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Article

Open Geospatial System for LUCAS In Situ Data Harmonization and Distribution

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Abstract: The use of in situ references in Earth observation monitoring is a fundamental need. LUCAS (Land Use and Coverage Area frame Survey) is an activity which has performed repeated in situ surveys over Europe every three years since 2006. The dataset is unique in many aspects, however it is currently not available through a standardized interface, machine-to-machine. Moreover, the evolution of the surveys limits the change analysis with the dataset. Our goal was to develop an open-source system to fill these gaps. This paper presents a developed system solution for the LUCAS in situ data harmonization and distribution. We have designed a multi-layer client-server system which can be integrated into end-to-end workflows. It provides data through an OGC (Open Geospatial Consortium) compliant interface. Moreover, a geospatial user can integrate the data through a Python API (Application Programming Interface) to ease the use in the workflows with spatial, temporal, attribute, and thematic filters. On top of that, we have implemented a QGIS plugin to retrieve the spatio-temporal subsets of the data interactively. Additionally, the Python API includes methods to manage thematic information. The system provides enhanced functionality which is demonstrated in two application use cases.

Keywords: LUCAS; in situ; data harmonization; data distribution; web services; QGIS plugin

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1. Introduction

The use of independent in situ references in Earth observation monitoring is a fundamental need [1]. Currently, the volume of generated geospatial datasets is increasing significantly into big data [2]. Such data are characterized by a big volume, high value, high variety, and potentially a high velocity and high veracity [3]. In order to provide the geoscience community the full opportunity to uncover the previously unknown insights, such data sets shall be assessed through a standardized, scalable, and extensible technology allowing full integration into end-to-end scientific workflows.

The European continental land cover mapping activities, which use Earth observation images, require reliable and representative in situ references for the validation and calibration of automated mapping across the whole of Europe [4]. Such references are typically developed in land cover production campaigns ad hoc from aerial orthophotos or very high resolution images, but in situ surveys are rarely performed. The difficulties with representative references are magnified when land cover change detection mapping is performed.

LUCAS, the Land Use and Coverage Area frame Survey, is an activity managed by Eurostat, which has performed in situ surveys over Europe every three years since 2006 [5]. Today, there exist a series of 2006, 2009, 2012, 2015, and 2018 observations. The surveyors mainly examine the in situ land cover (76 classes) and land use (41 classes) and take photos (one facing photo and four landscape photos in the cardinal compass directions), but also evaluate the agro-environmental information and take a 500-gram topsoil sample at one out of ten points. Recently (2018 survey), the Copernicus, INSPIRE (Infrastructure for Spatial Information in Europe), and EUNIS (European Nature Information System) attributes were added. The primary goals of the sampling were area estimates for spatial and territorial analyses such as agricultural statistics [6]. However, the use of the LUCAS dataset is manifold. There are 168,402 (2006), 234,623 (2009), 270,272 (2012), 339,696 (2015), and 337,854 (2018) sample points surveyed in the LUCAS dataset. This gives a set of 651,377 individual surveyed points on the territory of the European Union (EU) member states, while there are 319,150 samples visited at least twice and 35,204 samples visited repeatedly in all surveyed years, allowing us to evaluate land changes. The datasets total 1,350,847 individual in situ analyzed points.

There are other sampling activities, such as Geo-Wiki.org [7] and ESA GlobCover [8], providing validation datasets; these are working, however, with a considerably smaller amount of collected data and without consistently repeated observations over time. In this respect, the LUCAS dataset is unique in a number of aspects; by its spatial sampling density (2×2 km grid) covering the EU member states including the total number of in situ visited sites, by its temporal resolution (three-year frequency), and by its thematic coverage.

The LUCAS dataset was used in numerous research activities. Close et al. [9] and Weigand et al. [10] used the LUCAS dataset as training and validation reference data together with Sentinel-2 for a per-pixel supervised classification at the national level of land use and land cover. Pflugmacher et al. [11] mapped the pan-European land cover using the Landsat spectral–temporal metrics based on the European LUCAS 2018 survey. Gao et al. [12] used LUCAS data to evaluate the current global land cover maps over the EU. d'Andrimont et al. [13] used LUCAS data, together with Sentinel-1 images, to map crop types at a 10 m spatial resolution at the European level for 2018. Borrelli et al. [14] integrated a soil erosion module with the 2018 LUCAS topsoil survey to monitor the soil health status across the EU and to support actions to prevent soil degradation. All of the above-mentioned authors used the LUCAS dataset as a status dataset in their analysis; however, they only used one year of the survey, while the potential of repeated in situ measurements remained unused. We believe that the data have a far higher potential.

However, as the LUCAS activity has evolved since 2006, there are differences in separate surveys to be harmonized. d'Andrimont et al. [13] proposed and applied a number of harmonization steps related to the renaming of the database columns, re-coding of the variables, and correcting the theoretical location coordinates. Weigand et al. [10] proposed several pre-processing schemes for the LUCAS data (two positioning approaches and three semantic selection approaches). The use of the utilized LUCAS data showed a positive effect on the land cover classification accuracy, especially the positional correction of points.

Additionally, we argue that it is also important that the open reference data sets are available on-line using the state-of-the-art geospatial technology in order to allow full integration of the data (machine-to-machine) into automated processing pipelines, for instance, in the cloud environments. It is natural to use the OGC compliant interface, allowing wide integration using standards. Interoperability and standardization are crucial for achieving the information system modularity in order to seamlessly connect various software modules or components as presented in the publication of Jeppesen et al. [15]. The OGC standards have been designed to assure the interoperability of Geographical Information Systems (GIS) and the Spatial Data Infrastructure (SDI) in general [16]. Many OGC compliant implementations of scientific workflows are available [17–20]. An example of the automated coordination of OGC web services to produce thematic maps is described in the publication of Rautenbach et al. [21]. OGC specifies several open data formats and web services suitable for the geospatial data distribution and data exchange. Of particular interest are the Web Feature Service (WFS) [22] and the OGC API Features [23] suited for requesting raw vector data. In OGC-based SDI, a user can seamlessly access data stored in different file-based or database-oriented geospatial formats [24]. Vector features are commonly stored and maintained by object-relational database management systems with a geospatial extension installed. In open-source settings, the PostgreSQL database system with a geospatial PostGIS extension is widely adopted as OGC compliant DB [25,26].

Currently, individual LUCAS datasets are available for downloading in Comma Separated Values (CSV) files from the Eurostat portal [27], and the photos are available through the online LUCAS Viewer [28]. This type of distribution technology lacks the integration convenience, which prevents the data from being employed in wider end-to-end workflows. We reviewed individual surveys while preparing the spatio-temporal Land Cover mapping over the period of 2000–2019 on the European scale [29] and identified three areas of possible enhancements: (1) harmonization of the data values in the database (including variable names and data types), (2) spatio-temporal aggregation of individual datasets (including spatial coordinates harmonization), and (3) setting up an OGC compliant distribution system to provide interactive machine-to-machine accessibility.

This paper proposes and develops a technological solution to retrieve the spatio-temporal subsets of harmonized LUCAS data as part of the Geo-harmonizer project development and shares the system as an open-source code with the geoscience community.

Here, we are presenting a SpaceTime_LUCAS (ST_LUCAS) system which we have developed to process the three areas mentioned above. We have divided the overall goal into several partial objectives:

- O1 Data storage in a persistence layer;
- O2 Full and configurable automation of the harmonization process for the past and future LUCAS survey updates and space–time aggregation for change analysis;
- O3 Development of software to access the data via a standardized (OGC) web service;
- O4 Development of the client Python API and QGIS plugin to retrieve the subsets of LUCAS data based on spatio-temporal and thematic filters;
- O5 Additionally, development of translation methods to provide LUCAS land cover data in other nomenclatures and allow user-defined analytics such as, e.g., the legend aggregation.

Finally, we have demonstrated the use of the developed system in two application use cases in Section 5.

2. Materials and Methods

The architectural design of the ST_LUCAS system was derived from the objectives listed in the introduction. The methodological process follows several steps. Given the objectives (system requirements), we designed a high-level static architecture with generic functionality. For each of the system components, we specified the purpose, function, inputs, and outputs. This enabled us to evaluate the overall functionality of the system. Next, we identified the interfaces between the components and designed the data flow. After the static architecture, we designed a system dynamic architecture to evaluate the system interaction in a sequential manner. Additionally, we defined a set of tests to validate all the components, interfaces, and the data.

We designed the system using general workflow diagrams in the Unified Modeling Language (UML) 2.5, especially the UML component and sequential diagrams. The system was coded using Bash, Python 3, and Structured Query Language (SQL). The overall system was deployed using the Docker virtualization technology.

LUCAS Data Harmonization

The Eurostat LUCAS primary data collected during the five surveys of 2006, 2009, 2012, 2015, and 2018 [30–34] are the main inputs to the system. Individual surveys distributed as CSV files were downloaded to the file system along with the respective technical documentations. Additionally, the theoretical LUCAS 2018 2×2 km^2 grid from Eurostat [35] was added.

Having defined the second objective (O2) to harmonize the LUCAS dataset across the survey years, we first reviewed the instructions for surveyors and classification technical references [36–39] and the record descriptors of the primary data [40–44] to identify the changes between individual LUCAS surveys, which evolved from 2006 to 2018. These findings are the base for the harmonization process. Generally, the process consists of the spatial coordinates harmonization, attributes renaming, data values harmonization, and data types unification. We consider the 2018 survey as the most developed, also consisting of new thematic information, hence we used this year as a reference. All the database attributes and their values are harmonized to this reference. These harmonization steps were cross-checked with assumptions made by d'Andrimont et al. [13] during the system development in the Geo-harmonizer project. The harmonized attributes of the ST_LUCAS dataset are listed in Appendix A Table A2. Additionally, users can explore the coding and mapping tables online at the ST_LUCAS web page (https://geoforall.fsv.cvut.cz/st_lucas, release 1.0 published by the authors on 9 June 2022).

Individual harmonized datasets of 2006, 2009, 2012, 2015, and 2018 were consequently merged into a common database through the space–time aggregation. The goal was to create a common LUCAS database where the vector of thematic information which allows direct evaluation of, for instance, the land cover changes over individual years can be retrieved by the user for each point visited repeatedly in situ. Given the fact that the respective visits were measured by GPS, the spatial coordinates of the collected information differ in time for each point with a unique ID. The differences vary from meters to hundreds of meters (Figure 1 below).

