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Validation samples for the Land Cover Map of Europe 2017

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Abstract. Accuracy assessment is an integral part of the production of land cover/ land use maps. The process requires the availability of a good-quality validation dataset for the qualitative and quantitative evaluation of generated products. This paper describes the development of the validation dataset that was used for the accuracy assessment of the Land Cover Map of Europe 2017 in the context of the Sentinel-2 Global Land Cover project. Sample selection was based on a two-step stratified random sampling process. In the first step, validation sites (Sentinel-2 tiles) were selected randomly and in proportion to the area covered by each country. In the second step, validation sites were stratified with the CORINE Land Cover dataset, which enabled the proportional selection of land cover classes. The selected samples were visually inspected by experts who categorised them into 13 classes. This resulted in a large set of 52,024 samples, spread over Europe. The final dataset can be used to validate European land cover products at continental scale, and may also be included in larger (e.g. global) datasets, or for country-based studies.

1 Background & Summary

Validation datasets as a result of well-designed validation methodology are a prerequisite for performing reliable and objective accuracy assessments (validation) of remote sensing products, notably land cover/ land use (LCLU) thematic maps (Herold et al., 2009). Such an assessment is essential to verify the quality of LCLU thematic products and thus their usability for purposes such as spatial planning, the assessment and management of natural resources, or climate change analyses. Well-designed and correctly prepared validation data can be used for many different purposes, and allow the assessment of the quality of maps at different resolutions or thematic levels. Although several efforts have been made to create multi-purpose global or regional LCLU reference datasets (Olofsson et al., 2012; Tsendbazar et al., 2015), their practical application remain limited and the proposed validation systems are difficult to re-use due to either their spatial extent, sample distribution or temporal coverage. Furthermore, existing reference datasets are often irrelevant due to the coarse spatial resolution used for global mapping. However, the number of high spatial resolution LCLU databases that are coherent with, and inherited from Sentinel-2 data (10 m) is increasing (Gong et al., 2019; Li et al., 2020; Malinowski et al., 2020; Venter and Sydenham, 2021), and the development and provision of a performant reference dataset is highly beneficial.

In this context, we present the validation dataset created within the Sentinel-2 Global Land Cover (S2GLC) project (Sentinel-2 Global Land Cover Project, 2026). Development of this dataset and the sampling strategy used aimed at supporting accuracy assessment of pan-European LCLU database at both continental and country levels. The outcome was a large dataset composed of over 50,000 samples covering Europe, which have been used only for accuracy assessment purposes. The prepared samples represent different climatic regions and conditions, and all of the countries mapped within the context of the S2GLC project. The classification system consists of 13, relatively common and general LCLU classes that can either be used directly, or easily adjusted for the validation of other products. The dataset was prepared for validation of products with 10 m spatial resolution and, more specifically, is suited to products based on the Sentinel-2 pixel alignment. Our samples can be used for validation of products covering selected regions, or the whole European continent, and could be fused with other samples as part of a global validation dataset.

Two-stage stratified random sampling (the most common method used for existing global reference datasets (Tsendbazar et al., 2015)) was applied. First, validation sites (Sentinel-2 tiles) were selected with country borders as stratum. In the second stage, (proportional) sample selection was performed for each validation site by stratifying samples between LCLU classes using the CORINE Land Cover (CLC) data. Therefore, the selected samples represent a relatively proportional distribution between countries of interest.

Labelling of sample candidates was based on a visual interpretation of Earth observation (EO) data (with higher quality than Sentinel-2, e.g. Planet Labs and Google Earth) by experts, using the Sentinel-2 pixel as the sample unit. Labelled data were further verified by an team of independent specialists.

