 1.1.2 Discontinuous urban fabric in Corine land cover, which could be high, medium or low intensity depending on the soil sealing. Hence, the Copernicus high-resolution soil sealing layer was used to disaggregate class 1.1.2 into high, medium and low intensity based on the thresholds provided in Table 10.

Table 10: The urban LUM classes and the corresponding classes from Corine land cover for the year 2000 and any urban areas not covered by the Urban Atlas in 2006, 2012 and 2018.

URBAN LAND USE MANAGEMENT CLASSES	CLASSES FROM CORINE LAND COVER AND THE COPERNICUS HIGH RESOLUTION LAYER ON SOIL SEALING
High intensity urban (buildings)	1.1.1 Continuous urban fabric 1.1.2 Discontinuous urban fabric + soil sealing > 50%
Medium intensity urban (buildings)	1.1.2 Discontinuous urban fabric + soil sealing between 30 to 50%
Low intensity urban (buildings)	1.1.2 Discontinuous urban fabric + soil sealing < 30% 1.4.1 Green urban areas 1.4.2 Sport and leisure facilities
Infrastructure	1.2.1 Industrial or commercial units 1.2.2 Road and rail networks and associated land 1.2.3 Port areas 1.2.4 Airports
Other urban	1.3.1 Mineral extraction sites 1.3.2 Dump sites

Finally, the urban layer for 2010 was created. Taking the Corine 2010 layer from the time series and the urban intensity layers for 2006, 2012 and 2018, the layers were first analyzed for stability over time. For those pixels that were stable, the urban intensity classes were assigned to the 2010 urban layer. Where there was change, the remaining urban pixels were reclassified based on Table 10. If the urban class was 1.1.2 Discontinuous urban fabric, the value of the urban intensity from the 2012 layer was assigned to the 2010 urban layer.

No specific validation of the urban land use intensities was carried out since the Urban Atlas and the Copernicus high-resolution soil sealing layers have been validated as part of their production. Since these products were reclassified into the urban intensities, the resulting map will have the same quality as their respective input maps.

2.4.2. Availability of the maps of urban land use management

Layers containing only the urban land use management classes for 2000, 2006, 2012 and 2018 can be visualized in the LAMASUS LUM Geodatabase branch of the Geo-Wiki application (https://www.geo-wiki.org) and in the LUM Data Explorer. The urban land use management classes have been integrated into the complete land use management layers for 2000, 2010 and 2018; further details of availability are provided in section 3.6.

2.5. ALIGNING THE DATA SETS TO OFFICIAL STATISTICS FOR 2000, 2010, AND 2018

The Corine land cover layers have been produced using remote sensing and then made spatially and temporally consistent using the change layers as outlined previously in section 2. However, this means that when the data are aggregated to NUTS2 regions, the major classes of forest, cropland (arable and permanent) and grassland do not match the official statistics from Eurostat and FAO/National Forest Inventories. For this reason, a methodology is needed that modifies the Corine land cover layers so that the resulting map matches the official statistics when aggregated. Note that not all data are available at NUTS2; some data are only released at NUTS1 or nationally due to Member State preferences, while NUTS3 data are occasionally available for individual countries.

2.5.1. Methodology

The first part of the methodology involved the generation of probability layers for forest, cropland, and grassland, which were calculated from a series of input layers as outlined in Table 11. The probabilities were calculated based on consensus between the products, where the ranking indicates the precedence of the layer in the probability calculation; the ranking was assigned by experts in the group and reflects a higher quality product. The method used for allocating the probability follows the procedure outlined in Fritz et al. (2015). All layers were first resampled to the Corine grid at 100 m resolution before generating the probability layers. A filter was then applied to each probability layer (i.e., a moving window of the average of the nearest neighbors) to avoid fragmented land cover patterns. Experiments were undertaken with and without the filter, indicating that the filtered layers produced more coherent spatial patterns.

Table 11: The input data sets for the generation of the forest, cropland and grassland probability layers along with their rankings for quality.

RANKING OF LAYERS	FOREST	CROPLAND	GRASSLAND
1	GLAD forest layer	Cropland layers from Potapov et al. (2022)	Copernicus high resolution layer on grassland
2	Corine 10m product	WorldCereal cropland extent	C-GLOPS land cover
3	C-GLOPS land cover	C-GLOPS land cover	WorldCover global land cover map
4	JAXA forest product	WorldCover global land cover map	ESRI global land cover map
5	-	ESRI global land cover map	-

Official statistics for areas of cropland (arable and permanent), permanent grassland and forest were compiled for 2000, 2010 and 2018. The cropland and permanent grassland data were obtained from the Eurostat website, while forest statistics were obtained from a range of sources. These include FAOSTAT for national totals, publications, and national forest inventory websites for NUTS1, 2 and 3 level data (where available). Note that the high-resolution forest data were available for 2018/2020 and rescaled based on the national totals from FAO for 2000 and 2010.

For each country, where forest, arable cropland, permanent cropland and permanent grassland Corine classes occurred, the probability layers were used to assign these classes based on the highest probabilities until the totals matched those of the official statistics. In the situation where insufficient pixels were available to match the statistics, these were taken from the highest probabilities of forest, cropland and grassland, respectively, and from other Corine land classes, except for urban areas, that were masked out and hence not changed.

The main problem that occurred during the fitting procedure was an insufficient number of pixels to match the statistics, and only urban areas were available. This occurred for the countries listed in Table 12 along with the solution for how this was handled.

Table 12: The countries where problems were encountered in the fitting of Corine to the official statistics and the method used to solve the problem.

COUNTRY	PROBLEM	SOLUTION
Belgium, Hungary, Italy and Poland	Insufficient amount of land to allocate to cropland or grassland because of a largely urban NUTS region.	The urban NUTS region was merged with the surrounding NUTS region so that sufficient pixels could be reallocated to cropland and grassland
France	Insufficient amount of permanent cropland available in the mid-Pyrenees and Corsica NUTS2 zones.	Pixels were taken from other land use types, guided by an official map of permanent cropland in France.
Greece	Insufficient amount of permanent cropland available in some NUT2 regions including many of the islands.	Since forest statistics were available on an aggregated level (3 zones only), we aggregated cropland grassland to these zones and then did the allocations.
Ireland	Forest reported using old NUTS2 boundaries (and counties) and cropland and grassland reported using new ones in 2018	Counties were matched to new NUTS2 boundaries and then statistics fitted. For 2000 and 2010, only older NUTS2 boundaries were used.
Portugal	The sum of cropland, grassland and forest for Alentejo was greater than the area in this NUTS 2 region. This may be due to some kind of double counting in the forest and cropland statistics due to agroforestry.	The cropland and grassland areas were fit to the statistics while forest will be underestimated in this NUTS region (code PT18).
Spain	Insufficient amount of forest and permanent cropland in Extremadura and Andalucia, respectively.	The cropland and grassland areas were fit to the statistics while forest will be underestimated in Extremadura (code ES43). For Andalucia, additional grassland was allocated to forest.
UK	Too much forest in the statistics and not enough forest in the probability	The cropland and grassland areas were fit to the statistics while forest will be

COUNTRY	PROBLEM	SOLUTION
	layer. This was particularly problematic for Wales where not enough land was available for allocation to forest.	very underestimated in this NUTS region (code UKL). There must be an error in the statistics.