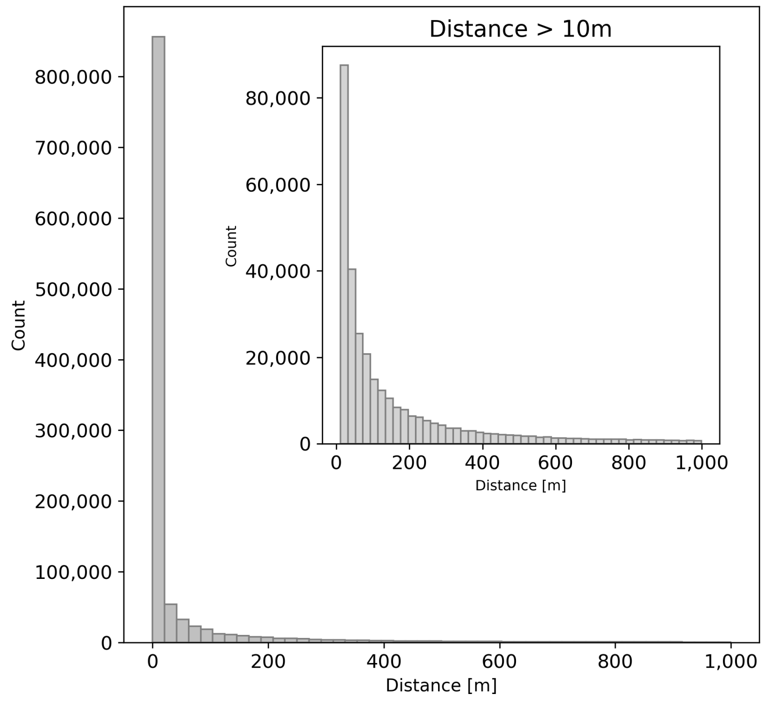


Figure 1. Distance between GPS measured and theoretical points (attribute OBS_DIST). Additionally, 35,509 points with a distance of more than 1000 m are not shown in this figure.

Therefore, we calculated the representative geometry as a geometric median of the repeated GPS measurements (Figure 2). The median was computed by the PostGIS function [45] using the Weiszfeld algorithm [46] to avoid the influence of possible outliers which are present. Additionally, we introduced a new attribute (SURVEY_DIST, Appendix A Table A2), which measures the distance between the survey GPS coordinates and the geometric median coordinates. All spatial coordinates (measured, theoretical, and median) were transformed to the common ETRS89-extended/LAEA Europe coordinate reference system (EPSG 3035).

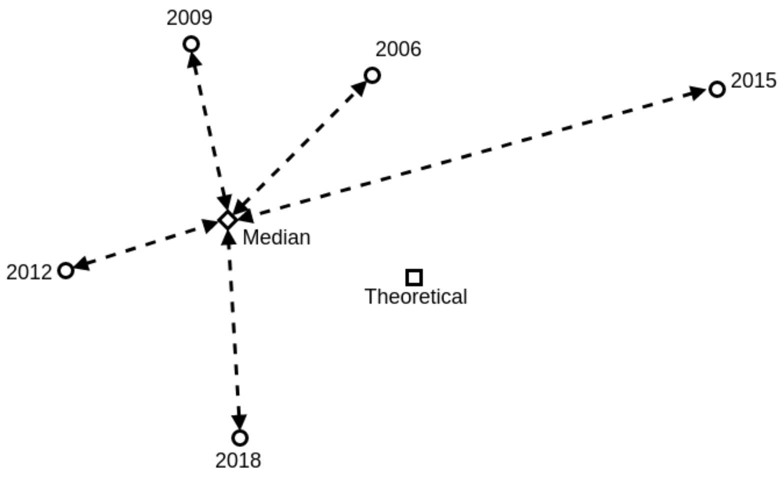


Figure 2. Space–time aggregation of observed LUCAS GPS locations (circle symbol) using the geometrical median (diamond symbol). The theoretical location snapped to a LUCAS 2 $\times$ 2 km^2 grid is represented by a rectangle symbol. The distances between GPS and median locations are shown by arrowed dashed lines.

3. System Design

This chapter presents the system design. It is split into several linked subchapters defining the system at different abstraction levels. The design starts with a high-level static architecture and the main system components, their logical structure, and decomposition. Next, the interfaces are identified and elaborated, and, finally, the system behavior is designed in the dynamic architecture.

3.1. System High-Level Architecture

The system architecture follows a typical multi-layer client-server model customized to meet the objectives defined in Section 1. The system partitions the tasks between the server side with the LUCAS dataset and clients, and the users consuming the spatio-temporal subsets of the LUCAS data. Moreover, the design also follows the idea of Component-Based Software Engineering (CBSE) as described, for instance, by Vale et al. [47].

The system, as depicted in Figure 3, is decomposed into three main layers consisting of several components (Table 1) in each of the layers. The persistence layer provides means to store the input, intermediate (separate years), and final harmonized space–time aggregated LUCAS data (O1). The main role of this layer is to preserve the data in non-volatile storage for further distribution. The main component of this layer is a database system (spatially enabled SQL database). The application layer provides the system deployment and harmonization (O2) procedures and the data distribution web service (O3). The distribution functionality is achieved by the OGC Web Feature Service. The client layer communicates—through an internal interface—with the data distribution service that provides harmonized LUCAS data to the end user. The client layer's main functionality is provided by the Python software package. The main requirement is to create requests based on user-defined spatial, attribute, thematic, and temporal filters. The client layer provides two ways to retrieve and filter the subsets of the data (O4), through a command line interface (CLI) or through a graphical user interface (GUI). The client layer has an additional defined functionality to translate the LUCAS land cover nomenclature to other legends (O5) or aggregate the legend based on customer requirements.

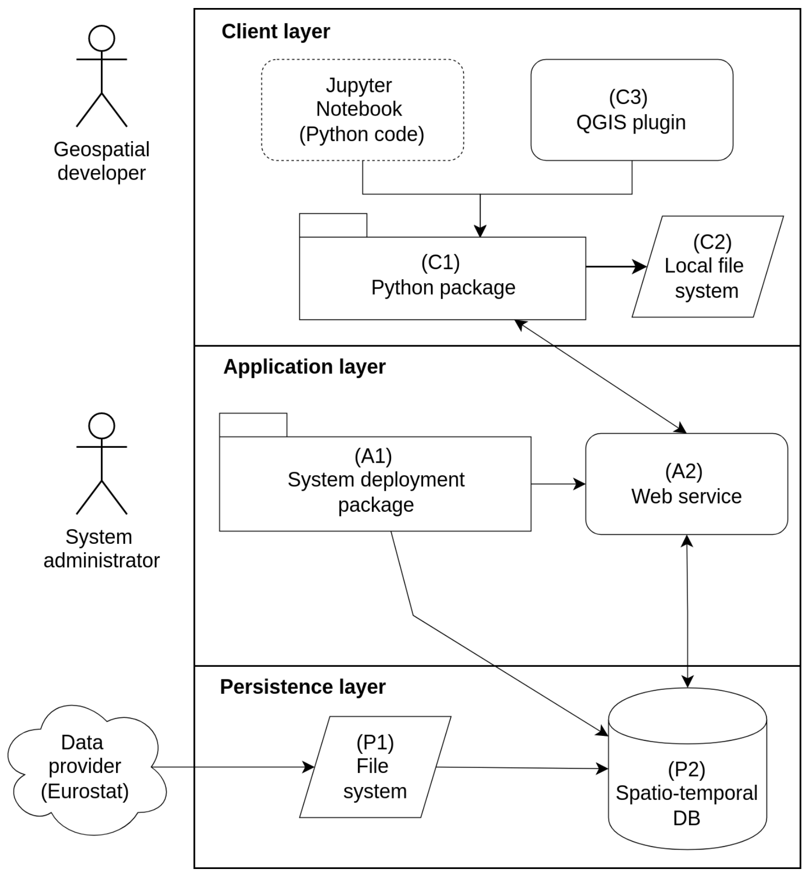


Figure 3. ST_LUCAS system's static high-level architecture. The Jupyter Notebook (dotted line) is not intended to be a software component. The Jupyter Notebook is used for presenting the Python package (C1) functionality and a manual verification in this work.

Table 1. ST_LUCAS system components overview.

ID	Name	Layer	Role	Objective
P1	File system	Persistence	Store primary data	O1
P2	Database	Persistence	Store and provide harmonized data	O1
A1	Deployment package	Application	Deploy the system including data harmonization	O2
A2	Web service	Application	Provide access to harmonized data through a web service	O3
C1	Python package	Client	API interface to a web service and a set of analytical functions	O4, O5
C2	Local file system	Client	Store locally harmonized LUCAS data	O4, O5
C3	QGIS plugin	Client	Provide GUI interface via GIS to a web service and a set of selected analytical functions	O4, O5

The system is designed for three potential high-level users. The system administrator can deploy the system as it is designed or can configure it for customized application use. The geospatial developer can access the harmonized LUCAS dataset through the Python API (e.g., using the Jupyter Notebook or directly by the Python code) in a fully automated processing pipeline. The GIS user can interactively explore and download the subsets of the LUCAS dataset via the desktop QGIS application (QGIS plugin).

The ST_LUCAS system is devised to allow full scalability. The vertical scalability can be achieved by deploying the system in the cloud environment. The horizontal scalability of the presented system can be achieved by adding multiple map server instances in the application layer.

3.2. System Interfaces

The overall system is designed as encapsulated individual software components, which provide a set of related functions. The software components communicate with each other via interfaces [48]. There are two types of interfaces, internal interfaces and external interfaces. The internal and external interfaces are illustrated using the UML component diagram in Figure 4. The internal interface provides communication between the persistence layer and the application layer (IF1). It is an interface between the database system and the web service using the OGC WFS specification where harmonized LUCAS data flow. The other internal interface provides communication between the application layer (web service) and the client Python package (IF2), which is defined by the OGC WFS specification. The external interfaces are between the client application (CLI or GUI) and the client layer Python package (IF3). Here, the web service sends requests to the spatio-temporal database and the service provides harmonized LUCAS data to the end users' client in the form of the Geography Markup Language (GML) features. A QGIS plugin/Jupyter Notebook (client layer) communicates with the ST_LUCAS system via the Python package API. This interface provides the access and functionalities to retrieve and filter harmonized spatio-temporal LUCAS data subsets from the application layer.