The data described in this paper were acquired for a single time frame, namely the year 2017, but given the limited annual change in European land cover (in the range of 1.5–2.5%) (Feranec et al., 2010; Winkler et al., 2021) the produced dataset could also be used directly to assess products derived for a few years before or after 2017 (e.g. ±1 or 2 years). This is not unusual, as numerous existing LCLU products have been produced and cross-validated using databases that date back a couple of years (Inglada et al., 2017; Malinowski et al., 2020; Pflugmacher et al., 2019).

The advantage of producing and maintaining such a dataset is that it ensures that data are fully independent. This, in turn, enables a highly objective assessment of LCLU products, and overcomes the need for cross-validation techniques that are based on samples that are used in both the training and validation of spatial products. Moreover, as annual change in land cover is limited, the reuse of such data would only require, in most cases, verification of the class, rather than a new visual interpretation of updated EO data.

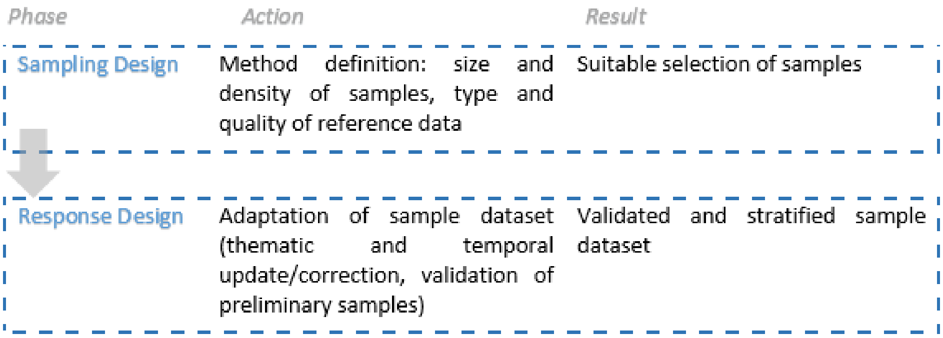
2 Methods

The aim of the S2GLC project was to develop a LCLU classification of Europe based on the set of Sentinel-2 imagery (Malinowski et al., 2020). The specific objective of the validation dataset that was created was to assess the accuracy of the

LCLU map produced by the project. The method adopted to create the validation dataset required consideration of the map specification, data limitations, as well as the final end use. The following issues were considered:

- Thematic reference data used for sample labelling should be independent of any data used during production;
- Reference data should cover the same time period as the classification product being validated;
- Validation approaches must consider product characteristics, including technical specifications (e.g. generalization criteria), production methods and limitations of the underlying data (e.g. geometric misregistration of EO data);
- Regional information and knowledge should be included, as they are very important factors.

The construction of the validation dataset consisted of two steps: sampling design and response design (see Figure 1).



Phase	Action	Result
Sampling Design	Method definition: size and density of samples, type and quality of reference data	Suitable selection of samples
Response Design	Adaptation of sample dataset (thematic and temporal update/correction, validation of preliminary samples)	Validated and stratified sample dataset

Figure 1: The overall workflow used to develop the validation dataset.

Sampling design defines the locations where map information will be validated and where reference data will be collected (and, if necessary, verified). It includes the selection of layers, the definition of sampling frame, sampling units, and the determination of sample sizes. Details of this step are presented in the following sections (*Sampling Design – site selection* and *Sampling Design – initial dataset selection*).

Response design refers to the protocol used to obtain the situation on the ground (i.e. selecting, preparing, and extracting information from ground or reference data) for each sample unit. Access to consistent *in-situ* data (even if collected via “virtual truthing”) is a key factor in the successful creation of a reliable validation dataset. Details of this step are presented in the section *Response Design – verification of the selected sample dataset.*

The applied methodology follows the Committee on Earth Observation Satellites (CEOS) guidance (Tyukavina et al., 2025), where map accuracy assessment is based on three main steps: 1) sampling design, 2) response design and 3) analysis. The first two are the subject of this paper; the third step is presented in Malinowski et al. (2020). Moreover, a complementary technical guideline, developed within INSPIRE (European Commission et al., 2013), has been implemented for general data quality evaluation of the developed database - Validation samples for the Land Cover Map of Europe 2017.

