Product Quality Assessment Report

CDR and ICDR Sentinel-3 Land Cover (v2.1.1)

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History of modifications

Version	Date	Description of modification	Chapters / Sections
V1.0	22/02/2024	First version	All
V1.1	12/03/2024	Document amended to account for feedback from independent reviewer and finalized for publication.	All
V1.2	06/05/2024	Document amended to account for feedback from independent reviewer and finalized for publication.	Summary section (2.1)

List of data sets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
WP2-FDDP-LC-2021-SENTINEL3-300m-v2.1.1	ICDR Land Cover 2021	ICDR	2.1.1	15/07/2023
WP2-FDDP-LC-2022-SENTINEL3-300m-v2.1.1	ICDR Land Cover 2022	ICDR	2.1.1	30/04/2024

Related documents

Reference ID	Document
RD-1	E.U. Copernicus Climate Change Service (2024), Product Quality Assurance Document – CDR and ICDR Sentinel-3 Land Cover (v2.1.1), 22/02/2024 WP2-FDDP-LC-2021-2022-SENTINEL3-300m-v2.1.1_PQAD_v1.3 (not yet published)
RD-2	E.U. Copernicus Climate Change Service (2024), Product User Guide and Specification (PUGS) – CDR and ICDR Sentinel-3 Land Cover (v2.1.1), 22/02/2024, WP2-FDDP-LC-2021-2022-SENTINEL3-300m-v2.1.1_PUGS_v1.0 (not yet published)
RD-3	E.U. Copernicus Climate Change Service (2024), Algorithm Theoretical Basis Document (ATBD) – CDR and ICDR Sentinel-3 Land Cover (v2.1.1), 22/02/2024, WP2-FDDP-LC-2021-2022-SENTINEL3-300m-v2.1.1_ATBD_v1.2 (not yet published)
RD-4	E.U. Copernicus Climate Change Service (2024), Target Requirements and Gap Analysis Document - Land Cover, 29/01/2024, C3S2_WP3-TR-GAD-2023_LC_v1.1 (not yet published)

Acronyms

Acronym	Definition
AATSR	Advanced Along-Track Scanning Radiometer
ADS	Annotation Data Set
AMF	Airmass Factor
AOD	Aerosol Optical Depth
AOD550	AOD at 550nm
ARTDECO	Atmospheric Radiative Transfer Database for Earth Climate Observation
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High-Resolution Radiometer
BBDR	Broadband Directional Reflectance
BRDF	Bi-Directional Reflectance Distribution Function
C3S	Copernicus Climate Change Service
C3S BA	C3S Burned Area C3S Fire-BA
C3S LC	C3S Land Cover
CCI	Climate Change Initiative
CCI-LC	Climate Change Initiative Land Cover
CDR	Climate Data Record
CDS	Climate Data Store
CEOS	Committee on Earth Observation Satellites
CEOS-WGCV	CEOS Working Group on Calibration and Validation
CMC	Climate Modelling Community

Acronym	Definition
CMIP	Coupled Model Intercomparison Project
CMUG	Climate Modelling User Group
CRS	Coordinate Reference System
CTH	Cloud top height
CWV	Water Vapor Column Content
DARD	Data Access Requirement Document
DJF	Design Justification File
DOM	Dark Object Method
DPM	Detailed Processing Model
DUE	Data User Element
EC	European Commission
ECV	Essential Climate Variable
ELEV	Elevation
Envisat	Environmental Satellite
EO	Earth Observation
ERS	European Remote Sensing Satellite
ERA Interim	Global atmospheric reanalysis from 1979
ESA	European Space Agency
ET	Evapotranspiration
EU	European Union
fAPAR	Fraction-Absorbed Photosynthetically Active Radiation
FOV	Field Of View
FR	Full Resolution
Gamma-RS	Gamma Remote Sensing
GCOS	Global Climate Observing System
GCS	Global Coordinate System
GDAL	Geospatial Data Abstraction Library
GeoTIFF	Georeferenced Tagged Image File Format
GFED	Global Fire Emissions Database
GHSL	Global Human Settlement Layer
GIMMS	Global Inventory Monitoring and Modelling System
GIS	Geographic Information System
GLC2000	Global Land Cover 2000 Project
GlobAlbedo	ESA Data User Element (DUE) project
GlobCover	ESA Data User Element (DUE) Project
GMM	Global Monitoring Mode
GRASS	Geographic Resources Analysis Support System
GUF	Global Urban Footprint
HYGEOS	HYGEOS (company)
ICDR	Intermediate Climate Data Record
IMM	Image Mode Medium

Acronym	Definition
IPCC	Intergovernmental Panel on Climate Change
ISIN	Integerised, sinusoidal grid
ISODATA	Iterative Self-Organising Data Analysis Technique
ISSI	International Space Science Institute
JD	Julian Day
KM	Kilometre
L0	Level 0
L1B	Level 1B
L2	Level 2
L3	Level 3
LAI	Leaf Area Index
Landsat	Land remote sensing Satellite
LC	Land Cover
LC-CCI	ESA Climate Change Initiative Land Cover Project
LCC	Land Cover Change
LCCS	Land Cover Classification System
LS	Land Surface
LUT	Look-Up Table
M	Metre
MC	Mean Compositing
MERIS	Medium Resolution Imaging Spectrometer
ML	Maximum Likelihood
MODIS	Moderate Resolution Imaging Spectroradiometer
MOMO	Matrix-Operator-Model
MRLC	Medium Resolution Land Cover
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NetCDF	Network Common Data Format
NIR	Near InfraRed
NLCD	National Land Cover Database
NN	Neuron Net
OLCI	Ocean and Land Colour Instrument
OZO	Ozone Column Content
PDF	Probability Density Function
PDGS	Payload Data Ground Segment
PFT	Plant Functional Types
PQAD	Product Quality Assurance Document
PQAR	Product Quality Assessment Report
PROBA	Project for On-Board Autonomy
PROBA-V	Project for On-Board Autonomy, with the V standing for Vegetation instrument