Additional errors were found in 2010 and 2000 related to missing statistics, which were then estimated from a neighboring year, or numbers at the NUTS level that did not add up to national totals, which were corrected as much as possible.

Finally, the management classes for forest, cropland and grassland were assigned to the 2000, 2010 and 2018 layers that were now aligned with official statistics. A nearest neighbor procedure was used to allocate management types in those situations where the pixels had shifted location during the fitting procedure.

Finally, the shares of the different management types were calculated for each country by NUTS 2 region so that these could be used by some of the LAMASUS models.

2.5.2. Validation

We used LUCAS data for 2018 and compared the results for all classes and for forest, cropland and grassland separately before and after the layers were aligned with the official statistics. The results are summarized in Table 13. For the majority of countries, the overall accuracy before fitting with statistics is lower than that after the fitting, which is a positive result, as it indicates that the fitting is improving the spatial distribution of Corine. There are exceptions, which are bolded in Table 13. Some of these differences are very small, and some can be attributed to small numbers of LUCAS points either overall (e.g., Cyprus) or in specific areas (e.g., grassland in Finland).

Table 13: The comparison of LUCAS data before and after fitting Corine land cover to official statistics.

COUNTRY	OVERALL ACCURACY (%)	FOREST (%)	CROPLAND (%)	GRASSLAND (%)
	BEFORE FITTING STATISTICS/AFTER FITTING STATISTICS			
Austria	59.6 / 62.4	**75.9 / 74.7**	75.1 / 76.7	60.6 / 66.7
Belgium	45.3 / 55.5	**80.8 / 79.5**	73.0 / 74.2	53.8 / 69.3
Bulgaria	56.4 / 60.9	91.0 / 91.8	72.8 / 79.7	**53.7 / 51.3**
Croatia	40.0 / 44.8	91.5 / 95.2	55.7 / 60.4	40.3 / 48.2
Cyprus	**37.0 / 35.7**	92.3 / 93.5	46.1 / 65.9	0.0 / 100.0
Czechia	67.7 / 68.8	84.3 / 86.5	79.0 / 85.4	75.7 / 78.7
Denmark	60.2 / 63.3	**87.5 / 79.3**	69.2 / 75.5	50.0 / 57.3

COUNTRY	OVERALL ACCURACY (%)	FOREST (%)	CROPLAND (%)	GRASSLAND (%)
	BEFORE FITTING STATISTICS/AFTER FITTING STATISTICS			
Estonia	52.5 / 60.7	77.6 / 83.1	66.4 / 70.7	54.6 / 64.8
Finland	51.3 / 59.9	76.4 / 79.9	**62.7 / 60.2**	**100.0 / 28.6**
France	57.4 / 64.1	**82.5 / 81.0**	**70.6 / 69.1**	64.8 / 71.1
Germany	**71.1 / 69.3**	**83.5 / 83.3**	76.2 / 80.9	59.9 / 72.2
Greece	34.5 / 42.2	**89.0 / 87.6**	**51.0 / 48.7**	**39.7 / 34.1**
Hungary	62.0 / 65.1	84.9 / 85.8	72.5 / 76.3	64.8 / 77.1
Ireland	61.4 / 64.2	**78.9 / 72.3**	**66.4 / 62.2**	74.5 / 77.3
Italy	49.1 / 55.5	**87.1 / 84.7**	61.2 / 69.9	**43.4 / 41.9**
Latvia	52.0 / 61.8	69.4 / 72.1	**72.0 / 71.3**	66.0 / 77.5
Lithuania	50.8 / 58.6	78.9 / 82.9	71.6 / 75.0	64.3 / 68.4
Luxembourg	49.1 / 67.2	73.5 / 84.4	**71.1 / 66.3**	61.8 / 70.1
Malta	32.9 / 44.7	Numbers too small	Numbers too small	Numbers too small
Netherlands	54.3 / 59.6	**81.4 / 77.3**	67.1 / 68.5	72.7 / 84.2
Poland	62.7 / 63.8	83.4 / 88.2	67.8 / 78.3	65.3 / 73.9
Portugal	37.3 / 50.3	85.6 / 85.8	41.5 / 42.4	**65.6 / 33.0**
Romania	52.5 / 57.0	61.4 / 71.3	63.7 / 65.2	**73.7 / 69.7**
Slovakia	58.7 / 62.9	87.9 / 93.7	67.6 / 80.4	71.3 / 71.2
Slovenia	53.1 / 67.4	86.9 / 87.3	**71.5 / 66.0**	57.9 / 71.1
Spain	43.6 / 53.9	**85.2 / 84.4**	57.1 / 57.1	**58.1 / 44.4**
Sweden	56.9 / 60.6	77.4 / 79.7	50.3 / 57.5	**65.9 / 65.7**
UK	53.3 / 56.8	**68.5 / 57.6**	47.2 / 53.7	68.9 / 73.1

2.6. AVAILABILITY OF THE LUM GEODATABASE

The land use management maps at 100m resolution for 2000, 2010 and 2018 can be viewed on Geo-Wiki (https://www.geo-wiki.org) and in the LUM Data Explorer. The 1 km and NUTS2 aggregated data sets that match the statistics can be downloaded from the LAMASUS Zenodo Community (10.5281/zenodo.13254324).