2.1 Sampling Design – primary sample units

In this specific case, two stage cluster sampling was applied. Primary sample units (validation sites) were randomly selected fromthe list of all Sentinel-2 tiles, intersecting with the area of European countries (classified within S2GLC project) with additional condition, that tile's area is covered by land in at least 75%. In this way, 10% of the Sentinel-2 tiles covering each of the mapped countries were randomly selected, except Andorra, the Vatican, San Marino and Lichtenstein (Figure 2). Luxemburg is presented within one of the three locations selected for Germany, and in the summary we refer to the validation sample for Germany and Luxemburg as one area of interest (Figure 3a). For the smallest countries, 10% of the number of tiles was close to zero. In these cases, it was decided to randomly select one tile. These tiles are referred to as 'added' sites (Figure 2). Table 1 presents a summary of the randomly selected sites. **Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.**Table 1

Table 1. Summary of randomly selected sites.

No. of 'base' sites (10% per country)	No. of 'added' sites	Total no. of sites	Mean country area coverage
45	10	55	21%

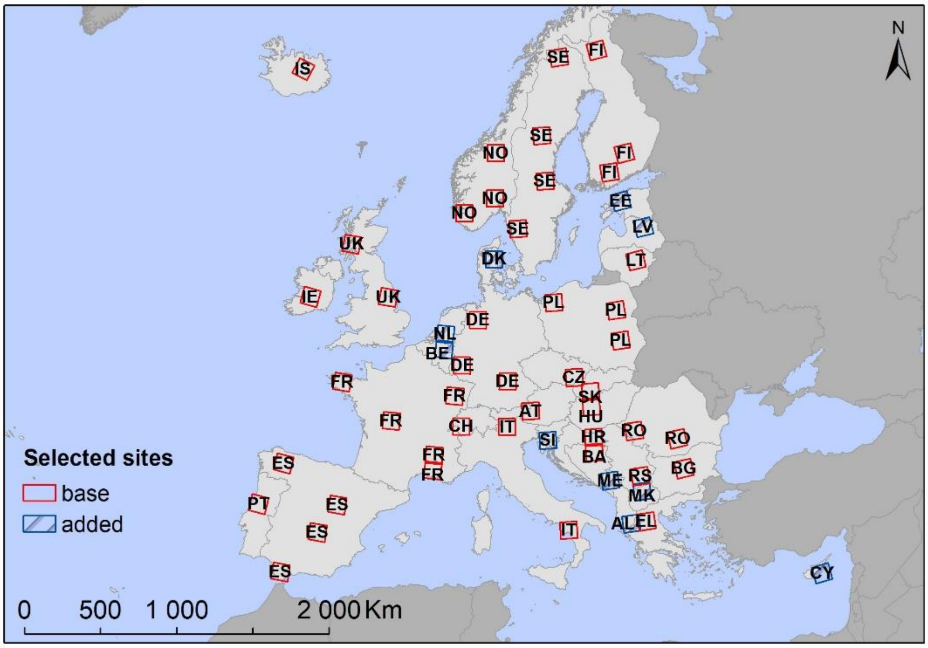


Figure 2: Map showing randomly selected primary sampling units – validationssites (country names are coded). 'Base' indicates 10% of tiles per country. 'Added' refers to small countries where the default selection of 10% of tiles was close to zero.

In the set of added sites, two were located on the border of two countries (Figure 3b and c). These sites were therefore combined with the sites that were selected for the neighbouring country, and are presented in the summary as validation sites for two countries (Table 3). This was the case for the following pairs: Albania and Greece, and Croatia and Slovenia.