Acronym	Definition
PSD	Product Specification Document
PUG	Product User Guide
PUGS	Product User Guide and Specification
PVASR	Product Validation and Algorithm Specification Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
QA	Quality Assurance
RRA	Relative Azimuth Angle
RR	Reduced Resolution
SAFE	Standard Archive Format for Europe
SAR	Synthetic Aperture Radar
SDR	Surface directional reflectance
SLSTR	Sea and Land Surface Temperature Radiometer
SMAC	Simplified Method for Atmospheric Correction
SM_FLAgs	PROBA-V Status Map
SPOT	Satellite Pour l'Observation de la Terre
SPOT-VGT	SPOT- Vegetation
SR	Surface Reflectance
SRTM	Shuttle Radar Topography Mission
SWBD	SRTM Water Body Database
SWIR	Short Wave Infrared
SYN	Synergy
SZA	Solar Zenith Angle
TOA	Top of Atmosphere
TOC	Top of Canopy
TR	Target Requirements
UCLouvain	Université Catholique de Louvain
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UR	User Requirements
URD	User Requirements Document
USGS	U.S. Geological Survey
VISCAL	VISible CALibration system
VNIR	Visible and Near-Infrared
VZA	Viewing Zenith Angle
W	Weight
WB	Water Body
WBP	Water Body Product
WGS84	World Geodetic System 84
WSM	Wide Swath Mode

General definitions

Satellite Data Processing Levels

Description of data processing levels ranging from Level 0 to Level 4 has been cited from the following National Aeronautics and Space Administration (NASA) Earth Observation Data website: https://www.earthdata.nasa.gov/engage/open-data-services-and-software/data-information-policy/data-levels

- **Level 0** (L0) data are reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e.g., synchronization frames, communications headers, duplicate data) removed. (In most cases, NASA's EOS Data and Operations System [EDOS] provides these data to the DAACs as production data sets for processing by the Science Data Processing Segment [SDPS] or by one of the SIPS to produce higher-level products.)
- **Level 1A** (L1A) data are reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to L0 data.
- **Level 1B** (L1B) data are L1A data that have been processed to sensor units (not all instruments have L1B source data).
- **Level 1C** (L1C) data are L1B data that include new variables to describe the spectra. These variables allow the user to identify which L1C channels have been copied directly from the L1B and which have been synthesized from L1B and why.
- **Level 2** (L2) data are derived geophysical variables at the same resolution and location as L1 source data.
- **Level 2A** (L2A) data contains information derived from the geolocated sensor data, such as ground elevation, highest and lowest surface return elevations, energy quantile heights ("relative height" metrics), and other waveform-derived metrics describing the intercepted surface.
- **Level 2B** (L2B) data are L2A data that have been processed to sensor units (not all instruments will have a L2B equivalent).
- **Level 3** (L3) are variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
- **Level 3A** (L3A) data are generally periodic summaries (weekly, ten-day, monthly) of L2 products.
- **Level 4** data are model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Pre-processing

Data pre-processing in the case of Land cover processing refers to the preparation of the data for the classification, which includes the pixel identification and atmospheric correction and temporal resampling. The algorithms used are adapted to the requirements of the subsequent application.

Classification
Image classification in remote sensing is defined as the process of categorising all pixels in satellite data/images to obtain a given set of labels (Lillesand & Keifer, 1994).

Land cover
Land Cover (LC) and land cover change (LCC) are becoming increasingly related to the climate modelling effort. Land cover change is a pressing environmental issue acting as both a cause and a consequence of climate change. The importance of these issues requires continuous monitoring systems and the most accurate data. The Copernicus Climate Change Service provides Intermediate Climate Data Records for many Essential Climate Variables, including LC. The global C3S LC maps 2016 – 2022 are/will be consistent with the existing European Space Agency Climate Change Initiative global annual LC maps from 1992 – 2015.

Land cover is the observed bio-physical cover on the Earth's surface (Townshend et al., 2008). It is not to be confounded with land use. Land use characterizes the arrangements, socio-economic activities and inputs people are undertaking on a certain land cover type.

The proposed land cover ontology assumes that the land cover is organized along a continuum of temporal and spatial scales and that each land cover type is defined by a characteristic scale, i.e. by typical spatial extent and time period over which its physical traits are observed (Miller, 1994). This twofold assumption requires introducing the time dimension in the land cover characterization to allow distinguishing between the stable and the dynamic components of land the land surface.

The stable component, named "land cover", refers to the set of land surface features which remain stable over time and thus define the land cover independently of any sources of temporary or natural variability. Conversely, the dynamic component is directly related to this temporary or natural variability that can induce some variation in land surface features over time but without changing the land cover in its essence. This dynamic component is referred to as "land cover conditions" (Lamarche et al., 2013).

LC Change
In this context, 'LC change' (LCC) is therefore considered as a permanent modification of the LC – and not of its conditions – in comparison with a baseline status.

LC Classes
A LC class refers to a LC category described by a stable ensemble of land surface features forming a LC class (e.g., forest, cropland). Land surface features consist of landscape elementary units (e.g., a house, a tree, a water body, etc.) described by:

(1) the type of the observed features, such as tree, shrub, herbaceous vegetation, moss/lichen vegetation, terrestrial or aquatic vegetation, inland water, built-up areas, permanent snow/ice, etc;

(2) the structure of the observed features, like the vegetation height, vegetation cover, building density, etc;
(3) the nature of the observed features, such as the level of artificiality or some species information (e.g., C3/C4 distinction);
(4) the homogeneity of the observed features at the level of observation, leading to pure or mosaic classes.