3. Area Estimates of Land Use Change

The change data set from Corine land cover can be used to calculate transition matrices in major land cover types, but there is currently a lack of validation of these changes. By validating these changes using visual interpretation, it is possible to provide uncertainty estimates to accompany these area transitions. To date, no uncertainty estimates have ever been generated, which could be used by the LAMASUS models. Note that we have used both the original and the accounting CLC layers produced by the EEA in this exercise, where the latter explicitly includes the change layer, even though the EEA clearly states that ONLY the accounting CLC layers should be used for change estimates. We have done this to illustrate that there is much higher uncertainty in land use change (LUC) estimates in the original CLC layers, we are not using the LUC estimates from the original CLC layers in LAMASUS. We plan to publish this comparison as a research study in the future, highlighting these differences in uncertainty.

The methodology for validating the change is outlined in sections 4.1 and 4.2, while section 4.3 provides an analysis of the validated change data. Finally, the transition area estimates with uncertainties are provided in section 4.4, along with their availability in section 4.5.

3.1. SAMPLE DESIGN AND GENERATION

A random sample of 50,000 points was first generated across Europe based on the Corine land cover grid at a 100 m resolution and an equal area projection (EPSG: 3035). These points were then overlaid on two different change layers from Corine, extracting only those locations where change occurred from:

- Change layers produced by comparing the original version of Corine land cover for these periods: 2000 to 2006, 2006 to 2012 and 2012 to 2018, and
- Change layers produced by the Copernicus land monitoring service that accompanied the Corine land cover products and were used in the development of the Corine accounting layers.

As mentioned above, although we are fully aware that change should not be calculated by comparing the original Corine layers, we decided to validate both sets of change layers so that these changes could be compared from a research perspective. A subsample of these locations that cover multiple types of change was then provided to the Geo-Wiki application for verification as outlined in the next section.

3.2. GEO-WIKI DATA COLLECTION

The Geo-Wiki application, in addition to visualization, is also used for visual interpretation of satellite and aerial imagery (Fritz et al., 2012). A specific LAMASUS data collection branch was set up, and the sample outlined in section 4.1 was loaded into the Geo-Wiki database. Using an expert network of validators, each location in the sample was validated for change using the interface shown in Figure 19. The blue box shown on the satellite image is the 100m Corine pixel where change occurred. In the year 2000, it was a construction site according to Corine while in 2006, it was classified as discontinuous urban fabric. The expert validators used different sources of information to determine whether this change was correct, e.g., historical imagery from Google Earth, vegetation index times series, etc.

Sometimes the information would not have been available to determine whether the change is correct, in which case the validator would select the 'I don't know' option. Information was also collected on whether any visible change that occurred differed from the type indicated in the Corine change layers as well as some of the other options indicated on the left hand side of Figure 19.

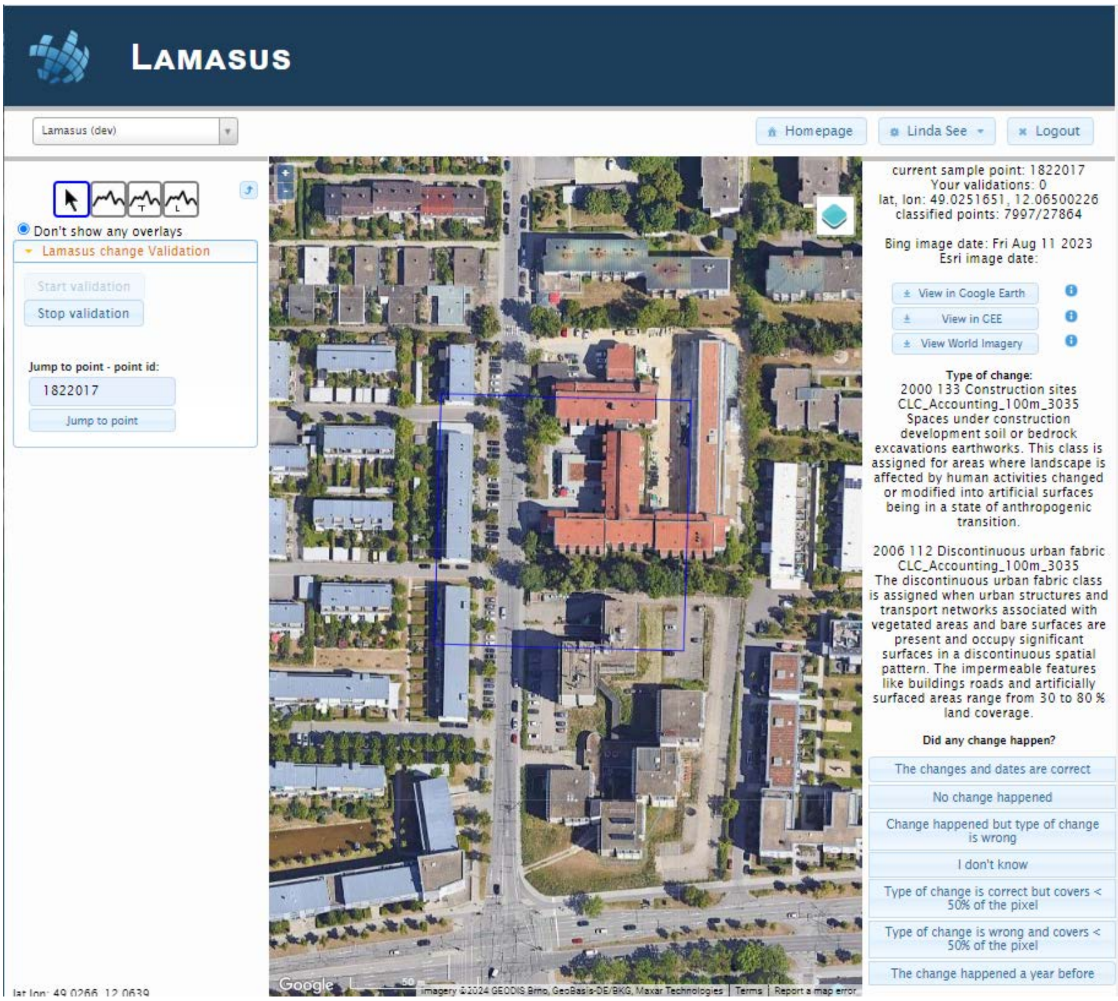

Figure 19: Screenshot from the Geo-Wiki application showing the data collection process for determining whether the change happened or not.

In total, there were 10,237 and 1,628 sample locations selected from the original CLC and the CLC accounting layers, respectively. These samples were then validated for change by two different expert validators. Where the validators did not agree, the locations were then further checked by IIASA validation expert Myroslava Lesiv.