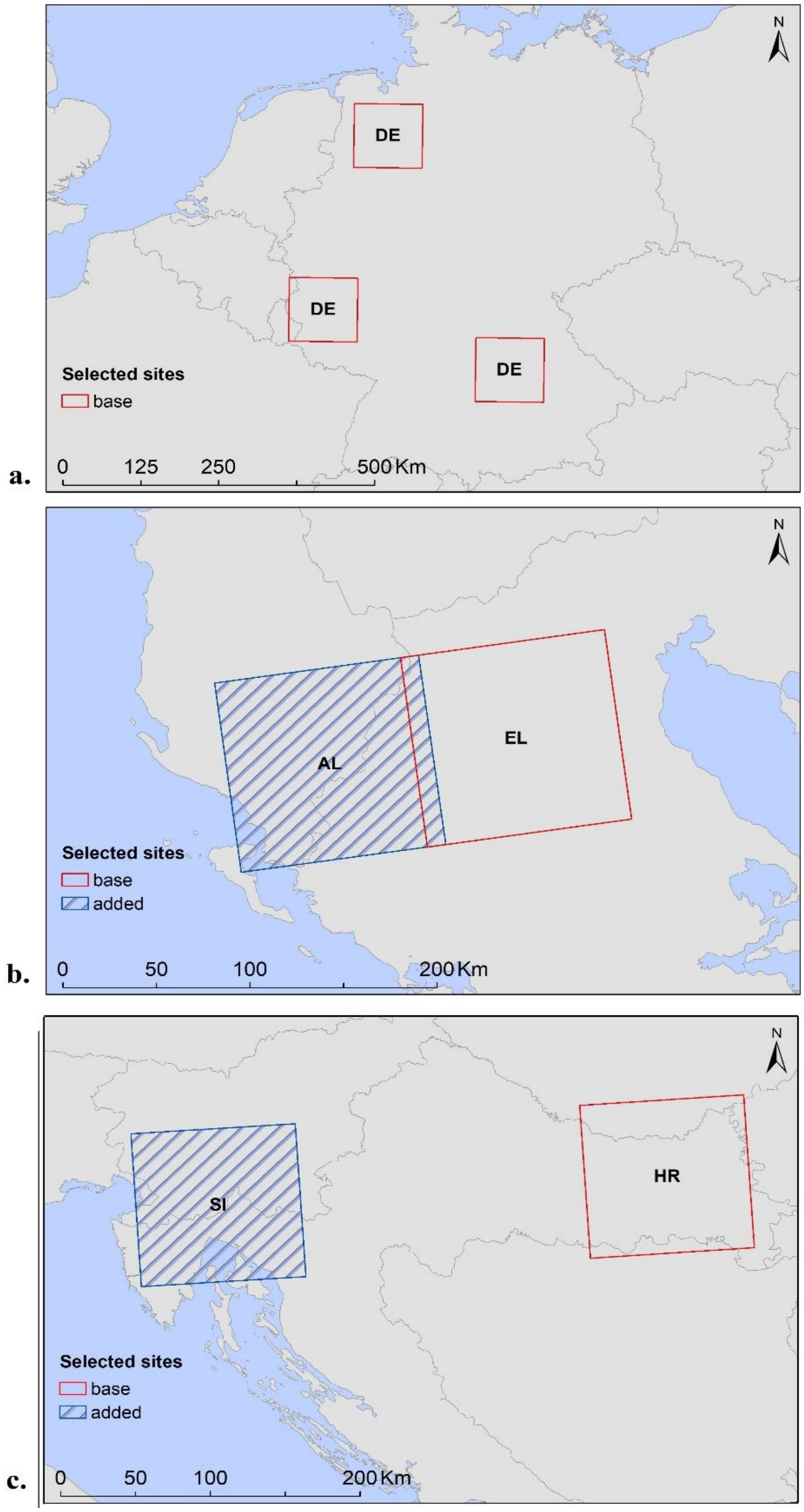


Figure 3: Example of merged country sites for: (a) Germany and Luxemburg, (b) Albania and Greece, and (c) Croatia and Slovenia.