The LC classes are well defined and described using the UN/FAO Land Cover Classification System (LCCS) (di Gregorio and Jansen, 2005).

Current pixel state
The current_pixel_state in the Land cover map product is the classification of the aggregated pixels regarding the following classes:

- invalid – no observation or all observations are not valid
- clear_land – at least one valid observation over clear land
- clear_water – at least one valid observation over clear water and no valid observations over clear land and clear snow/ice areas
- clear_snow_ice – at least one valid observation over clear snow/ice area and no valid observations over clear land
- cloud – all valid observations are covered by clouds
- cloud_shadow – at least one valid cloud shadow observation and no valid observation over clear snow/ice area, clear land and clear_water

Brokered data
Dataset provided by another institution/initiative and not produced within this service.

Goal
Goal is an ideal requirement above which further improvements are not necessary.

Breakthrough
Level between threshold and goal, which, if achieved, would result in a significant improvement for the targeted application. The breakthrough value may also indicate the level at which specified uses within climate monitoring become possible.

Threshold
Minimum requirement to be met to ensure that data are useful.

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Scope of the document

The Product Quality Assessment Report (PQAR) gives a complete report of the activities executed to assess the quality of the C3S global Land Cover maps from 2016 to 2022, resulting from the product assessment methodology based on the Product Quality Assurance Document (PQAD) [RD-1].

C3S has generated annual global LC maps for 2016 to 2022 consistent with the existing global annual LC maps from 1992 – 2015 produced by the ESA-CCI LC project [ESA,2017b].

This document is divided into 4 sections that are briefly described below:

- Section 1 summarises the product validation methodology and the 2016 – 2022 LC products,
- Section 2 presents the results obtained from the validation,
- Section 3 presents the visual quality assessment,
- Section 4 outlines the product's compliance with user requirements.

Executive summary

This Product Quality Assessment Report (PQAR) presents the results of the quality assessment of the C3S 2021 and 2022 v2.1.1 global LC maps, consistent with the existing European Space Agency (ESA) Climate Change Initiative (CCI) global annual LC maps from 1992 – 2015 and the C3S global annual LC maps from 2016 – 2020. The typology of the map is defined based on the hierarchical United Nations (UN) – Land Cover Classification System (LCCS), with a global level of 22 classes and a detailed, regional level.

A new theoretical LC concept, pre-processing and classification chains were initially developed in the LC component of the ESA CCI to generate a series of annual LC maps from 1992 to 2015. Within C3S, these processing chains were then adapted to generate annually and in an ongoing operational manner the LC maps 2016–2022 from PROBA-V (2016 – 2019), from the SENTINEL-3 Ocean and Land Colour (S3-OLCI) Instrument (2020), and the SENTINEL-3 Ocean and Land Colour (S3-OLCI) Instrument and the SENTINEL-3 Sea and Land Surface Temperature Radiometer (S3-SLSTR) (2021 &2022).

The PROBA-V instrument provided Earth Observation (EO) acquisitions in four spectral bands at 300 m and 1 km spatial resolution with a temporal revisit of two days. The S3-OLCI instrument inherits and outperforms ENVISAT's MERIS specifications and provides data continuity in terms of sensor specifications between MERIS and OLCI. It acquires global EO data over land every three days in 21 bands at a full resolution of 300 m. The SLSTR instrument provides radiometric measurements expressed in top-of-atmosphere (TOA) brightness temperatures for thermal IR and fire channels and expressed in TOA radiances for the visible / SWIR channels. The Level 1b SENTINEL-3 OLCI and SLSTR data were cloud screened and atmospherically corrected and like the Level 3 PROBA-V Top-of-Canopy daily aggregated into seasonal composites using the mean compositing strategy (Vancutsem et al., 2007).

Building on the ESA CCI LC heritage, annual classifications for 2016 – 2022 were generated at full (300 m) and low (1.2 km) resolutions, extending the annual map series for land cover change analysis. The 1 km spatial resolution served for LCC detection, later remapped in more detail using the 300 m data. These processing steps generate a series of C3S global annual LC maps for the period 2016 – 2022, based on PROBA-V, Sentinel-3-OLCI and Sentinel-3 SLSTR, consistent with the existing CCI global annual LC maps from 1992 – 2015. It is delivered with metadata, product documentation, and validation reports.

This document outlines the validation process designed to assess the C3S global land cover maps from 1992 to 2021,2 which were developed during the ESA CCI LC project for the period 1992 to 2015 and operationalized within the framework of the Copernicus Climate Change Service for the LC maps for the years 2016 to 2022. The validation exercise comprises two main components.

The quantitative assessment relies on the CCI Medium Resolution Land Cover (MRLC) validation database, comprising over 1300 samples photo-interpreted with certainty by regional experts and updated annually since 2016. The validation results, obtained using samples interpreted as "certain" and exhibiting a 90% homogeneity in land cover within the validation unit, are analysed using the confusion matrix. This analysis involves gathering the land cover classes among the 22 categories which indicate a clear agreement between the product and the reference based on the LC class definition. The resulting **mean overall accuracy** for the period 2016-2022 is determined to be 70.7% +/- 0.3%.

In comparison to previous LC mapping initiatives, the notable improvement offered by this LC map series dataset lies in its spatio-temporal consistency. This consistency is further confirmed by the qualitative assessment, which constitutes the second part of the validation exercise.

This version of the PQAR focuses on the processing for the 2021 and 2022 ICDR LC products. Its main specifications are summarised in Table 0-1.