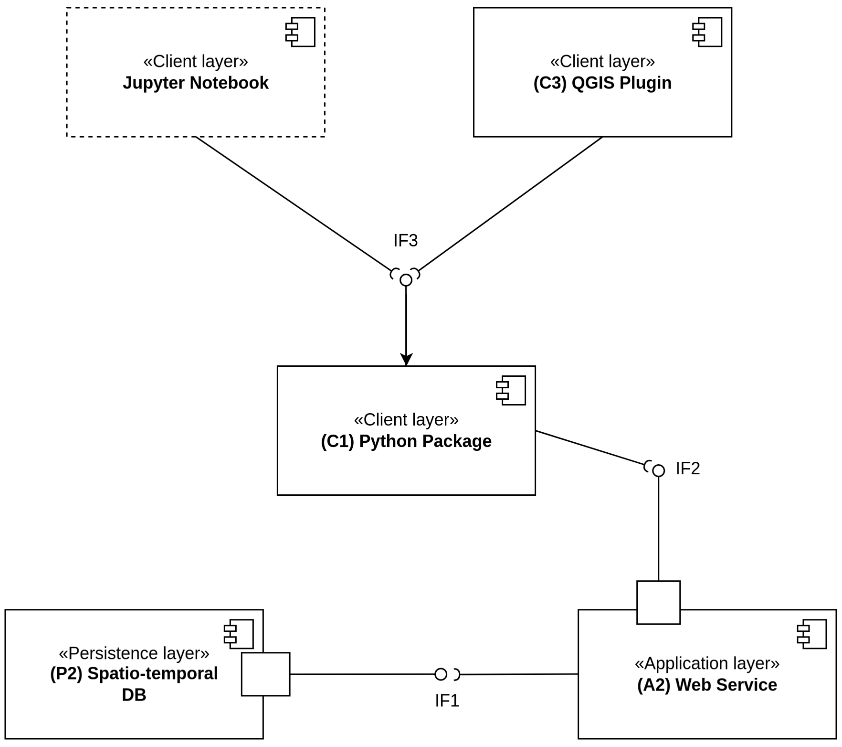


Figure 4. ST_LUCAS system software components diagram with defined interfaces.

3.3. System Dynamic Architecture

The dynamic architecture was designed by means of UML sequential diagrams to plan the interactions of the above-designed system components in time. The dynamic architecture was divided into two phases: the system deployment phase and the user interaction process.

Figure 5 presents the UML sequential diagram at the deployment phase, which is the interaction between the main components of the application layer (deployment package and web service) and the persistence layer (file system and database system). The process starts with the initial system configuration according to the administrator's requirements. Next, the deployment package (A1) performs three major operations. Firstly, the LUCAS primary data distributed in the plain CSV format are automatically downloaded from the data provider specified in the system configuration. Secondly, after a successful download of the primary CSV files to the server file system (P1), the deployment of the database system (P2) is performed. The database system deployment is split into ten sub-operations starting with a database initialization step and followed by importing the primary LUCAS data into the initialized database. The harmonization process includes the unification of spatial coordinates, attribute names, attribute data types, and data values. These operations are performed separately for each survey year. Subsequently, the space–time aggregation of harmonized LUCAS observations is applied. The deployment process is finished by creating a database dump file for the spatio-temporal database creation. Thirdly, the system web service (A2) component is deployed. Next, the harmonized LUCAS data in the database system can be published by the web service. Each of the sequential steps is followed by tests to evaluate the system performance.

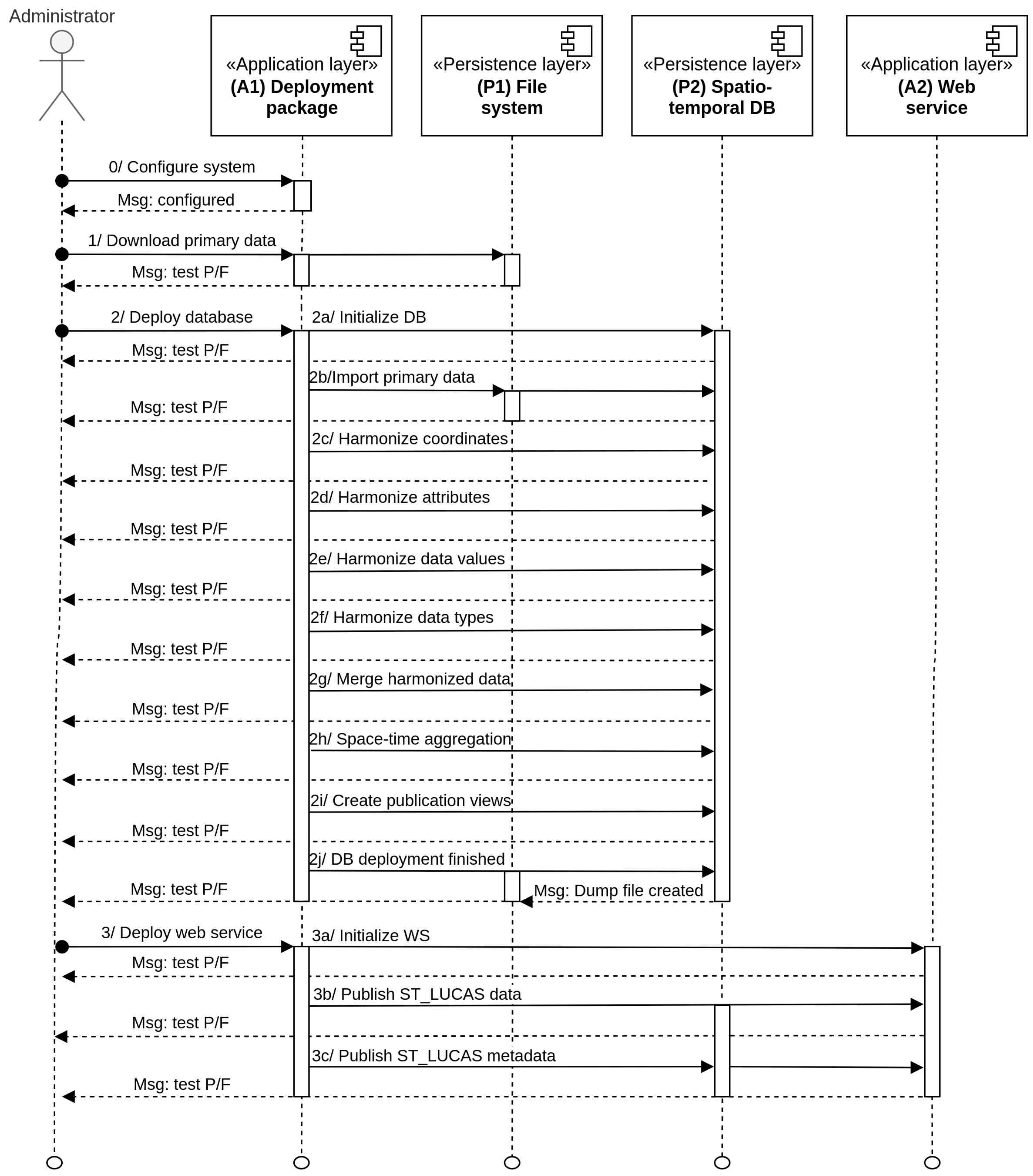


Figure 5. ST_LUCAS dynamic architecture (system deployment).

Figure 6 presents the UML sequential diagram of the user interaction process. This process is the interaction between the main components of the client side (CLI/GUI clients—C3, Python package—C1) and the server side represented by the application layer web service (A2) providing the data from the persistence layer (database system—P2). Additionally, the users' local file system (C2) is introduced in Figure 3 to illustrate the dynamic interaction with the ST_LUCAS system.

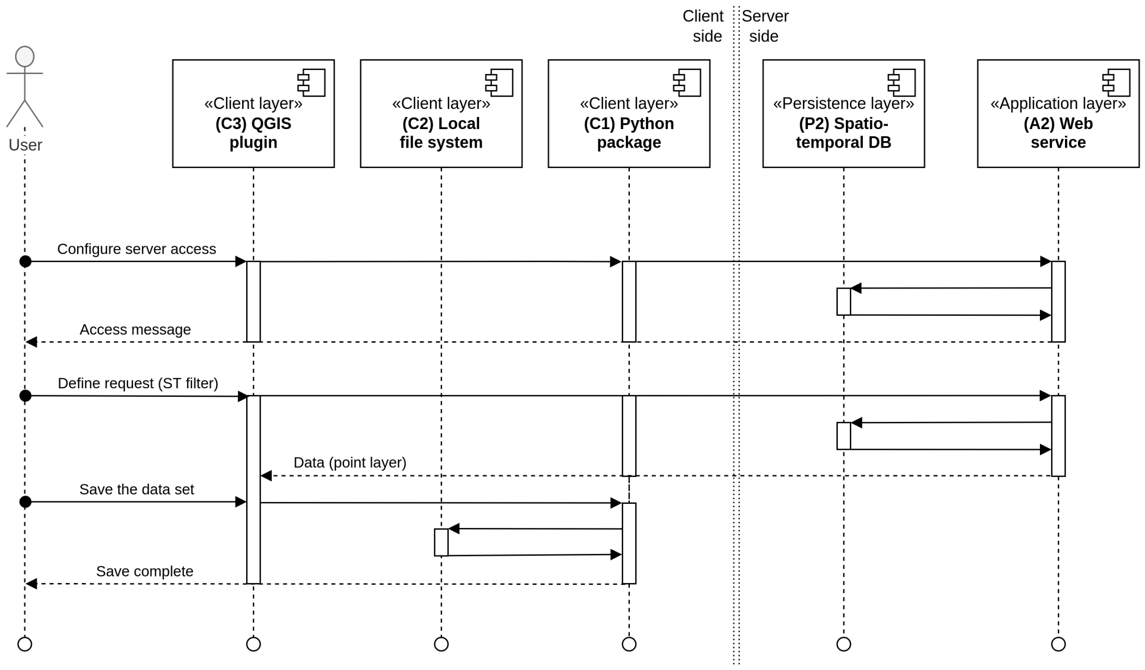

Client side
Server side
User
«Client layer» (C3) QGIS plugin
«Client layer» (C2) Local file system
«Client layer» (C1) Python package
«Persistence layer» (P2) Spatio-temporal DB
«Application layer» (A2) Web service
Configure server access
Access message
Define request (ST filter)
Data (point layer)
Save the data set
Save complete

Figure 6. ST_LUCAS dynamic architecture of the system user-interaction.