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2.2 Sampling Design – secondary sample units

The initial sampling design phase established the methods, notably the data to be used and the technology to be applied. It also included the selection of strata, the definition of sampling units, and their size.

An adequate sample set requires sufficient samples that are, on the one hand, representative (i.e. it must reflect all of the relevant information that sampling is intended to test) and, on the other hand, significant (i.e. it must be large enough to ensure that the results are reliable). Additionally, sample units must be well-distributed across the area of interest.

To meet these requirements, stratified random sampling was performed. The aim was to ensure that the accuracy estimation was sufficient for all classes, taking into account their frequency of occurrence (ISO 19157:2013). Stratification was based on available reference data, namely the CLC data. LCLU classes were selected based on the class legend developed in Malinowski et al. (2020), which lists classes of interest (Table 2). The legend originates from the S2GLC classification system, which was designed to include relatively general and common classes. The class definitions were determined, on the one hand, by the need to enable automated selection of reference samples for EO data classification from existing databases, e.g., CLC. On the other hand, the classes were required to be highly homogeneous and to represent similar characteristics across Europe.

An additional class was prepared by combining the remaining CLC classes into one ‘other’ class. Samples were randomly selected within strata according to the proportion of a given class covered by a Sentinel-2 tile, and were provided without the pre-determined LCLU class in the attribute table. Figure 4 illustrates the validation samples selected for the tile 29TNE (Portugal) as example.

Table 2. Description of land cover classes(Malinowski et al., 2020).

Code	S2GLC class name	Description
111	Artificial surfaces	All surfaces where the landscape has been changed by, or is under the influence of human activities that replace natural surfaces with artificial abiotic constructions or artificial materials.
121	Natural material surfaces (consolidated and un-consolidated)	Any kind of unvegetated surface material including consolidated and un-consolidated surfaces. Any surface with loose mineral particles of any size e.g. mountain slope debris, glacier moraines, river pebble banks, beaches, sand dunes (unvegetated) extraction sites or quarries.
211	Broadleaf tree cover	Land covered with broadleaved tree canopy that loses leaves seasonally, regardless of the plant height.
212	Coniferous tree cover	Land covered with needle-leaved tree canopy that do not lose needles seasonally, regardless of the plant height.
221	Herbaceous vegetation	Land covered by herbaceous vegetation, including both natural, low productivity grassland and managed grassland, used for grazing and/ or mowing.

Code	S2GLC class name	Description
222	Moors and Heathland	Low growing vegetation with closed cover, and with predominately shrub and bushy vegetation (limited herbaceous species allowed).
223	Sclerophyllous vegetation	Bushy sclerophyllous vegetation characteristic of the Mediterranean climate, including maquis and garrige. May exist in both closed and discontinuous cover.
311	Cultivated areas	Cultivated areas managed by humans that include non-irrigated and irrigated arable land with different crops, and land under rice cultivation. It also includes temporary bare soils (e.g. fallow lands).
312	Vineyards	Areas planted with vines.
411	Marshes	Low-lying areas covered with non-woody vegetation distinguished by the presence of water at the surface (waterlogged) either permanent or temporary, due to high precipitation rates or flooding by fresh or sea water.
412	Peatbogs	Peatlands with deposits of decomposed moss or other dead plant material (including exploited peatlands).
511	Water bodies	Water in a liquid state of aggregation regardless of location, shape, salinity and origin (natural or artificial).
611	Permanent snow cover	Snow cover that persists throughout the year, above the climatic snow line. Persistent ice cover formed by the accumulation of snow.