Table 0-1: Summary of the C3S LC products

Product	Coverage		Resolution		Sensor	Projection	Format
	Spatial	Temporal	Spatial	Temporal			
Annual LC maps	Global	2021	0.002778°	1-year	SENTINEL-3 OLCI / SLSTR	Plate-Carrée	NetCDF
Annual LC maps	Global	2022	0.002778°	1-year	SENTINEL-3 OLCI / SLSTR	Plate-Carrée	NetCDF

1 Product validation methodology

1.1 The global Land Cover products

1.1.1 Description

This document relates to the validation of the C3S 2016 to 2022 v2.1.1 global LC maps, at 0.002778° (approximately 300 m) spatial resolution. The Coordinate Reference System (CRS) used for the global land cover database is a geographic coordinate system (GCS) based on the World Geodetic System 84 (WGS84) reference ellipsoid. The product is processed to Level 4 (i.e. "variables that are not directly measured by the instruments but are derived from these measurements" [CEOS, 2008]).

The global 300 m LC maps are based on the PROBA-V and the S3-OLCI & SLSTR and are consistent with the existing CCI global annual LC maps from 1992 – 2015 (Table 1-1). A more detailed description can be found in the PUGS document [RD-2] and [ESA, 2017b].

Table 1-1: Summary of the global yearly LC maps

Product	Coverage		Resolution		Sensor	Projection	Format
	Spatial	Temporal	Spatial	Temporal			
Annual LC maps	Global	2016 - 2022	0.002778°	1-year	PROBA-V, S3-OLCI S3-SLSTR	Plate Carré	NetCDF

Figure 1-1 presents the LC map from the year 2022 at the global scale.

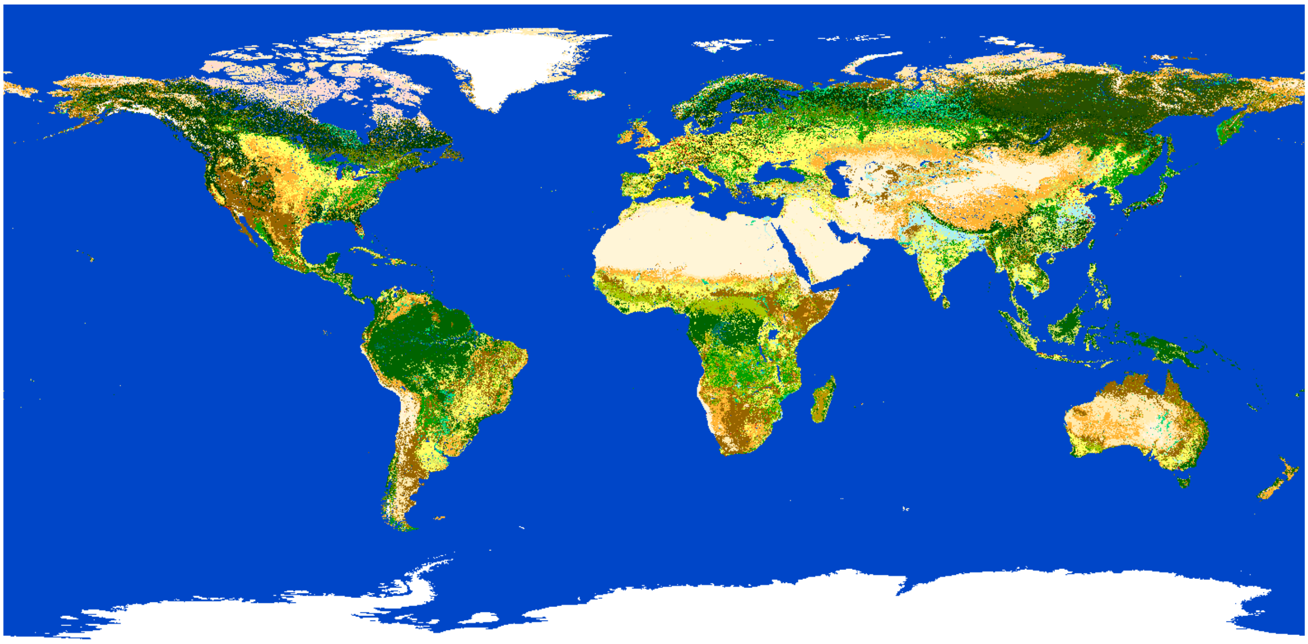

Figure 1-1: The most recent map from the LC map series from the year 2022, at 300 m spatial resolution.

1.1.2 Legend

The typology was defined using the LCCS developed by the United Nations (UN) Food and Agriculture Organization (FAO) [Di Gregorio, 2005], with the view to be as much as possible compatible with the GLC2000, GlobCover 2005 and 2009 products. In addition, the UN-LCCS was found to be quite compatible with the Plant Functional Types (PFTs) used in climate models [ESA, 2011].

The UN-LCCS defines LC classes using a set of classifiers. The system was designed as a hierarchical classification, which allows adjustment of the thematic detail of the legend to the amount of information available to describe each LC class, whilst following a standardized classification approach. As the LC maps are designed to be globally consistent, their legend is determined by the level of information that is available and that makes sense at the scale of the entire world. The "level 1" legend – also called the "global" legend – presented in Table 1-2 meets this requirement. This legend contains 22 classes and each class is associated with a ten value code (i.e. class codes of 10, 20, 30, etc.).

The LC maps are also described by a more detailed legend, called "level 2" or "regional". This level 2 legend makes use of more accurate and regional information – where available – to define more LCCS classifiers thereby reaching a higher level of detail in the legend. This regional legend has therefore more classes, which can be found in [RD-2]. The regional classes are associated with non-ten values (i.e. class codes such as 11, 12, etc.). They are not present all over the world since they were not properly discriminated at the global scale. The explicit LCCS definition of each LC global and regional class is provided in [RD-2].

Table 1-2: Level 1 (or global) legend of the LC maps, based on the UN-LCCS.