3.3. OVERVIEW OF THE CHANGE DATA COLLECTED

3.3.1. Spatial distribution of change across Europe

Figure 20 shows the spatial distribution of the original 50K samples selected across Europe from both the original and accounting versions of CLC across all three time periods (2000 to 2006, 2006 to 2012 and 2012 to 2018). This clearly shows that there is much more change detected in the original CLC maps compared to the accounting layers, although it is unclear whether this change is real or due to differences in the remote sensing. This is also the reason why these original layers are not to be used for change detection. The CLC change layers were manually digitized by individual countries, so the amount of change in the CLC accounting layer should therefore be a more accurate characterization of change. However, there is clearly a border effect showing those countries where CLC maps are likely to be less accurate, e.g., the UK, Spain, Germany, Finland, etc. Moreover, there is also some agreement between the change in the original CLC and CLC accounting, as indicated in blue in Figure 20.

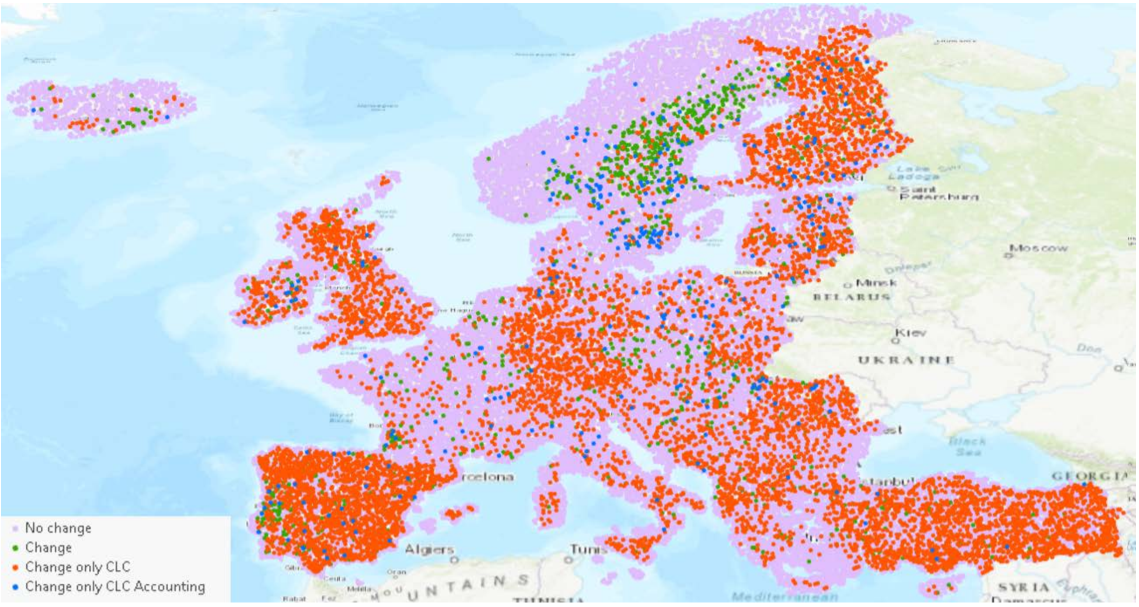

Figure 20: The distribution of 50K sample locations across Europe indicates where both the original CLC and CLC accounting agree on change (in green), changes that are only found in the original CLC (in red) and changes that are only found in the CLC accounting layer (in blue).

Figure 21 shows the results of the validation for the original CLC layers. Although some changes have been verified as actually occurring (in green), there are also a large number of changes in CLC that were validated as having no change (in red). This will be due to misclassification errors in CLC from remote sensing.

Figure 21: Results from the validation of change from Geo-Wiki for samples of change in the original CLC layers.

The validated change data for the CLC accounting layers are shown in Figure 22. Not only is there less change than in the original CLC layers, but a higher proportion of actual change has been validated through this process. Again, this is to be expected as these changes were manually digitized with a higher minimum mapping unit, so they should be more accurate than changes based on remote sensing alone. There are, however, cases where a change in the change layer has been validated as having no evident change based on examining the imagery in Geo-Wiki.

Figure 22: Results from the validation of change from Geo-Wiki for samples of change in the CLC accounting layers (which are based on the Copernicus CLC change layers).

Figure 23 provides an example of one of the types of errors that were identified in the change validation process. In 2006, CLC classified this area as a broad-leaved forest, and in 2012, it was the agroforestry class. However, change between these classes did not occur between 2006 and 2012.

Image from 2006 Image from 2011 Image from 2013

Figure 23: This is an area of agroforestry in Spain showing olive groves and pastures. In 2006, this area was classified as broad-leaved forest while in 2012, the image was classified as agroforestry. However, it is clear that no changes have taken place based on the satellite imagery and that this area has been agroforestry over this time period. Source of imagery: Google Maps.

3.3.2. Summary of the expert-based validations of change

The two validations per change location were compared for consensus and classified into three categories:

- High confidence: when two experts confirmed that the change was correct (both the time period over which the change occurred and the type of change).
- Medium confidence: when one expert said that the change either happened or did not happen, but the second expert expressed uncertainties in this assessment.
- No data: there were no very high-resolution satellite images available to confirm the
- change, and the time series analysis did not provide any additional evidence of
- change.

Table 14 and Table 15 provide a summary of the results of the validated change samples from the original and accounting versions of CLC. For the original version of CLC (Table 14), there are almost 60% of cases where a change was detected when comparing layers from two time periods, but no change was identified by the expert validators. Hence, this further confirms that there are commission errors in the original CLC layers due to errors of misclassification from the remote sensing, providing further evidence of why these layers should not be used for change detection.

In contrast, the amount of change verified in the CLC accounting layers is much higher, i.e., 90.6%, which is to be expected because the change layers digitized by countries should be much more accurate than using remotely sensed products alone. However, there are still omission errors where a change was detected by the expert validators but was not captured in the change layers.

Table 14: Validation of change for the original version of Corine land cover using the Geo-Wiki sample.

TYPE OF CHANGE	HIGH CONFIDENCE	MEDIUM CONFIDENCE	TOTAL	PERCENTAGE
No change occured	2807	1043	3850	57.9%
Change	1210	1238	2448	36.8%
No data	354	-	354	5.3%
Total			6652	100.0%

Table 15: Validation of change for the accounting version of Corine land cover using the Geo-Wiki sample.