The end user can interact with the system using a GUI designed for the open-source QGIS platform or through the Python API. The QGIS plugin (C3) is built on the top of the Python package (C1) allowing easy access to harmonized space–time LUCAS data. Alternatively, the Jupyter Notebook can be used for a code-based data interaction in the Python programming language.

Initially, the server access has to be configured for accessing a web service (A2) through the Python package (C1) on the client side. As soon as the server (web service) provides information on the successful connection, the user can define the data requests. The user builds a request based on spatial, attribute, thematic, and temporal filters in order to gain a subset of the harmonized LUCAS dataset. The request is sent to the server-side web service component (A2) by the Python package (C1). The response from the server comprises a subset of the harmonized LUCAS dataset which corresponds to the filters defined in the user's request. The data retrieved from a web service (A2) are stored by the Python package (C1) on the local file system (C2).

3.4. System Validation

The system validation is a constituent part of the system design. The validation is performed at two levels. At the design (documentation) level, which allows traceability between the model components in the architecture phase, and the software level to test each component and the interface of the designed system at the system deployment, execution and external users' access.

We defined unit tests for each software component according to the detailed architectural design of the system (Figures 3–5). The ST_LUCAS system deployment process is controlled by the A1 software component. The process is formed by three major steps as shown in Figure 5: (1) download primary data (P1), (2) deploy database (P2), and (3) deploy web service (A2). Unit tests (1) validate the LUCAS primary data download process as specified in the configuration. The following set of unit tests (2) validates whether DB (P2) was initialized (2a), the primary data imported (2b), the LUCAS data harmonization process applied (2c–2h), the harmonized LUCAS data prepared for publication (2i), and the DB recovery file created (2j). The last set of unit tests (3) validates whether the web service (A2) is operational (3a) and the ST_LUCAS data (3b) and metadata (3c) are published. For the client layer, the unit tests cover the Python package (C1) and the local file system (C2) components. For the QGIS plugin (C3), manual verification is performed. The overview of unit tests is depicted in Table 2. Each test is evaluated as successful if the test result is in compliance with the system configuration; otherwise, it is evaluated as failed.

Table 2. Unit tests overview. Test IDs reflect the system dynamic architecture as presented in Figure 5.

Component ID	Test IDs	Description
A1, P1	1_001	Primary data are downloaded according to the system configuration.
A1, P2	2a_001	DB is initialized according to the system configuration.
	2b_001-003	Primary data are imported according to the system configuration.
	2c_001-002	Coordinates are harmonized according to the system configuration.
	2d_001	Attributes are harmonized according to the system configuration.
	2e_001-002	Data values are harmonized according to the system configuration.
	2f_001	Data types are harmonized according to the system configuration.
	2g_001-004	Harmonized data are merged according to the system configuration.
	2h_001-003	Data are space–time aggregated according to the system configuration.
	2i_001-004	Publication views are created according to the system configuration.
	2j_001	DB recovery file is created according to the system configuration.
A1, A2	3a_001-003	Test case consists of checking OGC WFS operations: GetCapabilities, DescribeFeatureType and GetFeature.
	3b_001-003	ST_LUCAS dataset available via WFS.
	3c_001-003	The test cases consist of checking that ST_LUCAS metadata are published according to the deployed database.
C1, C2	001-007	Test cases consist of checking `LucasRequest` and `LucasIO` classes methods to build a request, download a LUCAS subset, store retrieved data on the local file system, and access associated photos.

The interaction between the software components is validated by integration tests. For each interface (Figure 4), a set of integration tests was designed (Table 3). Various combinations of spatial, temporal, attribute, and thematic filters are tested. A request based on a specified set of filters is built by the Python package (C1) and sent to the server. The web service (A2) returns a relevant subset of harmonized LUCAS data (IF2). The subset is compared with a recordset provided by a direct query to the database (P2) using SQL statements (IF1). The integration tests are evaluated with a pass result only if the both interfaces (IF1 and IF2) return the same subset of the LUCAS data. The system administrator is notified about the integration tests results regularly by email notifications. It ensures that system administrators will be informed about a potential system failure in real time, which is an important aspect of the operational deployment of the ST_LUCAS system. For interface IF3, manual verification was performed via the Jupyter Notebook.

Table 3. Integration tests overview. Interface IDs reflect the system architecture as presented in Figure 4.

Interface ID	Test IDs	Description
IF1, IF2	001–004	Test cases consist of checking WFS responses retrieved by the Python package (IF2) covering various combinations of spatial, attribute, thematic, and temporal filters. The responses are compared with the subsets retrieved from spatio-temporal DB via SQL statements (IF1). Test cases pass only if there is no difference between the WFS responses and the subsets retrieved from DB.

The unit (Table 2) and integration (Table 3) tests are automated with the Python pytest package [49]. A verification is, therefore, performed during the software execution, which dynamically checks the software behavior. The verification of the unit test results is performed by the system administrator at the deployment phase. In the case that one of the unit tests fails, the deployment process is terminated and the system is not deployed. The integration test results verification is performed repeatedly at the system execution phase. The result of each test operation is sorted in a log file, which is publicly available (Demonstration of the ST_LUCAS system, https://geoforall.fsv.cvut.cz/st_lucas, release 1.0 published by the authors on 9 June 2022) and, therefore, can also be verified by the user.

4. System Implementation

The ST_LUCAS system implementation and deployment follow the design as developed in Section 3. The system is completely based on open-source software components to ensure its reproducibility, transparency, and extensibility (Appendix A Table A1). Overall, the architecture splits the system into the client (frontend) and the server side (backend), hence the implementation aspects are described separately accordingly.

4.1. Backend

The backend, the server side consisting of the persistence and application layers, is composed of software components which are responsible for the data storage, the LUCAS data harmonization, and data distribution. The components (represented in Figure 3) are implemented as a collection of services (see Section 4.3). Each service is managed in an isolated Docker container running on any operating system supported by the Docker virtualization technology [50]. There are two core backend software components: the database management system, operating a spatio-temporal DB (P2), and the map server, providing a web service (A2). The database management system is represented by an object-relational open-source PostgreSQL server [51]. This database system has a strong reputation for reliability, data integrity, and correctness. Moreover, it provides extension to geospatial data, the so-called PostGIS, which “spatially enables” the PostgreSQL database [52]. PostGIS also follows the OpenGIS “Simple Features Specification for SQL” by OGC. Here, we use the PostGIS version 3.1. The P2 and A2 components are deployed by the system deployment package (A1).

The database population process is controlled by a collection of scripts implemented in the Python 3 and Bash programming languages covering all steps as described in the dynamic system architecture (Figure 5). The harmonization process of the LUCAS data is procedural. It is decomposed as a series of computational steps carried out at the database level by scripts written in SQL. The configuration of the harmonization process is managed by a collection of CSV and JavaScript Object Notation (JSON) files. The robust but still easy-to-use configuration allows system administrators to affect the result of the harmonization process. In the same way, the system can be easily extended by new LUCAS observations planned to be published in 2022. The GDAL library [53] is used to import the primary LUCAS data from the file system (P1) to the PostGIS database tables (P2).

The web service (A2) is implemented as a map server, provided by an open-source GeoServer software version 2.19 [54]. The GeoServer is an OGC compliant implementation of a number of open standards such as the Web Map Service (WMS) and the Web Coverage Service (WCS). Additional formats and publication options are available as extensions, including the Web Processing Service (WPS) and the Web Map Tile Service (WMTS). It also conforms to the OGC WFS standard, which allows the sharing of the vector features to be used on the client side. The users can incorporate the LUCAS dataset into their processing pipelines and applications, freeing the data and permitting greater transparency. When the data becomes available from the deployment process, the GeoServer provides harmonized LUCAS data via a standardized WFS interface through the Hypertext Transfer Protocol (HTTP) protocol.

The deployment package source code is available from the GitLab repository (https://gitlab.com/geoharmonizer_inea/st_lucas/st_lucas-system-deployment, release 1.0 published by the authors on 9 June 2022).

4.2. Frontend

The frontend, the client side, is composed of the Python package (C1) and the CLI client or GUI clients as depicted in Figure 3. The Python package keeps the main functionality of the client side to be used by the end-user, either through the QGIS plugin (C3) without a necessity of any additionally programming/scripting, or the geospatial developer which can directly use the Python API package to integrate harmonized LUCAS subsets into their own coded Earth observation pipelines.

4.2.1. Python Package

The frontend is developed based on the core component, the Python package (C1), which provides communication between the web server (A2) and the users' clients through API. The package implemented in the Python 3 programming language consists of three modules: (1) `request` to create a request by specifying spatial, temporal, attribute, or thematic filters; (2) `io` to retrieve harmonized LUCAS data provided by the web service (A2) based on the submitted request, and to store the retrieved data in the user local file system (C2) in a specified data format; and (3) `analyze` to process the received harmonized LUCAS data—LUCAS land cover classes aggregation and nomenclature translation.

To use the Python API, the user creates a request by the `LucasRequest` Python class. In a single request, a combination of spatial, temporal, attribute, and thematic filters can be used. The spatial filter can be defined either by a bounding box, the NUTS0 country code, or by a user-defined polygon vector layer. Spatial coordinates must be specified in the ETRS89-extended/LAEA Europe coordinate reference system (EPSG 3035). The spatial filter is required by request; the other filters are optional. The temporal filter is specified by a list of survey years to be queried. The attribute filter is provided by an operator, an attribute name, and a list of values. The thematic filter defines the subset of harmonized LUCAS attributes to be retrieved. The example below (Listing 1) demonstrates the combination of all possible filters; the spatial filter is defined by a bounding box (`request.bbox`) covering the whole EU territory; the temporal filter (`request.years`) restricts the result to the 2015 and 2018 survey years; the attribute filter (`request.propertyname`, `request.operator`, `request.literal`, and `request.logical`) selects only the LUCAS observations with land cover classes (LUCAS attribute LC1), C21 (Spruce dominated coniferous woodland), or C22 (Pine dominated coniferous woodland). The thematic filter (`request.group`) defines a subset of harmonized LUCAS attributes only to those which are relevant to the "Land Cover, Land Use" thematic group (LC_LU code in Appendix A Table A2).