Value	Label	Colour	RGB
0	No Data		0, 0, 0
10	Cropland, rainfed		255, 255, 100
20	Cropland, irrigated or post-flooding		170, 240, 240
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)		220, 240, 100
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)		200, 200, 100
50	Tree cover, broadleaved, evergreen, closed to open (>15%)		0, 100, 0
60	Tree cover, broadleaved, deciduous, closed to open (>15%)		0, 160, 0
70	Tree cover, needleleaved, evergreen, closed to open (>15%)		0, 60, 0
80	Tree cover, needleleaved, deciduous, closed to open (>15%)		40, 80, 0
90	Tree cover, mixed leaf type (broadleaved and needleleaved)		120, 130, 0
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)		140, 160, 0
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)		190, 150, 0
120	Shrubland		150, 100, 0
130	Grassland		255, 180, 50
140	Lichens and mosses		255, 220, 210
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)		255, 235, 175
160	Tree cover, flooded, fresh or brackish water		0, 120, 90

Value	Label	Colour	RGB
170	Tree cover, flooded, saline water		0, 150, 120
180	Shrub or herbaceous cover, flooded, fresh/saline/brackish water		0, 220, 130
190	Urban areas		195, 20, 0
200	Bare areas		255, 245, 215
210	Water bodies		0, 70, 200
220	Permanent snow and ice		255, 255, 255

1.2 Validation methodology

The validation of the 2016 to 2022 global LC products consists of both a systematic confidence-building procedure and an independent statistical validation.

The global annual LC maps were first systematically examined visually and compared to previous global annual LC maps, and very high-resolution imagery in Google Earth (GE) to identify macroscopic errors and inconsistencies.

A statistical validation using independent data was then carried out based on the validation design used in the CCI LC project. The sampling design construction and specifications of the validation database can be found in [RD-1] and [ESA, 2017a]. It consists of a set of validation units, i.e. secondary sampling units (SSU). They are equivalent to the size of 3x3 pixels at 300 m spatial resolution (i.e. 81 ha) and were segmented into objects which were then validated by LC experts.

Several steps were taken to consolidate the validation database. Comments provided by the LC experts on the LC interpretation of the SSU were analysed. The 2010 LC interpretation of some of these SSUs was revisited thanks to the better availability of high-resolution imagery. In addition, each SSU interpretation has a level of confidence attributed by the expert (certain, reasonable, and doubtful). Attributing a confidence label to the interpretation of a sample can be subjective. Two experts consistently assigned particularly low confidence levels to their interpretations (e.g., designating a confidence level of 'certain' for less than 10% of their interpreted SSU). Upon re-evaluation of the samples considered 'reasonable' by the respective experts, these samples were ultimately reinterpreted as 'certain'.[1].

The validation database was updated on an annual basis to represent the year of the LC product being validated. For each sampling unit, it was determined whether a LC change had occurred since the most recent validated year in the validation database (initially 2010). The spatial resolution of the LC map products is 0.0027°, corresponding to an area of approximately 9 ha per pixel. LC changes bigger than 9 ha will therefore significantly affect the attributed LC of a pixel, and as such are considered to be a major change. Where change was detected, LC experts re-interpreted the LC of sampling units, using high-resolution satellite imagery, and annual multi-temporal Normalized Difference Vegetation Index (NDVI) profiles, derived from PROBA-V 300 m for 2016 to 2019, and Sentinel 2 (S2) high and very high spatial resolution imagery.

The accuracy of the 2016 to 2022 LC maps was assessed using the LC validation dataset. As the SSUs are segmented into objects that are labelled separately, each SSU can be interpreted into one class according to the dominant class. The homogeneity of each SSU can then be also quantified as an area proportion occupied by the dominant class. As the homogeneity or heterogeneity can vary from one SSU to another, the dataset was split according to various homogeneity thresholds: 100%, 90%, 80%, 70%, 60%, and 50%. A threshold of 50% means that at least half of the SSU area is covered by the dominant LC class.

By comparing the LC map with the independent interpretations by the experts, various accuracy parameters were produced and analysed. Confusion matrices were built, and overall accuracies were calculated based on not only the diagonal cells of the matrix but also accounting for other cells that mark agreement between the product and the validation dataset as explained in the PQAD [RD-1]. User, producer, and overall accuracies are provided.

The Committee on Earth Observation Satellites (CEOS) [Olofsson et al., 2014] recommends the calculation of the weighted overall accuracy, however, the limited number of SSUs for some of the LC classes prevents doing so.

A detailed description of the product validation methodology can be found in the PQAD [RD-1].

2 Validation results

The statistical validation of the 2016 to 2022 LC maps is presented here below, performed using the LC validation database.

2.1 Summary

Table 2-1 provides a comprehensive overview of LC mapping accuracy from 2016 to 2022, delineated across three distinct response designs: certain and homogeneous samples at 100%, certain and homogeneous samples at 90% considering 22 LCCS LC classes, and certain and homogeneous samples at 90% considering agreement between similar LC classes from a photo-interpretation perspective.

Table 2-1. Summary of overall accuracy figures determined yearly since 2016 for certain and homogeneous samples with varying homogeneities and legends

Response design	**Overall Accuracy (%) for samples interpreted as certain and with varying degrees of homogeneity**							**Overall accuracy (%) mean ± std**
	2022	2021	2020	2019	2018	2017	2016	
Certain and homogeneous samples at 100%	71.7	71.9	71.9	72.0	72.2	72.6	72.6	72.13 +/- 0.35
Certain and homogeneous samples at 90% using 22 LCCS LC classes	60.7	60.9	60.9	60.9	60.9	61.2	61.2	61 +/- 0.15
Certain and homogeneous samples at 90% considering agreement in close LC classes	70.3	70.5	70.5	70.6	70.8	71.1	71.1	70.77 +/- 0.28

The highest overall accuracy percentages, ranging from 71.7% to 72.6% are obtained when the reference sample is 100 % homogeneous. This consistency is reflected in a mean accuracy of 72.13% with a narrow standard deviation of ±0.35, emphasizing the reliability of land cover mapping.