TYPE OF CHANGE	HIGH CONFIDENCE	MEDIUM CONFIDENCE	TOTAL	PERCENTAGE
No change occured	101	31	132	8.2%
Change	1001	451	1452	90.6%
No data	19	-	19	1.2%
Total			1603	100.0%

Table 16 and Table 17 provide a summary of the results of the validated change samples from the original and accounting versions of CLC by time period. For the original version of CLC (Table 16), 64.4% of change did not happen between 2000 and 2006 in areas where change is detected when comparing the two products. However, this improves over time, and only 21.3% of the change did not happen in the most recent period (2012 to 2018). This may reflect improvements in remote sensing, availability of imagery, improvement in classification algorithms, availability of other data sources used in the development of CLC, etc., which have resulted in a more temporally consistent product from 2012 to 2018. In terms of the accounting version of CLC, Table 17 shows that change is well detected across all three time periods, with slight improvements from 2006 onwards. However, there are some omission errors in the change detection in all three periods.

Table 16: Validation of change by time period for the original version of Corine land cover using the Geo-Wiki sample.

PERIOD	NO CHANGE		CHANGE OCCURRED		NO DATA	TOTAL		PERCENTAGE		
	High confidence	Medium confidence	High confidence	Medium confidence		No change	Change	No change	Change	No data
2000-2006	1539	813	427	575	299	2352	1002	64.4%	27.4%	8.2%
2006-2012	1177	221	560	517	55	1398	1077	55.3%	42.6%	2.2%
2012-2018	91	9	223	146	0	100	369	21.3%	78.7%	0.0%
Totals					354	3850	2448			

Table 17: Validation of change by time period for the accounting version of Corine land cover using the Geo-Wiki sample.

PERIOD	NO CHANGE		CHANGE OCCURRED		NO DATA	TOTAL		PERCENTAGE		
	High confidence	Medium confidence	High confidence	Medium confidence		No change	Change	No change	Change	No data
2000-2006	15	19	282	128	17	34	410	7.4%	88.9%	3.7%
2006-2012	44	9	408	179	2	53	587	8.3%	91.4%	0.3%
2012-2018	42	3	311	144	0	45	455	9.0%	91.0%	0.0%
Totals					19	132	1452			

3.4. AREA TRANSITIONS WITH UNCERTAINTIES

To calculate the area transitions with uncertainties, the CLC classes were first grouped into broader categories as outlined in Table 18, along with the corresponding classes from the original CLC and the CLC accounting layers.

Table 18: Mapping of CLC classes to broad categories of land cover/land use for use in the transition matrices.

CATEGORY	CLASS CODES FROM ORIGINAL CLC LAYERS	CLASS CODES FROM CLC ACCOUNTING LAYERS
Artificial surfaces	1 to 11	111, 112, 121, 122, 123, 124, 131, 132, 133, 141, 142
Arable land	12, 13, 14	211, 212, 213
Permanent crops	15, 16, 17	221, 222, 223
Pastures	18	231
Heterogeneous agricultural areas	19, 20, 21, 22	241, 242, 243, 244
Forests	23, 24, 25	311, 312, 313
Scrub and/or herbaceous vegetation associations	26, 27, 28, 29	321, 322, 323, 324
Open spaces with little or no vegetation	30, 31, 32, 33, 34	331, 332, 333, 334, 335
Wetlands	35 to 39	411, 412, 421, 422, 423
Water bodies	40 to 44	511, 512, 521, 522, 523

Table 19 summarizes the transitions for the original CLC layers. Since there were many more changes in the original CLC layers compared to the CLC accounting layers, the transition classes are much more detailed than for the accounting layers. The mapped area of change from 2000 to 2018 is provided in ha for each category of change. Based on the Geo-Wiki sample, the actual areas of change have been calculated in two different ways:

- Minimum change area, which uses only the change/no change data to make the calculation, and
- Maximum change area, which assumes that no data is a change.

For example, in Table 19, the transition from artificial surfaces to other classes is around 2.4 million ha according to CLC but when the Geo-Wiki sample is taken into account, this number is drastically reduced to 222K ha if the no change/change data from the sample are considered and 489K if the no data are assumed to be change. This basically indicates that CLC overestimates this type of change by an order of magnitude. In contrast, Table 20 provides the transitions for the CLC accounting layers. Unfortunately, as the number of changes is much smaller, it was not possible to provide detailed transition classes in the same way as for the original CLC layers. To provide an example, the transitions from artificial surfaces to other classes is 201K based on the change layer (which is much closer to the minimum estimate for the original CLC layers). Adjusting this figure using the Geo-Wiki sample results in an estimate of 117K if the change/no change data are considered and 134K if no data are considered as change. Hence these change figures are even further reduced.

Table 19: Transition matrices for the original version of Corine land cover with uncertainties.

FROM	TO	NO CHANGE	CHANGE	NO DATA	PERCENTAGE NO CHANGE		PERCENTAGE CHANGE		MAPPED AREA (HA)	CHANGE AREA (NO OMISSION INCLUDED)	
					Min	Max	Min	Max		Min	Max
Artificial surfaces	Other classes	126	15	18	79.25%	90.57%	9.43%	20.75%	2,356,011	222,265.2	488,983.4
Arable land	Pasture	213	93	27	63.96%	72.07%	27.93%	36.04%	4,922,017	1,374,617.4	1,773,699.8
Arable land	Other classes	261	159	41	56.62%	65.51%	34.49%	43.38%	6,090,297	2,100,558.0	2,642,211.3
Permanent cropland	Other classes	62	38	34	46.27%	71.64%	28.36%	53.73%	1,806,969	512,424.0	970,908.7
Pasture	Arable land	171	102	20	58.36%	65.19%	34.81%	41.64%	3,869,817	1,347,171.8	1,611,323.1
Pasture	Other classes	202	57	24	71.38%	79.86%	20.14%	28.62%	4,143,920	834,641.1	1,186,069.0
Heterogeneous agricultural areas	Forests	182	34	7	81.61%	84.75%	15.25%	18.39%	2,962,372	451,662.1	544,651.4
Heterogeneous agricultural areas	Short woody vegetation	225	34	32	77.32%	88.32%	11.68%	22.68%	4,022,626	469,997.5	912,348.2
Heterogeneous agricultural areas	Other classes	121	33	26	67.22%	81.67%	18.33%	32.78%	2,782,813	510,182.4	912,144.3
Forests	Heterogenous agricultural areas	118	10	3	90.08%	92.37%	7.63%	9.92%	1,841,339	140,560.2	182,728.3
Forests	Other classes	165	48	9	74.32%	78.38%	21.62%	25.68%	3,438,563	743,473.1	882,874.3
Short woody vegetation	Heterogenous agricultural areas	171	32	20	76.68%	85.65%	14.35%	23.32%	3,162,755	453,848.3	737,503.4