Listing 1. Build a request.

```
from st_lucas import LucasRequest
from owslib.fes import PropertyIsEqualTo, Or

request = LucasRequest()
request.bbox = (1510105, −2292253, 8582000, 5306000)
request.years = [2015, 2018]
request.propertyname = 'LC1'
request.operator=PropertyIsEqualTo
request.literal = ['C21', 'C22']
request.logical = Or
request.group = 'LC_LU'
```

The LUCAS subsets retrieval according to the defined filters and data storage is managed by a `LucasIO` Python class. The LUCAS data are retrieved from the web service (A2) by the `LucasIO.download()` method based on the specified `LucasRequest` class instance. The number of retrieved LUCAS samples is returned by the `LucasIO.count()` method (Listing 2).

Listing 2. Download LUCAS subset based on the request.

```
from st_lucas import~LucasIO

lucasio = LucasIO()
lucasio.download(request)
print('Number of LUCAS points:', lucasio.count())
```

The downloaded LUCAS data can be stored on a local file system (C2) as a OGC GeoPackage file by the `LucasIO.to_gpkg()` method for further processing in GIS applications or converted by the `LucasIO.to_geopandas()` method into a `GeoDataFrame` object, which can be processed and analyzed in the Python code by the GeoPandas library [55].

The `analyze` Python module provides two analytical functionalities. The Python class `LucasClassAggregate` implements the LUCAS land cover classes aggregation. In addition to the aggregation of land cover classes, the module also offers the possibility of translating the LUCAS nomenclature into other nomenclatures using the `LucasClassTranslate` Python class. Complex Python API usage is demonstrated in several use cases and is discussed in Section 5.

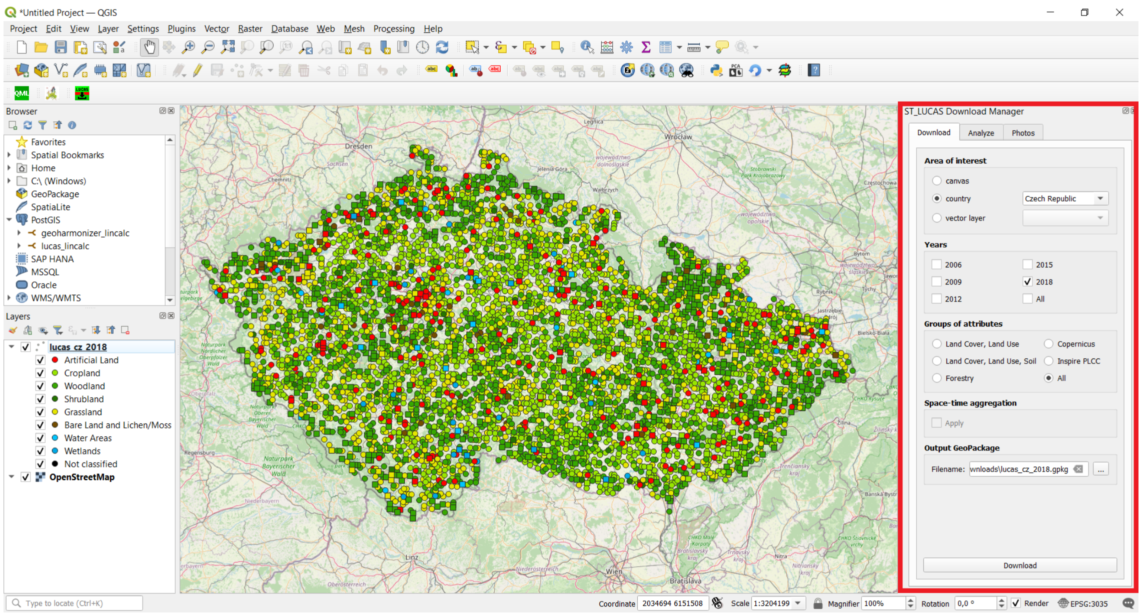
The client Python API can be used directly by the Python code (CLI), running the Jupyter Notebook, or by the QGIS developed plugin (GUI). The Jupyter Notebook as a web-based interactive computing platform allows interactive data exploration [56] for geospatial developers. The Python package source code and the Jupyter Notebooks demonstrating the capabilities of the system are available in the GitLab repository (https://gitlab.com/geoharmonizer_inea/st_lucas/st_lucas-python-package, release 1.0 published by the authors on 9 June 2022).

4.2.2. QGIS Plugin

The other option for the harmonized space–time LUCAS dataset exploration is to use the ST_LUCAS QGIS plugin. The plugin is a GUI integrated into the open-source QGIS platform. The user interface (Figure 7) is split into three tabs: (1) Download; (2) Analyze; and (3) Photos. The added value of using GIS is to interactively select the spatial, attribute, temporal, and thematic filters from the GUI (Download tab). In particular, it allows us to select an area of interest (spatial filter) by the extent of the map canvas, specifying a country from a list of EU countries or using a user-defined vector polygon data layer. The plugin interface also allows us to specify a list of selected years (temporal filter) and a group of attributes (thematic filter). There are five thematic groups in total to choose from, where each group contains specific thematic attributes in addition to the basic attributes. The following groups are available: Land Cover, Land Use; Land Cover, Land Use, Soil; Forestry; Copernicus; and Inspire PLCC (Appendix A Table A2). The user can also download LUCAS points with all available attributes.

The Analyze tab integrates functionality for performing a user-defined class aggregation using a JSON file and a nomenclature translation using a CSV file. An example of usage is included in the plugin documentation available online on the ST_LUCAS web page (https://geoforall.fsv.cvut.cz/st_lucas/qgis_plugin/, release 1.0 published by the authors on 9 June 2022).

Additionally, users can browse photos (a facing photo and four landscape photos in the cardinal compass directions) of a selected LUCAS point in the Photo tab (Figure 8) as provided by the GISCO service [57].



ST_LUCAS Download Manager

Download | Analyze | Photos

Area of interest
- canvas
- [✓ country] Czech Republic
- vector layer

Years
2006, 2009, 2012, 2015, [✓ 2018], All

Groups of attributes
Land Cover, Land Use; Land Cover, Land Use, Soil; Forestry; Copernicus; Inspire PLCC; [✓ All]

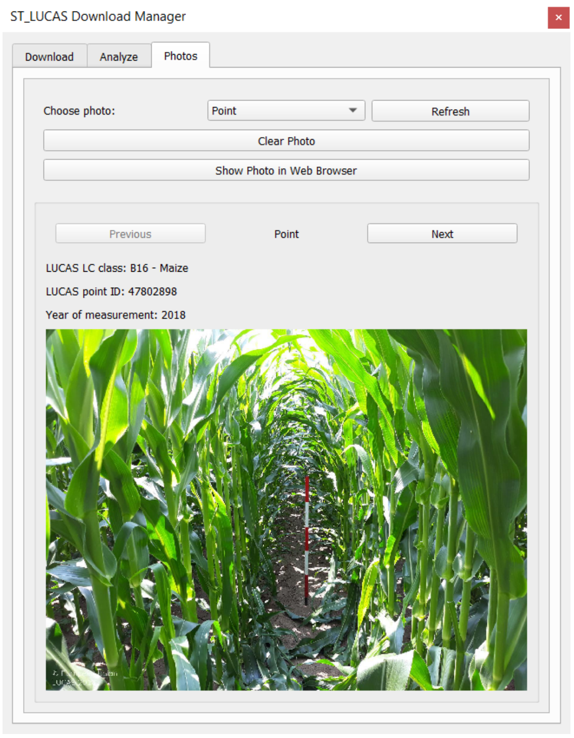
Space-time aggregation
Apply

Output GeoPackage
Filename: wnloads\lucas_cz_2018.gpkg

Download

Figure 7. ST_LUCAS QGIS plugin (highlighted by a red box) retrieving harmonized LUCAS data for the Czech Republic territory (background basemap: OpenStreetMap—public WMS view service).

The subset of harmonized space–time LUCAS data retrieved from the server is stored in the OGC GeoPackage format with a predefined style for further usage. The style of LUCAS points is defined to distinguish the land cover classes at the first level of the LUCAS nomenclature as shown in Figure 7. In addition, points with a circular symbol indicate that photos are available for display. Points with a square symbol indicate the opposite.



Choose photo: Point

Point

LUCAS LC class: B16 - Maize

LUCAS point ID: 47802898

Year of measurement: 2018

Figure 8. Showing LUCAS photos from the GISCO service by the ST_LUCAS QGIS plugin.

The QGIS plugin source code is available in the GitLab repository (https://gitlab.com/geoharmonizer_inea/st_lucas/st_lucas-qgis-plugin, release 1.0 published by the authors on 9 June 2022).

4.3. ST_LUCAS System Deployment

In order to enhance the portability of the developed ST_LUCAS system, the Docker virtualization technology [50] was employed. All the backend components are deployed through virtualization. There are four deployed services managed by the Docker-compose tool, each running in an isolated Docker container: (1) db: responsible for the spatio-temporal database (P2) deployment including harmonized space–time LUCAS data; (2) gs: responsible for running a map server providing the OGC WFS service (A2); (3) gsp: responsible for publishing harmonized space–time LUCAS data as a WFS service. The publication process is performed when the database deployment is successfully finished. At this point, the system metadata and documentation is also populated. The service is terminated when the publishing process is successfully finished; and (4) gst: performs repetitive integration tests (Table 3) controlling whether the system is operational. Logs are publicly available; additionally, the system administrator is notified by email.

The ST_LUCAS system deployment controls components in the persistence and application layers as shown in Figure 3. Spatio-temporal DB (P2) is managed by a Docker container (db), which mounts the server file system (P1) as a volume. As the system deployment package (A1) manages all deployment steps, it is available to all Docker containers (db, gs, gsp, and gst) through the mounted volume.

The complete deployment of the ST_LUCAS system is performed by a single command: `docker-compose up`.

The demonstration ST_LUCAS system installation, available at https://geoforall.fsv.cvut.cz/st_lucas (release 1.0 published by the authors on 9 June 2022), is deployed on GNU/Debian operating system version 11.