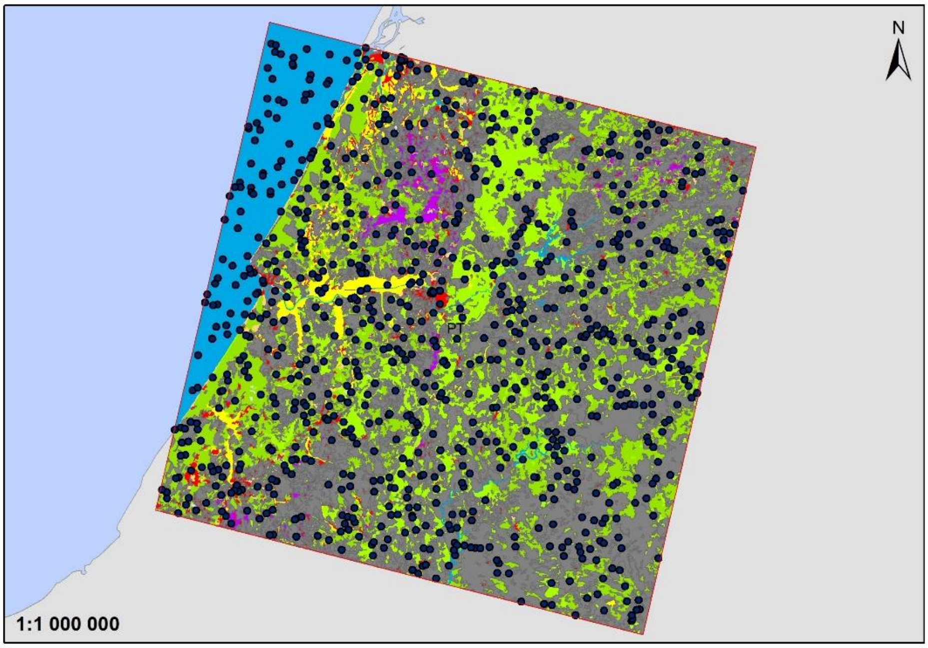

Figure 4: Illustration of randomly selected validation samples from the 29TNE Sentinel-2 granule. LCLU classes of interest are shown in random colours, while the grey area represents the 'other' class.

As the number of reference sample units can vary depending on several factors, notably the scale of the generated map, and the size of the area of interest (Congalton and Green, 2009), the total number of sample units (representing the area of a single pixel) was estimated as $n = 800$ per validation site. Although this number was limited by time and resource constraints, the selected set is statistically representative of LCLU classes.

The initial number of the number of preselected sample units was increased to approximately 1,000, because some of them could be eliminated due to their location at the LCLU class boundary or because an interpreter had great difficulty distinguishing between classes.

In addition, the following conditions were applied during stratification:

- LCLU classes that covered less than 0.95% of the area of a tile (granule) were excluded from validation, and no sample was selected;
- for LCLU classes that covered 0.95–2% of a tile (granule), the minimum number of sample units was adjusted manually, and equalled 20;
- for the LCLU classes *Artificial surfaces and constructions* and *Natural material surfaces*, the minimum number of sample units was set to a default of 20, even if the class covered less than 0.95% of the tile (granule).

This process ended in the production of a set of 55,000 initial validation samples for 55 tiles.

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2.3 Response Design – verification of the selected sample dataset

The response design encompasses all activities related to ensuring the thematic and geometric quality of the initially-selected validation samples.

The first step was to verify the location of the initial samples together with their nearest neighbourhood by drawing a 3×3 pixel window. These locations needed to clearly show the occurrence of a single, definitive class. The aim of the process was to limit any potential geometric errors caused by misregistration of Sentinel-2 time series (Kukawska et al., 2017). The second step was to verify the thematic relevance of the initial samples with respect to the real world, represented by reference data. This procedure involves sample labelling based on visual image interpretation by experienced and trained interpreters. These interpreters examine EO imagery that is independent of the production phase, and that is of the same or higher resolution, and of the same date compared to the data used to classify the LCLU map.

In cases where it was difficult to distinguish between two similar classes shown on satellite imagery (e.g. vineyards and fruit trees), additional sources of information such as aerial or ground photography provided by Google Earth were consulted. If the extended analysis did not result in a clear class identification, the considered sample was removed from the database.