FROM	TO	NO CHANGE	CHANGE	NO DATA	PERCENTAGE NO CHANGE		PERCENTAGE CHANGE		MAPPED AREA (HA)	CHANGE AREA (NO OMISSION INCLUDED)	
					Min	Max	Min	Max		Min	Max
Short woody vegetation	Open spaces/sparse vegetation	272	31	10	86.90%	90.10%	9.90%	13.10%	4,480,294	443,735.2	586,875.6
Short woody vegetation	Wetlands	155	6	1	95.68%	96.30%	3.70%	4.32%	2,222,871	82,328.6	96,050.0
Short woody vegetation	Other classes	222	66	36	68.52%	79.63%	20.37%	31.48%	4,154,017	846,188.6	1,307,746.1
Sparse vegetation	Short woody vegetation	252	46	12	81.29%	85.16%	14.84%	18.71%	4,553,202	675,636.4	851,889.4
Sparse vegetation	Other classes	123	19	13	79.35%	87.74%	12.26%	20.65%	2,011,952	246,626.4	415,370.7
Wetlands	Other classes	98	25	2	78.40%	80.00%	20.00%	21.60%	1,892,411	378,482.2	408,760.8
Water	Other classes	57	4	0	93.44%	93.44%	6.56%	6.56%	919,124	60,270.4	60,270.4
Forests	Natural vegetation	332	665	8	33.03%	33.83%	66.17%	66.97%	13,882,496	9,185,930.2	9,296,437.6
Natural vegetation	Forests	322	932	10	25.47%	26.27%	73.73%	74.53%	17,229,897	12,704,322.8	12,840,635.3

Table 20: Transition matrices for the accounting version of Corine land cover with uncertainties.

FROM	TO	NO CHANGE	CHANGE	NO DATA	PERCENTAGE NO CHANGE		PERCENTAGE CHANGE		MAPPED AREA (HA)	CHANGE AREA (NO OMISSION INCLUDED)	
					Min	Max	Min	Max		Min	Max
Artificial surfaces	Other classes	4	7	1	33.33%	41.67%	58.33%	66.67%	201,098	117,307.2	134,065.3
Arable land	Other classes	18	108	5	13.74%	17.56%	82.44%	86.26%	1,922,690	1,585,118.5	1,658,503.6
Permanent crops	Other classes	5	20	2	18.52%	25.93%	74.07%	81.48%	271,414	201,047.4	221,152.1
Pastures	Other classes	0	78	4	0.00%	4.88%	95.12%	100.00%	992,898	944,464.0	992,898.0

FROM	TO	NO CHANGE	CHANGE	NO DATA	PERCENTAGE NO CHANGE		PERCENTAGE CHANGE		MAPPED AREA (HA)	CHANGE AREA (NO OMISSION INCLUDED)	
					Min	Max	Min	Max		Min	Max
Heterogeneous agricultural areas	Other classes	4	35	3	9.52%	16.67%	83.33%	90.48%	442,383	368,652.5	400,251.3
Forests	Other classes	2	30	0	6.25%	6.25%	93.75%	93.75%	541,889	508,020.9	508,020.9
Scrub and/or herbaceous vegetation associations	Other classes	10	48	1	16.95%	18.64%	81.36%	83.05%	861,098	700,554.3	715,149.2
Open spaces with little or no vegetation	Other classes	8	32	0	20.00%	20.00%	80.00%	80.00%	538,238	430,590.4	430,590.4
Wetlands	Other classes	5	4	2	45.45%	63.64%	36.36%	54.55%	118,106	42,947.6	64,421.5
Water bodies	Other classes	1	8	0	11.11%	11.11%	88.89%	88.89%	99,555	88,493.3	88,493.3
Forests	Scrub and/or herbaceous vegetation associations	45	637	1	6.59%	6.73%	93.27%	93.41%	9,690,753	9,038,081.5	905,2270.0
Scrub and/or herbaceous vegetation associations	Forests	31	444	0	6.53%	6.53%	93.47%	93.47%	6,638,233	6,205,001.0	6,205,001.0

4. Conclusions and Next Steps

This deliverable has outlined the three main components of the LUM geodatabase: (i) the annual CORINE time series from 2000 to 2018; (ii) the LUM maps for 2000, 2010 and 2018; and (iii) the area estimates with uncertainties.

Two main activities as part of WP2 will take place during the remainder of the LAMASUS project. These are described in the sections below.

4.1. MONITORING THE RELEASE OF NEW DATA SETS

The release of new data sets that could be relevant for updating or validating the LUM geodatabase will be monitored. For example, the Corine 2024 legacy product will be produced in 2025 because it will use satellite imagery from 2024. Change layers will also need to be produced to ensure that the 2024 Corine layer is temporally and spatially consistent with previous Corine products. The new Copernicus High Resolution Layers, e.g., on mowing events, could be useful for validating the grassland management layer. The emergence of other data sets will be monitored accordingly, e.g., new annual crop type maps.

4.2. COMPLETION OF REMAINING DELIVERABLES (D2.2 AND D2.4)

D2.2 *Report on land use monitoring for policy evaluation* will consist of a policy brief on the LUM geodatabase. As part of this policy brief, a protocol (or roadmap) will be provided as a supplementary document, which will outline how the LUM geodatabase will be updated in the future.

D2.4 consists of updates to the LUM Geodatabase to 2025. For this deliverable, we will use new data sets that have emerged since the release of this deliverable and update the LUM Geodatabase, where possible. Given that the release of the 2024 Corine land cover will most likely occur after the end of the LAMASUS project, the updating will mainly consist of adjusting thematic classes to incorporate new data, e.g., the new wetland map produced by the ALFAWetlands project, the new Copernicus Vegetated Land Cover Characteristics (VLCC) layers and LUCAS data from 2022.