5. Discussion

The developed ST_LUCAS system has multiple uses. System managers may take the system and install it (Docker containers) in their institutes as it is (objective O1). Geospatial developers may utilize (e.g., configure) the current system and let it run for their own purposes (O2). Geospatial users may access the harmonized spatio-temporal LUCAS dataset, and its subsets, using either the machine-to-machine Python API or the interactive QGIS plugin (O4). The data are provided by a standardized interface defined by OGC WFS (O3). The system offers the developers and geospatial users full and configurable automation of the harmonization process for the past and future LUCAS survey updates, the spatio-temporal and thematic subsetting of the data based on user-defined filters, land cover legend translation to a defined nomenclature, and the legend aggregation (O5).

Next, we demonstrate and discuss the use of the ST_LUCAS system on two use cases (Sections 5.1 and 5.2), apart from the use of the system described by Witjes et al. [29] for the European scale land cover mapping of the years 2000–2019.

5.1. LUCAS Data for Land Cover Change Analysis

In the first use case, we demonstrate how to retrieve a vector of a changing land cover from the ST_LUCAS system. Assuming the geospatial user wants to calibrate the classification change model or validate the existing land cover change product, we need to retrieve a subset of data with repeated visits on the same geographical points. The task can be simply set up as selecting LUCAS points where repeated visits are higher than one. As mentioned in Section 1, there are 319,150 sample points visited at least twice and 35,204 samples visited five times.

Below, a Python snippet code (Listing 3) demonstrates how to retrieve LUCAS points with repeated visits for land cover change analysis using the SURVEY_COUNT attribute for AOI (areas of interest) in the Czech Republic. There were 11,084 points retrieved with the initial spatial and temporal filter, while by adding the condition SURVEY_COUNT > 1 we received a subset of 6175 points.

Listing 3. Build a request for land cover change analysis.

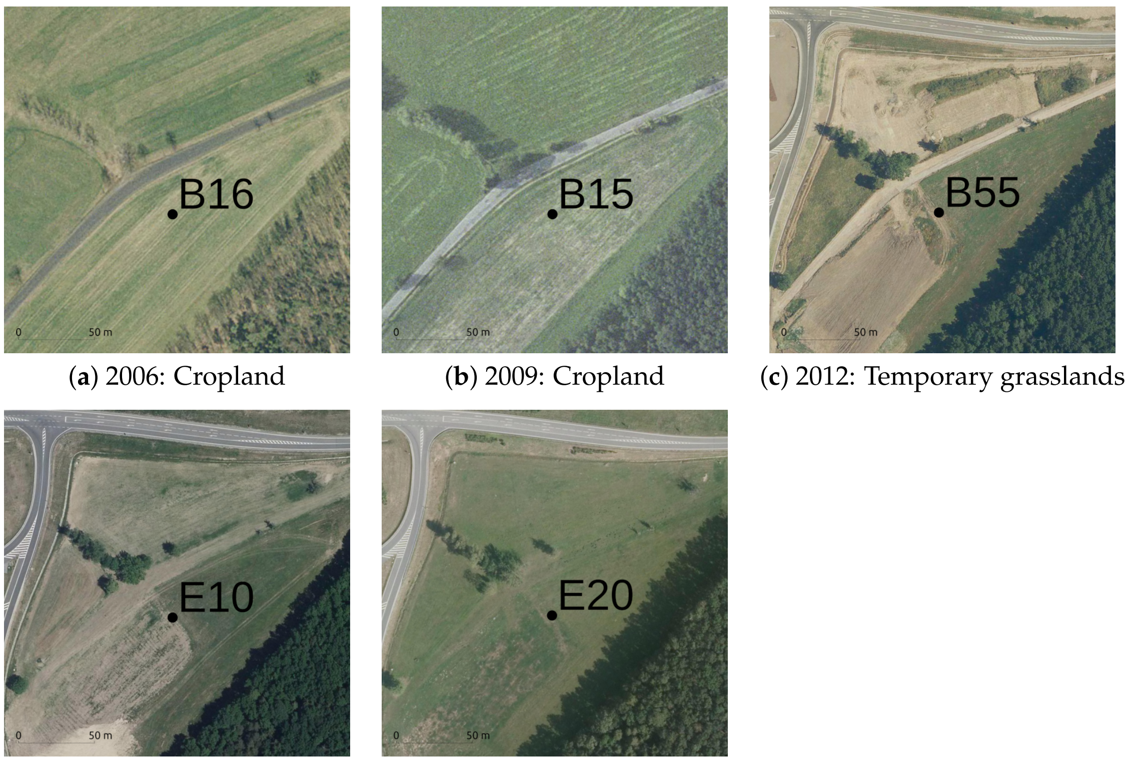
```
from st_lucas import LucasRequest
from owslib.fes import~PropertyIsGreaterThan

request = LucasRequest()

request.countries = ['CZ']
request.st_aggregated = True
request.group = 'LC_LU'

request.propertyname = 'SURVEY_COUNT'
request.operator = PropertyIsGreaterThan
request.literal = 1
```

In Figure 9, we illustrate an example of the land cover change vector (LC1 codes: B16, B15, B55, E10, and E20) for the case of five in situ repeated visits (2006, 2009, 2012, 2015, and 2018), together with orthophotos in the background. It clearly shows the changing landscape documented by the orthophotos and the changing LC codes in the LUCAS database accordingly.



(**a**) 2006: Cropland (**b**) 2009: Cropland (**c**) 2012: Temporary grasslands

(**d**) 2015: Grassland (**e**) 2018: Grassland

Figure 9. Example of changing land cover in time for POINT_ID = 46642928 as recorded in the LUCAS dataset (background orthophotos: Czech State Administration of Land Surveying and Cadastre—public WMS view service).

5.2. LUCAS Data for Land Product Validation

In the next application example, we demonstrate the use of LUCAS data for land product validation. In this case, the validation of the national-level Land Parcel Identification System (LPIS) of the Czech Republic for 2018, which is an open dataset [58]. We simplified the validation into two agriculture classes, cropland (class 1) and grassland (class 2), which represent the majority of the agricultural land in LPIS. Initially, we retrieved the subset of LUCAS data with the respective spatial and temporal filters in the validation process, similarly as in the code snippet in Listing 1. Next, we used the `LucasClassAggregate` Python class from the developed Python package to simplify the nomenclature to the above-defined legend (Listing 4). The method's argument is a Python dictionary defining the class mappings for the aggregation process.

Listing 4. Perform land cover class aggregation.

```
from st_lucas import~LucasClassAggregate

lc1_to_agri = {
"1": ["B11", "B12", "B13", "B14", "B15", "B16", "B17", "B18",
      "B19", "B21", "B22", "B23", "B31", "B32", "B33", "B34",
      "B35", "B36", "B37", "B41", "B42", "B43", "B44", "B45",
      "B51", "B52", "B53", "B54", "B55", "B71", "B72", "B73",
      "B74", "B75", "B76", "B77", "B81", "B82", "B83", "B84"],
"2": ["E10", "E20", "E30"]
}

lucasaggr = LucasClassAggregate(lucasio.data, mappings=lc1_to_agri)
lucasaggr.apply()
```

The retrieved vector layer with the aggregated nomenclature was overlaid with the LPIS product and validation indicators were calculated (Table 4). We can conclude that the LPIS product has a high thematic accuracy, with an overall F1-score of 96%, as compared with the LUCAS in situ survey of 2018.

Table 4. LPIS validation indicators.

Class	Code	Support	F1-Score	Precision	Recall
Cropland	1	1941	98.1	97.1	99.1
Grassland	2	690	94.1	96.1	92.1
Overall		2631	96.1	97.1	95.1

6. Conclusions

We have presented the developed ST_LUCAS geospatial data system. A versatile open-source framework for the LUCAS dataset harmonization, distribution by the OGC compliant interface, Python client API and QGIS plugin to retrieve the subsets of data, and methods to manage nomenclature translation, class aggregation, and thematic information. The source code, documentation, and installation instructions are publicly available on GitLab (https://gitlab.com/geoharmonizer_inea/st_lucas, release 1.0 published by the authors on 9 June 2022). The ST_LUCAS deployment package and the Python client package are published under the MIT license, the QGIS plugin under GNU GPL v3.

The system is designed in a multi-layer client-server model allowing integration to end-to-end workflows. The integration of the system in the full end-to-end workflows is facilitated by the Python API. The system transferability to different server end-points is eased by the OS-level virtualization using the Docker containers. This allows a diverse audience of geospatial developers and scientists to use the capabilities of the ST_LUCAS system in their own environments. Moreover, the system can be configured based on a specific user requirement. The system is prepared for the new LUCAS survey of 2022 as soon as it is publicly available.

We have discussed the use of the ST_LUCAS system in two examples (Section 5). Additionally, the workflow management capabilities were already tested to prepare a harmonized spatio-temporal LUCAS dataset for the European scale land cover mapping of the years 2000–2019 [29]. The experience from this large scale use case proved the necessity of auxiliary methods for the land cover nomenclature translation and aggregation, which is not a common feature in purely distribution systems.

Overall, we believe the ST_LUCAS system allows better accessibility and usability of the European LUCAS dataset through a standardized OGC interface. The specific enhancement is in the space–time aggregation of the data that emphasizes the use of a highly valuable in situ survey database for change analysis as a priority of all land monitoring projects. On top of that, the ST_LUCAS system is fully integrated into the QGIS desktop platform, allowing a fully interactive exploration of the LUCAS data and direct GIS analysis. As a continuation of the ST_LUCAS development, we plan to run extended demonstration use cases. In particular, we intend to explore the value of repeated in situ visits for the land cover change detection. To fulfill this task, we shall develop translation tables from LUCAS land cover legend to various nomenclatures. Additionally, we shall explore the spatial representativeness of the sampled points in order to use the data for validation and land cover calibration activities in varying spatial resolutions.