In this context, statistics were generated regarding the initial number of samples per tile, the final number of samples per tile, and the distribution of selected classes per tile (Table 3). In total, 7% of samples were rejected, meaning that over 900 samples could be classified for most tiles.

Table 3. *S*ummary of validation sites represented by Sentinel-2 tiles and sample selection.

Country	Country code	Validation sites	Area covered (%)	No. of validation samples	No. of validated classes
Albania, Greece	AL, EL	34TDK, 34TEK	15%	1949	9
Austria	AT	33TUN	14%	951	9
Belgium	BE	31UFS	39%	1013	9
Bosnia and Herzegovina	BA	33TYK	24%	901	9
Bulgaria	BG	35TLH	11%	999	8
Croatia, Slovenia	HR, SI	33TVL, 33TYL	32%	1846	9
Cyprus	CY	36SWD	46%	872	8
Czechia	CZ	33UXQ	15%	968	9
Denmark	DK	32VNH	28%	979	9
Estonia	EE	35VLF	27%	935	10
Finland	FI	34VFN, 35WMR, 35VMJ	11%	2765	10

Country	Country code	Validation sites	Area covered (%)	No. of validation samples	No. of validated classes
France	FR	30UVU, 31TCM, 31TFK, 31TFJ, 31UGP	9%	4901	12
Germany, Luxemburg	DE	32ULA, 32UMD, 32UPV	10%	2963	11
Hungary	HU	33TYN	13%	928	9
Iceland	IS	27WXN	12%	976	7
Ireland	IE	29UNU	17%	936	10
Italy	IT	32TPS, 33TWE	8%	1770	11
Latvia	LV	35VMD	19%	910	10
Lithuania	LT	35ULB	19%	988	10
Montenegro	ME	34TCN	87%	941	9
Netherlands	NL	31UFT	32%	934	10
North Macedonia	MK	34TEM	48%	986	8
Norway	NO	32VLL, 32VNM, 32VNQ	7%	2732	10
Poland	PL	33UWV, 34UEB, 34UED	8%	2856	10
Portugal	PT	29TNE	13%	908	11
Romania	RO	34TER, 35TLK	10%	1963	10
Serbia	RS	34TCN	14%	1052	9
Slovakia	SK	33UYP	25%	976	9
Spain	ES	29TPH, 30STF, 30SVJ, 30TWL	10%	3531	12
Sweden	SE	33VUE, 33VWH, 33VWL, 34WDA	11%	3848	10
Switzerland	CH	32TLS	29%	908	10
United Kingdom	UK	30VUH, 30UXE	10%	1906	10

3 Data Records

Validation samples were stored in the form of a vector dataset (ESRI Shapefile) and can be assessed from the PANGAEA repository (https://doi.pangaea.de/10.1594/PANGAEA.934197). Each sample includes three attributes:

- S2GLC – the LCLU class code according to the S2GLC classification system (Sentinel-2 Global Land Cover Project, 2026). Class names and descriptions are presented in Table 2.
- TILE – the Sentinel-2 granule or a tile in the Military Grid Reference System (Anon, 2013; Gascon et al., 2017).
- NAME_ENG – the English name of the country (for both inland and coastal areas). Country names and administrative boundaries are provided by Eurostat, notably the Countries 2020 Administrative Units Dataset (Country names, 2020).

The total number of samples was 52,024, covering both land and water. An example of a data record is presented in Table 4. The Lambert Azimuthal Equal Area (LAEA) projection was used (EPSG: 3035).

Table 5 lists the number of samples located within the borders of specific countries.

Table 4. An example of the attributes table for selected samples.

S2GLC	TILE	NAME_ENG
231	27WXN	Iceland
312	33UWV	Poland
211	35ULB	Lithuania

Table 5. The number of S2GLC validation samples in each country.