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6. Annexes

ANNEX A: SUMMARY OF GRASSLAND AND LIVESTOCK EXPERTS CONTACTED VIA EMAIL AND ONLINE WORKSHOPS

COUNTRY	ORGANIZATIONS	NUMBER OF EXPERTS CONTACTED
Austria	Ministry of Agriculture; BOKU; BMLRT Ministry of the Environment (UBA)	5
Belgium	INBO - Research Institute for Nature and Forest; EC DG Environment	3
Bulgaria	Society for Territorial and Environmental Prosperity	2
Czechia	Institute of Agricultural Economics and Information	1
Croatia	Oikon; Ecologica.hr	2
Denmark	Agrovi.dk, University of Kopenhagen, EEA	3
Estonia	Agricultural Research Center	3
Finland	LUKE - Natural Resources Institute	3
France	L'Institut Agro; Association Française pour la Production Fourragère (A.F.P.F.); CIHEAM Montpellier Solagro; Association Francais de Pastoralisme (AFP)	4
Germany	Thünen Institut; Deutscher Grünlandverband; IFAB Mannheim	4
Greece	Hellenic Range and Pasture Society (HERPAS)	3
Hungary	Szent Istvan University; Ecological research, Hungary	4
Ireland	Irish Grassland Association; Atlantic Technological University; EFNCP	3
Italy	Retepastorizia; University of Torino - Agriculture department; CREA; ISPAAM; UN FAO; IIASA Austria	7
Latvia	Institute Agricultural Resources and Economics; University of Latvia	2
Lithuania	Baltic Environmental Forum	1
Luxembourg	Head of plant production, ASTA CONVIS, a farmer's consulting organization	1

Netherlands	Alterra; European Grassland Federation; RVO; IVM VU Amsterdam; Netherlands and Flemish Society for Grassland and Fodder Crops	5
Poland	OTOP; Polish Academy Science - Institute of Rural and Agricultural Development; Poznan University of Life Science - Department of Grassland and Natural Landscape Science	3
Portugal	Sociedade Portuguesa de Pastagens e Forragens (SPPF), University of Evora; Instituto Politecnico Castelo Branco	2
Romania	Romanian Society for Grasslands (ROPAJ); University of Cluj	2
Slovakia	Slovak Academy of Agricultural Sciences	1
Slovenia	University of Maribor, Faculty for Agriculture and Biosystem Sciences University of Ljubljana Biotechnical faculty	3
Spain	Entretantos.org; Fundacion Global Nature; Spanish Society of Pastures; Grazing Connection	4
Sweden	SLU; Jordbruksverket	4
UK	EFNCP	1
EU Wide	EFCNP Wales; EEA; L'Institut Agro France; European Grassland Federation; VU Amsterdam; IIASA Austria; Birdlife Europe and Central Asia	6

ANNEX B: COUNTRY-SPECIFIC VALIDATION OF THE GRASSLAND MANAGEMENT MAP

Below is a summary of the feedback received from experts in different countries.

Feedback from Austria

The experts indicated that the actual grassland extent, as mapped by CLC, is uncertain, leading to lower densities (since Corine maps too many grasslands). In many areas that were checked in more detail (e.g., the state of Styria in Austria), we found that areas mapped as grasslands in Corine were, in fact, quarries, construction sites and parts of road infrastructure. By potentially removing such areas, the densities of cattle grazing or managed grasslands would be higher. For example, in a specific area in Styria, we mapped 0.9 LSU/ha of grazing, whereas experts indicated it should be between 1.2 and 1.4 LSU/ha. With a more detailed grassland map in this area, the actual grassland extent would be smaller, leading to slightly higher livestock densities.

The overall spatial pattern of different grassland classes for Austria makes sense according to the experts. While a comparison with Austrian IACS (Invekos) is not directly possible due to different definitions and spatial extents, the overall spatial pattern seems to have a reasonable agreement with the actual situation according to the experts.

Feedback from Greece

The experts felt that for some specific areas (such as the Aegean islands) such an approach cannot fully capture livestock grazing. Animal densities on such islands are low, and most graze on seminatural areas or in systems with a high share of shrub cover. They also felt that while the classification makes sense on a European scale, for specific regions, more local classifications would make sense. For example, there are a few specialized grazing or mown grasslands on the Greek Islands, with most of them being multifunctional mosaic areas.

Feedback from Hungary

While the feedback on our map for Hungary was very critical, the actual comments of the expert indicate a high accuracy of the map, as expressed by the feedback. For example, the expert indicated that most of the cattle in Hungary do not graze with grasslands being mown, and that many seminatural areas are grazed with low densities. Our maps indicate exactly this, that predominantly, cattle do not graze, and that there is quite some seminatural grazing.

The expert did not indicate specific locations, but they provided feedback on two of the crucial input sources. One was critical feedback on the Corine land cover, as it does not capture grasslands well for Hungary. In addition, the expert said that the official data on the subnational distribution of livestock for Hungary has high uncertainties, and it may not represent the actual livestock density and spatial distribution of cattle in Hungary. For example, most of the cattle are kept indoors, with only sheep grazing in many areas. The LUCAS data maps these areas as grazed, but it does not distinguish between different animals. This means that the potential grazing distribution is also biased towards small ruminants. The expert advised us to use IACS data, but unfortunately, these are not publicly available.

The overall opinion of our map by the expert was highly negative, especially in terms of the detailed locations of grassland management. Therefore, we consider that the detailed mapping of grassland management for Hungary is highly uncertain, but that no alternatives currently exist.

Feedback from Ireland

The initial map (left side of Figure 24) did not have sufficient spatial variability according to the experts because we initially used NUTS3-level livestock data. After we managed to obtain more detailed livestock statistics (for electoral areas), the spatial pattern indicated much more diversity in grazing densities and grassland management. The experts were satisfied with the new map (right side of Figure 24). The use of Corine land cover did not seem to be a large issue for Ireland, probably due to the fact that a large share of grasslands covers the country.