The ST_LUCAS system was implemented based on current knowledge of the primary data acquired in 2018 and the previous surveys since 2006. The system may require future updates according to the changes in LUCAS dataset from the next surveys.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
CBSE	Component-Based Software Engineering
CLI	Command Line Interface
CSV	Comma Separated Values (file format)
EPSG	EPSG Geodetic Parameter Dataset
EU	European Union
EUNIS	European Nature Information System
GIS	Geographic Information System
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
INSPIRE	Infrastructure for Spatial Information in Europe
JSON	JavaScript Object Notation

LC	Land Cover
LUCAS	Land Use and Coverage Area frame Survey
NUTS	Nomenclature of Territorial Units for Statistics
OGC	Open Geospatial Consortium
PLCC	Pure Land Cover Components
SDI	Spatial data Infrastructure
SQL	Structured Query Language
UML	Unified Modeling Language
WCS	Web Coverage Service
WFS	Web Feature Service
WMS	Web Map Service
WMTS	Web Map Tile Service
WPS	Web Processing Service

Appendix A

Table A1. Open-source software used by the ST_LUCAS system. Component IDs reflect the system architecture as presented in Figure 3.

Component ID	Software	License
P2	PostgreSQL	PostgreSQL licence
P2	PostGIS	GNU GPL
A1	Docker CE	N/A (free of charge)
A1	Docker Compose	Apache License 2.0
A1	psycopg2 *	GNU LGPL v3
A1	gdal *	MIT
A1	pytest *	MIT
A1	owslib *	BSD 3
A1	geoserver-rest *	MIT
A1	requests *	Apache 2.0
A2	GeoServer	GNU GPL
C1	json/os/csv/logging/tempfile/pathlib/shutil *	PSF 2.2/BSD 0
C1	gdal *	MIT
C1	owslib *	BSD 3
C1	requests *	Apache 2.0
C3	QGIS	GNU GPL

* Python package.

Table A2. List of ST_LUCAS attributes.

Attribute	Group	Description	Units	Origin
POINT_ID	DEFAULT	Unique point identifier		Primary
NUTS0	DEFAULT	NUTS Lvl 0		Primary
NUTS1	DEFAULT	NUTS Lvl 1		Primary
NUTS2	DEFAULT	NUTS Lvl 2		Primary
NUTS3	DEFAULT	NUTS Lvl 3		Primary
SURVEY_DATE	DEFAULT	Date of observation	yyyy-mm-dd	Harmonized
CAR_LATITUDE	DEFAULT	GPS Car parking latitude	°	Primary
CAR_LONGITUDE	DEFAULT	GPS Car parking longitude	°	Primary
CAR_EW	DEFAULT	GPS Car parking East/West	1:East, 2:West, −1:Not Relevant	Primary
GPS_PROJ	DEFAULT	GPS Projection	1:WGS84, 2:GPS Problem, −1:Not Relevant	Harmonized
GPS_PREC	DEFAULT	GPS Precision	m	Primary
GPS_LAT	DEFAULT	GPS Observation latitude	°	Harmonized
GPS_EW		GPS Observation East/West	1:East, 2:West, −1:Not Relevant	Harmonized
GPS_LONG	DEFAULT	GPS Observation longitude	°	Harmonized
GPS_ALTITUDE	DEFAULT	GPS altitude	m	Primary
GEOG_GPS	DEFAULT	PostGIS geography (EPSG 4326) generated from GPS_LAT, GPS_LONG		New
GEOM_GPS	DEFAULT	PostGIS geometry (EPSG 3035) generated from GPS_LAT, GPS_LONG		New
GEOM_REPR_AREA	DEFAULT	PostGIS geometry (EPSG 3035) of representative area		New
TH_LAT	DEFAULT	Theoretical Latitude	°	Primary
TH_EW		Theoretical East/West	1:East, 2:West, −1:Not Relevant	Harmonized
TH_LONG	DEFAULT	Theoretical Longitude	°	Primary
GEOG_TH	DEFAULT	PostGIS geography (EPSG 4326) generated from TH_LAT, TH_LONG		New
GEOM_THR	DEFAULT	PostGIS geography (EPSG 3035) generated from TH_LAT, TH_LONG snapped to LUCAS grid		New
GEOM	DEFAULT	PostGIS geometry (EPSG 3035) generated from measured GPS location (GEOM_GPS) if no GPS problem detected otherwise theoretical location (GEOM_THR)		New
DIST_THR_GRID	DEFAULT	Distance computed from GEOG_THR and LUCAS grid	m	New
OBS_DIST	DEFAULT	GPS Distance to theoretical point	m	Harmonized
OBS_DIRECT	DEFAULT	Direction of observation in case of linear feature	1:on the point, 2:Look to the North, 3:Look to the East, −1:Not Relevant	Primary
OBS_TYPE	DEFAULT	Observation type	1:In Situ < 100 m, 2:In Situ > 100 m, 3:In Situ PI, 4:In Situ PI not possible, 5:Out of national territory, 6:Out of EU28, 7:In Office PI, −1:Not Relevant	Harmonized
OBS_RADIUS	DEFAULT	Radius of observation circle	1:1.5 m, 2:20 m, −1:Not Relevant	Primary
LC1	LAND COVER (LC_LU, LC_LU_SO)	Land Cover 1		Primary
LC1_H	LAND COVER (LC_LU, LC_LU_SO)	Harmonized Land Cover 1 to 2018 nomenclature	−1:Not Relevant	New

Table A2. *Cont.*

Attribute	Group	Description	Units	Origin
LC1_H_L3_MISSING	LAND COVER (LC_LU, LC_LU_SO)	Harmonized Land Cover 1 on lvl 1 or lvl 2 if lvl 3 is missing		New
LC1_H_L3_MISSING_LEVEL	LAND COVER (LC_LU, LC_LU_SO)	Level of available land cover 1 value if lvl 3 is missing	1:Level 1, 2:Level 2	New
LC1_SPEC	LAND COVER (LC_LU, LC_LU_SO)	Land Cover 1 Species	−1:Not Relevant	Harmonized
LC1_PERC	LAND COVER (LC_LU, LC_LU_SO)	Percentage of coverage of Land Cover 1	%, −1:Not Relevant	Harmonized
LC1_PERC_CLS	LAND COVER (LC_LU, LC_LU_SO)	Percentage of coverage of Land Cover 1 by codes	1:10%, 2:25%, 3:50%, 4:75%, 5:100%, −1:Not Relevant	New
LC2	LAND COVER (LC_LU, LC_LU_SO)	Land Cover 2		Primary
LC2_H	LAND COVER (LC_LU, LC_LU_SO)	Harmonized Land Cover 2 to 2018 nomenclature	−1:Not Relevant	New
LC2_H_L3_MISSING	LAND COVER (LC_LU, LC_LU_SO)	Harmonized Land Cover 2 on lvl 1 or lvl 2 if lvl 3 is missing		New
LC2_H_L3_MISSING_LEVEL	LAND COVER (LC_LU, LC_LU_SO)	Level of available land cover 2 value if lvl 3 is missing	1:Level 1, 2:Level 2	New
LC2_SPEC	LAND COVER (LC_LU, LC_LU_SO)	Land Cover 2 Species	−1:Not Relevant	Harmonized
LC2_PERC	LAND COVER (LC_LU, LC_LU_SO)	Percentage of coverage of Land Cover 2	%, −1:Not Relevant	Harmonized
LC2_PERC_CLS	LAND COVER (LC_LU, LC_LU_SO)	Percentage of coverage of Land Cover 2 by codes	1:10%, 2:25%, 3:50%, 4:75%, 5:100%, −1:Not Relevant	New
LU1	LAND USE (LC_LU, LC_LU_SO)	Land Use 1		Primary
LU1_H	LAND USE (LC_LU, LC_LU_SO)	Harmonized Land Use 1 to 2018 nomenclature	−1:Not Relevant	New
LU1_TYPE	LAND USE (LC_LU, LC_LU_SO)	Land Use 1 species	−1:Not Relevant	Primary
LU1_PERC	LAND USE (LC_LU, LC_LU_SO)	Percentage of coverage of Land Use 1	%, −1:Not Relevant	Harmonized
LU1_PERC_CLS	LAND USE (LC_LU, LC_LU_SO)	Percentage of coverage of Land Use 1 by codes	1:5%, 2:10%, 3:25%, 4:50%, 5:75%, 6:90%, 7:100%, −1:Not Relevant	New
LU2	LAND USE (LC_LU, LC_LU_SO)	Land Use 2		Primary
LU2_H	LAND USE (LC_LU, LC_LU_SO)	Harmonized Land Use 2 to 2018 nomenclature	−1:Not Relevant	New
LU2_TYPE	LAND USE (LC_LU, LC_LU_SO)	Land Use 2 species	−1:Not Relevant	Primary
LU2_PERC	LAND USE (LC_LU, LC_LU_SO)	Percentage of coverage of Land Use 2	%, −1:Not Relevant	Harmonized
LU2_PERC_CLS	LAND USE (LC_LU, LC_LU_SO)	Percentage of coverage of Land Use 2 by codes	1:5%, 2:10%, 3:25%, 4:50%, 5:75%, 6:90%, 7:100%, −1:Not Relevant	New
PARCEL_AREA_HA	LAND USE (LC_LU, LC_LU_SO)	Parcel Area - area of the parcel which the point belongs to	1:<0.1 ha, 2:0.1–0.5 ha, 3:0.5–1 ha, 4:1–10 ha, 5:>10 ha, −1:Not Relevant	Harmonized
TREE_HEIGHT_SURVEY	TREE PROPERTIES (FO)	Height of trees at survey time	1:<5 m, 2:>5 m, −1:Not Relevant	Primary
TREE_HEIGHT_MATURITY	TREE PROPERTIES (FO)	Height of trees at maturity	1:<5 m, 2:>5 m, −1:Not Relevant	Primary
FEATURE_WIDTH	LAND COVER (LC_LU, LC_LU_SO)	Feature width	1:<20 m, 2:>20 m, −1:Not Relevant	Primary
LM_PLOUGH_SLOPE	LAND MANAGEMENT (LC_LU, LC_LU_SO)	Slope of ploughed field	1:Flat, 2:Gently sloping, 3:Steeply sloping, 4:Undulating, −1:Not Relevant	Primary
LM_PLOUGH_DIRECT	LAND MANAGEMENT (LC_LU, LC_LU_SO)	Plough direction	1:Across the slope, 2:Down the slope, 3:Not Applicable, −1:Not Relevant	Primary
LM_STONE_WALLS	LAND MANAGEMENT (LC_LU, LC_LU_SO)	Presence of stone walls	1:No, 2:Stone wall not mantained, 3:Stone wall well mantained, −1:Not Relevant	Primary