Conversely, when considering slightly less homogeneous samples with the classification scheme of 22 LCCS land cover classes, overall accuracy percentages decrease to a range of 60.7% to 61.2%. This reduction is most probably due to the challenges associated with classifying a wide range of land cover classes and ambiguities in photo interpretation, rather than any inherent quality issues with the land cover maps.

Given the challenge of photo-interpreting mixed pixels and mosaic landscapes with similar life-form appearances, we implemented a strategy that ensures agreement between specific land cover classes at a 90% certainty threshold. This framework enables a more nuanced interpretation of the reference

database, resulting in higher and more representative overall accuracy percentages, ranging from 70.3% to 71.1%, with a mean of 70.77% and a standard deviation of ±0.28.
Despite accumulating data over time, the overall accuracy of LC maps does not improve. Nonetheless, we prioritized the maintenance of a high level of consistency in the methodology of LC map production, from pre-processing, classification, to land cover change detection, even though there have been methodological improvements in recent years. Currently, a reanalysis process is underway as part of the European Space Agency Climate Change Initiative Medium Resolution LC project. This process aims to integrate new developments to improve the spatial resolution and accuracy of the description of the LC and LCC in the map series.

2.2 Validation results: 2022

2.2.1 Validation Database 2022

The validation database was updated with regard to the previous 2021 version to be representative of the year 2022. The validation database consists of a set of 2945 SSU that were interpreted by LC experts. Confidence levels remain the same as the SSU for 2016, 2017, 2018, 2019, 2020 and 2021 (section 2.8.1), with 78% of the SSU interpreted as certain.

The SSU in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 0.18% of the SSU were affected by at least one major change between 2021 and 2022. Their spatial distribution is shown in Figure 2-1.

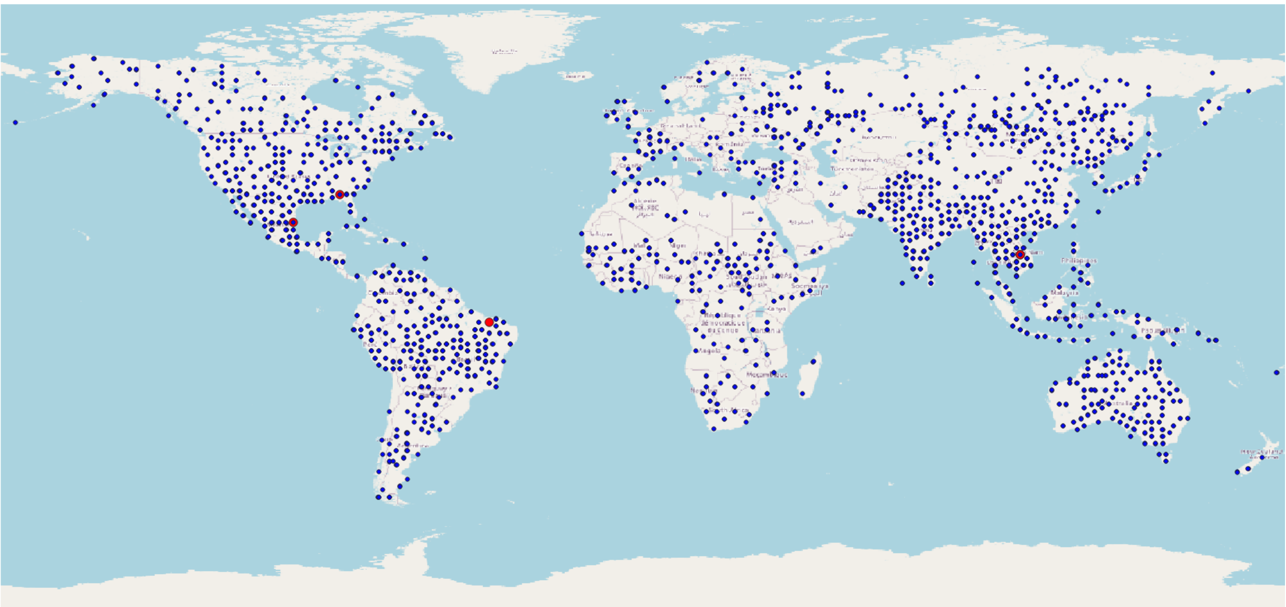

Figure 2-1: Presence of land cover change between 2021 and 2022 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-2 shows an example of major changes (i.e. >9ha) detected in the USA between 2021 and 2022.