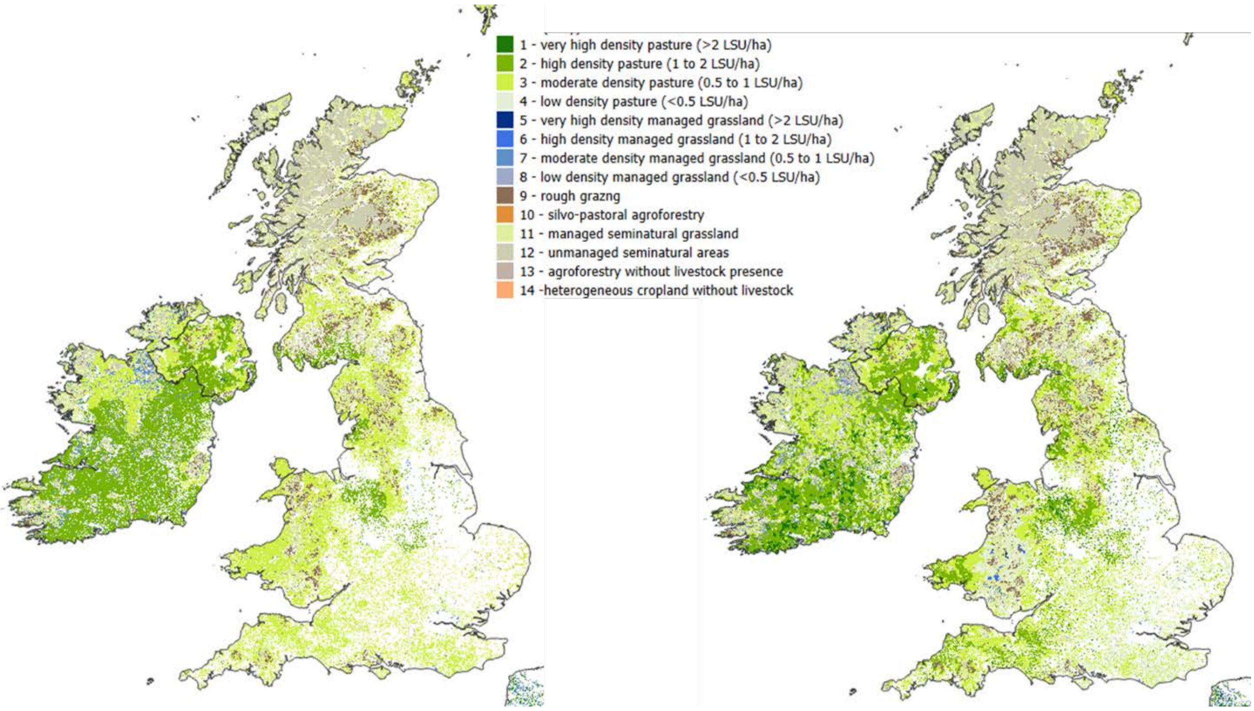

Figure 24: Initial classification with NUTS3 level statistics on livestock numbers (left) against the improved classification using detailed local statistics (right) for Ireland and the United Kingdom.

Feedback from Italy

Overall, the Italian grazing experts agreed with the map. However, they commented on the fact that we only focus on two main categories, i.e., grazing vs. non-grazing. In reality, there are systems in which both co-occur, or a system where the grass is being harvested once a year in extensive systems, and up to 8 times a year in more intensive systems. While livestock density could be used as a proxy for areas that are cut more often, the map omits systems that are both grazed and mown in the same year.

In addition, many permanent grasslands are maintained without hosting productive activities, for example, for landscape conservation. Our data misses such areas, potentially classifying them as unmanaged and ungrazed.

The experts see great potential for using the grassland management map to estimate biodiversity (e.g., bird species), pollution, etc., in order to identify areas where livestock activities are too intensive.

Finally, the Italian experts indicated that the reliability of the data is questionable in some instances, because we allocated grasslands in forests. This is a result of using Corine land cover, which maps forested areas as open landscapes in some instances.

Feedback from the Netherlands

The experts were satisfied with the western part of the Netherlands. However, they felt that grazing areas were underreported for the eastern part of the country. While statistics also suggest that there is less grazing in the eastern and southern provinces of the Netherlands, compared to the Western ones, they indicated that grazing in large holdings in the east and south of the country could also occur in shorter periods, right next to indoor barns where cattle are kept. For this reason, such grazing could be underreported both in the LUCAS data and in national statistics.

Additionally, the experts agreed that areas in the Netherlands with extremely high densities of indoor cattle cannot really be mapped well, as these are often systems with an unusually high share of calves in the total cattle due to the intensive nature of the dairy industry. Such calves are quickly removed from the farms (and are even exported in large numbers), meaning that they actually do not put pressure on local grasslands. Mapping such extremely intensive systems, therefore, remains a challenge. We addressed this challenge by allocating cattle in 'problematic' municipalities as zero-grazing systems, i.e., on managed grasslands and not on pastures.

Finally, the experts felt that the estimated share of grazed grasslands (around 50%) is slightly too low, and that it should actually be around 60%. With no data to support this, we kept the original share.

Feedback from Portugal and Spain

Portuguese and Spanish experts agreed with the diversity of the grazing systems for Portugal and Spain, particularly capturing the mosaic woodland-grasslands with low grazing densities in South and Central Spain, moderate density grazing systems in northwestern Spain, and intensive livestock systems with low grazing shares in Catalonia. Nevertheless, they highlighted that even within individual regions, there might be more diversity, and that the refinement of the map could improve areas in Granada and the Portuguese and Spanish islands. However, particularly in the Azores and the Canary Islands, such systems could be difficult to map.

The experts also emphasized that grazing cattle and cattle spending time outdoors are two different things in Spain. Due to semiarid conditions, in many regions, most of the cattle spend their time outdoors, but they do not graze and are provided feed from other sources or nearby regions. This means that while animals are outside, they do not directly impact the grasslands as they do not graze. The dehesas of Extremadura are one such case, where over 90% of cattle are on pastures, but less than a fifth (according to statistical data) actually graze.

Feedback from the Slovenia

The map for Slovenia represents grassland management well at the country scale. However, it was considered unsuitable for a detailed local scale. The experts indicated that the issue lies with using Corine land cover, as it is unable to map land cover at such a detailed scale. Many areas not managed at all are mapped as such, and even areas that are managed can be mapped as forests or other areas in Slovenia, meaning that Corine both under- and over-reports many land cover types.

The experts suggested using this map for identifying patterns at a landscape or regional scale rather than a local scale, and to prepare data with another input. For Slovenia, the IACS data are publicly available, so this is one option for the future.

Given all the comments and due to the uncertainty of Corine land cover, the map is of high uncertainty for Slovenia when looking at grazing at a local scale.

Feedback from the UK

Overall, the feedback on the cattle density and grassland management map for the UK was very positive. The feedback on the first version of the map indicated that the subnational data used was too coarse (as it was available for NUTS2 regions). Particularly in northern England, Cornwall and Wales, the regional average cattle densities resulted in relatively low densities across the whole region (Figure 23).

We managed to obtain more detailed data (now available at the ward level), which solved these issues. For example, instead of having low densities across most of Wales, we now identify individual clusters of high cattle density in Western Wales (right side of Figure 23). The experts involved in the validation process were satisfied with the updated map.