Table A2. *Cont.*

Attribute	Group	Description	Units	Origin
LM_GRASS_MARGINS	LAND MANAGEMENT (LC_LU, LC_LU_SO)	Presence of grass margins	1:No, 2:Grass margin < 1 m, 3:Grass margin > 1 m, −1:Not Relevant	Primary
CPRN_CANDO	COPERNICUS LAND COVER (CO)	Copernicus taken	1:Yes, 2:No, −1:Not Relevant	Primary
CPRN_LC	COPERNICUS LAND COVER (CO)	Copernicus Land Cover		Primary
CPRN_LC1N	COPERNICUS LAND COVER (CO)	Extension of LC North		Primary
CPRNC_LC1E	COPERNICUS LAND COVER (CO)	Extension of LC East		Primary
CPRNC_LC1S	COPERNICUS LAND COVER (CO)	Extension of LC South		Primary
CPRNC_LC1W	COPERNICUS LAND COVER (CO)	Extension of LC West		Primary
CPRN_LC1N_BRDTH	COPERNICUS LAND COVER (CO)	Percentage of breadth North	%, −1:Not Relevant	Primary
CPRN_LC1E_BRDTH	COPERNICUS LAND COVER (CO)	Percentage of breadth East	%, −1:Not Relevant	Primary
CPRN_LC1S_BRDTH	COPERNICUS LAND COVER (CO)	Percentage of breadth South	%, −1:Not Relevant	Primary
CPRN_LC1W_BRDTH	COPERNICUS LAND COVER (CO)	Percentage of breadth West	%, −1:Not Relevant	Primary
CPRN_LC1N_NEXT	COPERNICUS LAND COVER (CO)	Next copernicus Land Cover North		Primary
CPRN_LC1E_NEXT	COPERNICUS LAND COVER (CO)	Next copernicus Land Cover East		Primary
CPRN_LC1S_NEXT	COPERNICUS LAND COVER (CO)	Next copernicus Land Cover South		Primary
CPRN_LC1W_NEXT	COPERNICUS LAND COVER (CO)	Next copernicus Land Cover West		Primary
CPRN_URBAN	URBAN (CO)	Point in Urban area	1:Yes, 2:No, −1:Not Relevant	Primary
CPRN_IMPERVIOUS_PERC	IMPERVIOUS (CO)	Percentage of imperviousness	%, −1:Not Relevant	Primary
INSPIRE_PLCC1	INSPIRE PLCC (IN)	Percentage of Coniferous forest trees	%, −1:Not Relevant	Primary
INSPIRE_PLCC2	INSPIRE PLCC (IN)	Percentage of Broadleaved forest trees	%, −1:Not Relevant	Primary
INSPIRE_PLCC3	INSPIRE PLCC (IN)	Percentage of Shrubs	%, −1:Not Relevant	Primary
INSPIRE_PLCC4	INSPIRE PLCC (IN)	Percentage of herbaceous plants	%, −1:Not Relevant	Primary
INSPIRE_PLCC5	INSPIRE PLCC (IN)	Percentage of Lichens and mosses	%, −1:Not Relevant	Primary
INSPIRE_PLCC6	INSPIRE PLCC (IN)	Percentage of consolidated bare land	%, −1:Not Relevant	Primary
INSPIRE_PLCC7	INSPIRE PLCC (IN)	Percentage of unconsolidated bare land	%, −1:Not Relevant	Primary
INSPIRE_PLCC8	INSPIRE PLCC (IN)	Percentage of other land	%, −1:Not Relevant	Primary
EUNIS_COMPLEX	EUNIS (LC_LU)	EUNIS Complex	6:X06, 9:X09, 10:Other, 11:Unknown, −1:Not Relevant	Primary
GRASSLAND_SAMPLE	GRASS (LC_LU)	Sample Grassland module	0:FALSE, 1:TRUE	Primary
GRASS_CANDO	GRASS (LC_LU)	Grassland taken	1:Yes, 2:No, −1:Not Relevant	Primary
GRAZING	LAND USE (LC_LU, LC_LU_SO)	Signs of grazing	1:Visible sighns of grazing, 2:No sighn of grazing, −1:Not Relevant	Harmonized
WM	LAND USE (LC_LU, LC_LU_SO)	Presence of Water Management	1:Irrigation, 2:Potential irrigation, 3:Drainage, 4:Irrigation and drainage, 5:No visible Water management, −1:Not Relevant	Primary
WM_SOURCE	LAND USE (LC_LU, LC_LU_SO)	Source of irrigation	1:Well, 2:Pond/Lake/Reservoir, 3:Stream/Canal/Ditch, 4:Lagoon/Wastewater, 5:Other/Not identifiable, −1:Not Relevant	Harmonized

Table A2. *Cont.*

Attribute	Group	Description	Units	Origin
WM_TYPE	LAND USE (LC_LU, LC_LU_SO)	Type of irrigation	1:Gravity, 2:Pressure sprinkler irrigation, 3:Pressure micro-irrigation, 4:Gravity/Pressure, 5:Other/Not identifiable, −1:Not Relevant	Harmonized
WM_DELIVERY	LAND USE (LC_LU, LC_LU_SO)	Delivery System	1:Canal, 2:Ditch, 3:Pipeline, 4:Other/Not identifiable, −1:Not Relevant	Harmonized
SOIL_TAKEN	SOIL (LC_LU_SO)	Soil taken	1:Yes, 2:Not possible, 3:No, already taken, 4:No sample required, −1:Not Relevant	Harmonized
EROSION_CANDO	SOIL (LC_LU_SO)	Erosion taken	1:Yes, 2:No, −1:Not Relevant	Primary
BIO_SAMPLE	SOIL (LC_LU_SO)	Sample bio soil module	0:FALSE, 1:TRUE	Primary
SOIL_BIO_TAKEN	SOIL (LC_LU_SO)	Bio soil taken	0:FALSE, 1:TRUE, −1:Not Relevant	Primary
BULK0_10_SAMPLE	SOIL (LC_LU_SO)	Sample bulk 0–10 module	0:FALSE, 1:TRUE	Primary
SOIL_BLK_0_10_TAKEN	SOIL (LC_LU_SO)	Bulk 0–10 taken	1:Yes, 2:No, −1:Not Relevant	Primary
BULK10_20_SAMPLE	SOIL (LC_LU_SO)	Sample bulk 10–20 module	0:FALSE, 1:TRUE	Primary
SOIL_BLK_10_20_TAKEN	SOIL (LC_LU_SO)	Bulk 10–20 taken	1:Yes, 2:No, −1:Not Relevant	Primary
BULK20_30_SAMPLE	SOIL (LC_LU_SO)	Sample bulk 20–30 module	0:FALSE, 1:TRUE	Primary
SOIL_BLK_20_30_TAKEN	SOIL (LC_LU_SO)	Bulk 20–30 taken	1:Yes, 2:No, −1:Not Relevant	Primary
STANDARD_SAMPLE	SOIL (LC_LU_SO)	Sample standard soil module	0:FALSE, 1:TRUE	Primary
SOIL_STD_TAKEN	SOIL (LC_LU_SO)	Standard soil taken	1:Yes, 2:No, −1:Not Relevant	Primary
ORGANIC_SAMPLE	SOIL (LC_LU_SO)	Sample organic soil module	0:FALSE, 1:TRUE	Primary
SOIL_ORG_DEPTH_CANDO	SOIL (LC_LU_SO)	Organic soil taken	1:Yes, 2:No, −1:Not Relevant	Primary
OFFICE_PI	DEFAULT	Sample photo interpreted in office	0:FALSE, 1:TRUE	Harmonized
PI_EXTENSION	DEFAULT	Point on extened part of survey (photo-interpreted)	0:FALSE, 1:TRUE	Primary
LNDMNG_PLOUGH	LAND USE (LC_LU, LC_LU_SO)	Signs of ploughing	1:Yes, 2:No, −1:Not Relevant	Primary
SPECIAL_STATUS	LAND USE (LC_LU, LC_LU_SO)	Special status	1:Protected, 2:Hunting, 3:Protected and hunting, 4:No special status, −1:Not Relevant	Primary
LC_LU_SPECIAL_REMARK	LAND COVER (LC_LU, LC_LU_SO)	Special remarks in LC/LU	1:Harvested field, 2:Tilled/sowed, 3:Clear cut, 4:Burnt area, 5:Fire break, 6:Nursey, 7:Dump site, 8:Temporary dry, 9:Temporary flooded, 10:No remark, −1:Not Relevant	Harmonized
SOIL_STONES_PERC	SOIL (LC_LU_SO)	Percentage of Stones on the surface	%, −1:Not Relevant	Harmonized
SOIL_STONES_PERC_CLS	SOIL (LC_LU_SO)	Percentage of Stones on the surface by codes	1:5%, 2:20%, 3:40%, 4:75%, −1:Not Relevant	New
PHOTO_POINT	LAND COVER (LC_LU, LC_LU_SO)	Photo point taken	1:Taken, 2:Not Taken, −1:Not Relevant	Primary
PHOTO_NORTH	LAND COVER (LC_LU, LC_LU_SO)	Photo north taken	1:Taken, 2:Not Taken, −1:Not Relevant	Primary
PHOTO_EAST	LAND COVER (LC_LU, LC_LU_SO)	Photo east taken	1:Taken, 2:Not Taken, −1:Not Relevant	Primary
PHOTO_SOUTH	LAND COVER (LC_LU, LC_LU_SO)	Photo south taken	1:Taken, 2:Not Taken, −1:Not Relevant	Primary
PHOTO_WEST	LAND COVER (LC_LU, LC_LU_SO)	Photo west taken	1:Taken, 2:Not Taken, −1:Not Relevant	Primary
CROP_RESIDUES	LAND COVER (LC_LU, LC_LU_SO)	Presence of crop residues	1:Yes, 2:No, −1:Not Relevant	Harmonized
TRANSECT	LAND COVER (LC_LU, LC_LU_SO)	Transect LC sequence		Primary
EX_ANTE	DEFAULT	Visited in the field	0:FALSE, 1:TRUE	Primary
SURVEY_YEAR	DEFAULT	Survey year		New
SURVEY_COUNT	SPACE-TIME	Number of visits		New
SURVEY_DIST	SPACE-TIME	Distance computed from representative location (GEOM) and measured GPS location (GEOM_GPS)	m	New
SURVEY_MAXDIST	SPACE-TIME	Maximum distance computed from representative location (GEOM) and measured GPS location (GEOM_GPS)	m	New

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