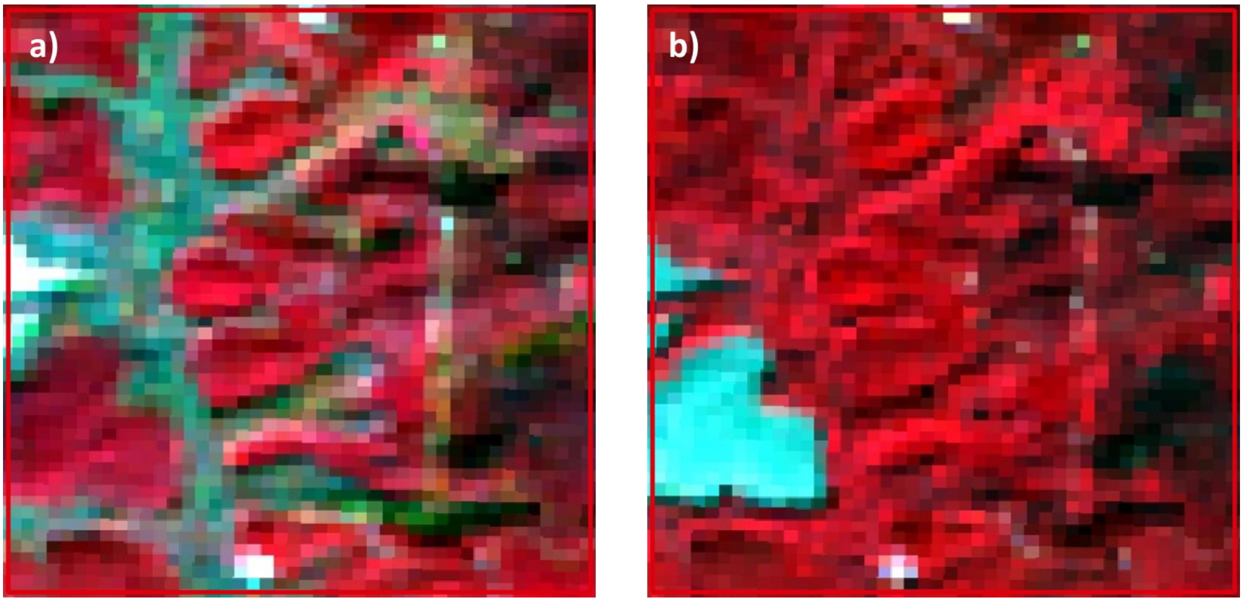

Figure 2-2: Major LC change from tree cover broadleaf evergreen to bare soil between a) 17/11/2021 and b) 19/10/2022 in the USA. (S2 imagery). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-3). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 32% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 21%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes. Looking at cumulative figures, it means that 60% of the SSU are covered by 2 or fewer LC types, 81% are covered by 3 or fewer LC types and 92% are covered by 4 or fewer LC types.

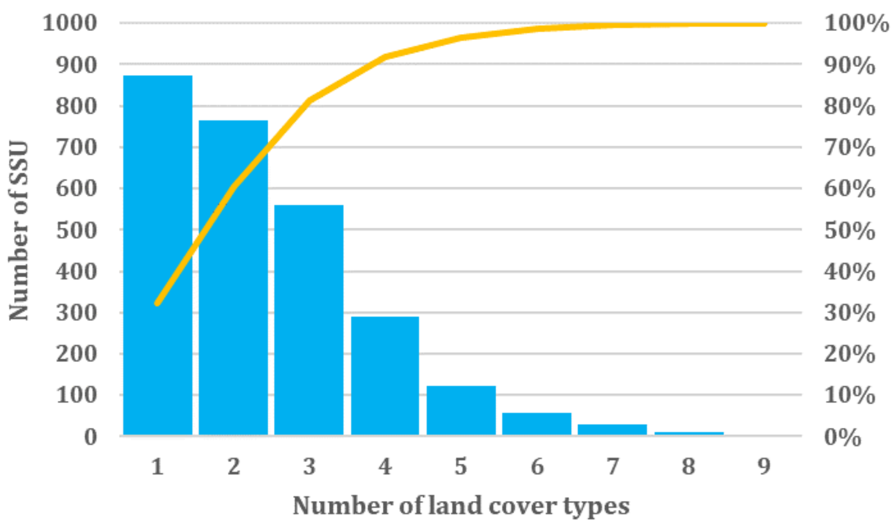

Figure 2-3: Distribution of the number of land cover classes per SSU.

2.2.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity thresholds. For the sake of the validation quality, only SSUs that were interpreted as "certain" by the LC experts were considered which corresponds to 78% of the SSUs. The results are summarized in Figure 2-4. With decreasing thresholds of homogeneity, overall accuracy slightly decreases. This is expected as the SSUs become more and more heterogeneous and more difficult to map.

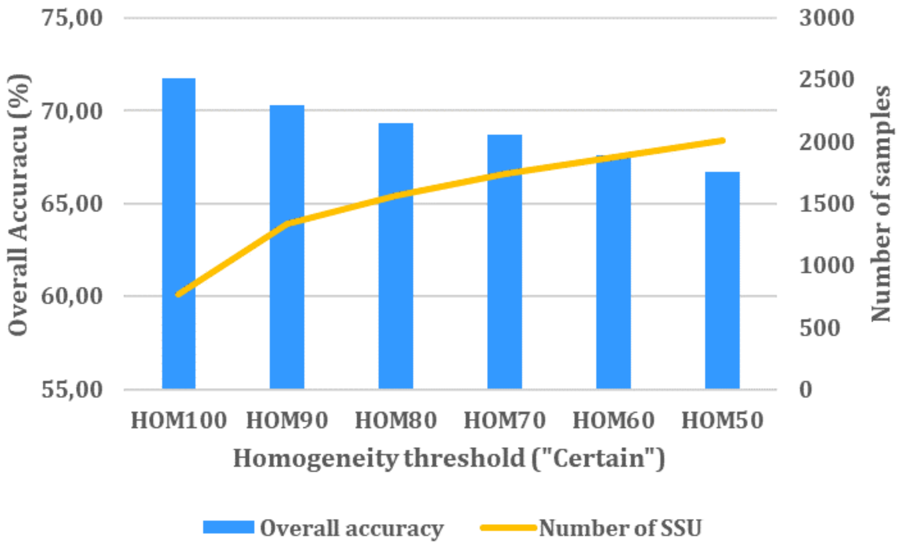

Figure 2-4: Overall accuracy values for 2022 depending on the "homogeneity" of the samples of the LC validation database that were interpreted as "certain", (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the "certain" and "homogenous" at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-3 presents the confusion matrix calculated by comparing the 2022 LC map with the samples interpreted as both "certain" by the experts, and "homogenous" at 90%. Considering only the diagonal cells, the overall accuracy is 60.67%. When considering the cells off the diagonal that are thematically compatible from a LC typology perspective, the overall accuracy value is **70.30%** and corresponds to a Kappa of 0.67.

The "certain" and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 71.73% when considering the cells thematically compatible from a LC typology perspective (green and yellow cells). Table 2-2 summarizes those accuracy figures.