Albania	Austria	Belgium	Bosnia and Herzegovina	Bulgaria
641	940	896	948	999
Croatia	**Cyprus**	**Czechia**	**Denmark**	**Estonia**
1149	872	817	979	1008
Finland	**France**	**Germany**	**Greece**	**Hungary**
2765	5056	2975	1361	1195
Iceland	**Ireland**	**Italy**	**Latvia**	**Lithuania**
974	936	1737	836	988
Luxembourg	**Montenegro**	**The Netherlands**	**North Macedonia**	**Norway**
64	807	1065	768	2762
Poland	**Portugal**	**Romania**	**Serbia**	**Slovakia**
2856	908	1901	1360	976
Slovenia	**Spain**	**Sweden**	**Switzerland**	**United Kingdom**
460	3531	3815	778	1901

4 Data quality by INSPIRE

In order to ensure the usability of the generated database (i.e. reading, interpreting, analysing and ultimately integrating the provided information) a technical verification must be conducted to eliminate any ambiguity and possible misuse. Under the INSPIRE Directive, a guideline was developed as complementary to CEOS guidelines, related to land cover data (European Commission et al., 2013).

Technical verification parameters, following INSPIRE technical guide, were grouped into three categories: the reliability of the information; its consistency; and the completeness of product information support (product usability). Reliability reflects the degree to which the information contained in the produced database is consistent and stable (i.e. the extent to which it is error-free and logical). The evaluation was supported by evidence that was gathered internally during the creation of the sample dataset, and externally consolidated by independent experts who carried out a visual inspection and gave their opinion on its geometric and thematic accuracy. These activities were carried out in the *Response Design* stage.

The two categories of consistency and the completeness of information support (product usability) focus on internal contradictions between different product components (including metadata) or with respect to specifications. If a contradiction was found between two or more components, the erroneous components were eliminated or corrected. Consistency verification only requires the product itself and the specification as input, in contrast to the reliability check where reference data are needed.

Different parameters and methods were used depending on the product information support. In these cases, checks were based on various quality attributes, and the results are presented in Table 6.

Table 6. Product quality evaluation.

Quality Check Attributes		Results	Remarks
Database			
Completeness of Support Information		Error count:0	Legend attached.
Thematic content		Error count:0	Presence of selected classes.
Reliability		Error count:0	Independent verification.
Readability		Error count:0	No spelling or numerical errors; consistent nomenclature.
Vector Data			
Consistency	**Temporal**	Error count:0	2017
	Topology	Error count:0 Error rate: 0.0%	Absence of overlapping; samples within tiles; stratification preserved.

	Projection	Error count:0	LAEA; EPSG: 3035.
Completeness		Error count:0	Vector data, metadata and ‘shp’ mandatory files are complete.

5 Usage Notes

The presented dataset contains information on LCLU classes identified for selected locations and representing areas of 10×10 m coherent with Sentinel-2 data pixels for the year 2017. Despite being based on 2017 data, the dataset continues to offer valuable insights for current applications. There are various scenarios regarding how this dataset could be reused. Two main approaches would be to train classifiers or validate LCLU maps that have been generated using other algorithms or satellite images. It can be used to assess the accuracy of pan-European or regional LCLU maps (Witjes et al., 2022, 2024), or fused with other datasets for global product analysis. Additionally, by selecting samples from a specific tile, the dataset could serve as a benchmark when comparing various classification approaches. Before application of the presented data, potential users are encouraged to consult the LCLU class definitions given in Table 2.

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7 Author Contributions

M.J-S. conceptualised, designed and supervised the process of sample selection, and wrote the paper. E.K. and P.S. were responsible for the response design phase. E.G. supervised the process of technical validation. R.M. and M.K. participated in the preparation and writing of this paper. S.L. led the S2GLC project and supervised the related activities. M.R. and C.W. were involved in the preparation of the spatial databases used for sample selection. All of the authors reviewed the manuscript and approved the final version.

8 Competing Interests

The authors declare no competing interests.

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