Table 2-2: LC map 2022 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	71.7
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	60.7
- considering thematically-close LC classes (yellow cells)	70.3

Table 2-3: Adjusted confusion matrix that considers the 2022 LC map and the “certain” and “homogenous 90” samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

		REFERENCE: LAND COVER VALIDATION DATASET																						
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. %**
PRODUCT: C3S LC 2022 MAP	**10**	120	30	0	0	2	1	0	0	0	0	0	5	13	0	2	0	0	1	0	1	0	0	175	**86**
	20	9	25	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	37	**92**
	30	8	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	18	**44**
	40	8	1	0	0	0	7	0	0	0	0	0	2	7	0	1	0	0	0	0	0	0	0	26	**62**
	50	3	0	0	0	194	14	3	0	2	0	0	3	1	0	0	0	0	0	0	0	0	0	220	**89**
	60	1	0	0	0	6	71	1	8	16	0	0	12	0	0	0	0	0	0	0	0	0	0	115	**76**
	70	0	0	0	0	9	3	50	2	16	0	0	2	0	0	4	0	0	0	0	1	0	0	87	**76**
	80	0	0	0	0	0	0	2	23	3	0	0	2	2	0	4	0	0	0	0	0	0	0	36	**72**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	3	0	0	0	8	10	2	1	0	0	0	5	5	0	2	0	0	1	0	0	0	0	37	**70**
	110	0	0	0	0	0	0	1	0	0	0	0	2	3	0	0	0	0	1	0	0	0	0	7	**43**
	120	7	0	0	0	8	19	2	1	0	0	0	104	22	0	8	0	0	0	0	1	0	0	172	**60**
	130	9	3	0	0	0	0	0	0	1	0	0	19	64	1	14	0	0	1	1	26	1	1	141	**45**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	23	0	0	0	0	12	0	0	88	**26**
	160	0	0	0	0	5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	12	0	0	0	0	59	0	0	77	**77**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	57	0	60	**95**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	175	60	0	0	236	131	62	36	53	0	0	182	152	6	72	1	0	10	4	100	59	1	1340	
	Prod. Acc. %	**78**	**92**	**N/A**	**N/A**	**86**	**67**	**84**	**67**	**96**	**N/A**	**N/A**	**61**	**49**	**33**	**32**	**0**	**N/A**	**40**	**75**	**59**	**97**	**0**		**70.30%**

2.3 Validation results: 2021

2.3.1 Validation Database 2021

The validation database was updated with regard to the previous 2020 version to be representative of the year 2021. The validation database consists of a set of 2945 SSU that were interpreted by LC experts. Confidence levels remain the same as the SSU for 2016, 2017, 2018, 2019 and 2020 (section 2.8.1), with 78% of the SSU interpreted as certain.

The SSU in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 0.33% of the SSUs were affected by at least one major change between 2020 and 2021. Their spatial distribution is shown in Figure 2-5.

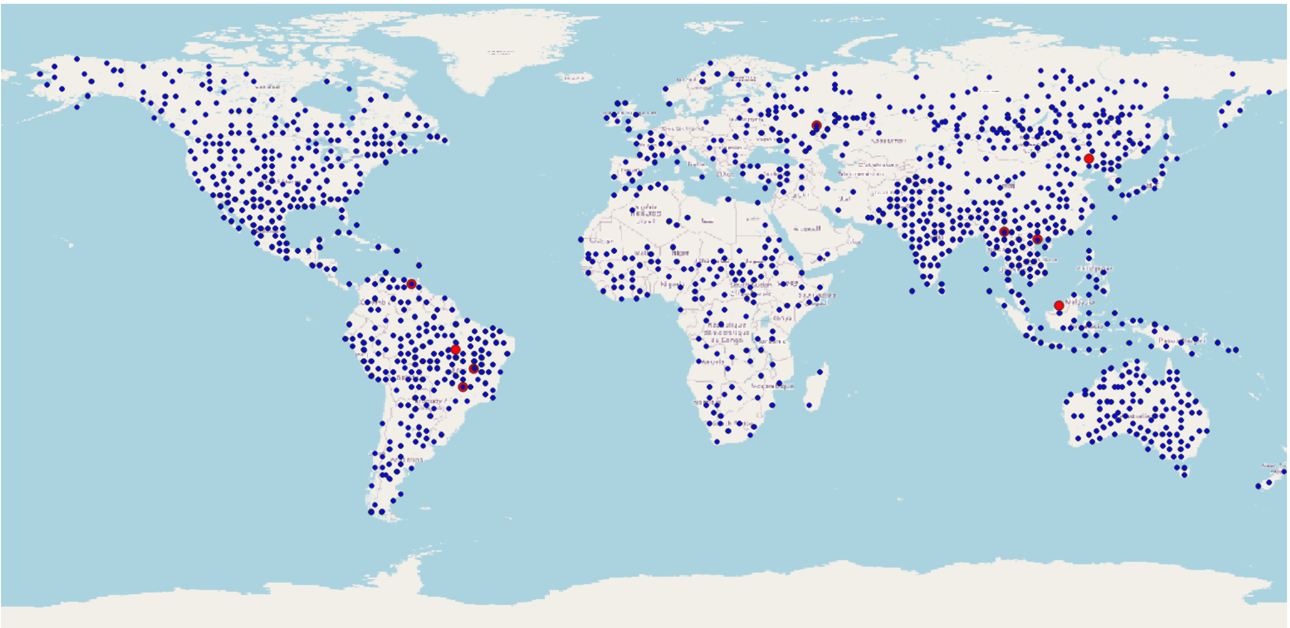

Figure 2-5: Presence of land cover change between 2020 and 2021 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-6 shows an example of major changes (i.e. >9ha) detected in Brazil between 2020 and 2021.

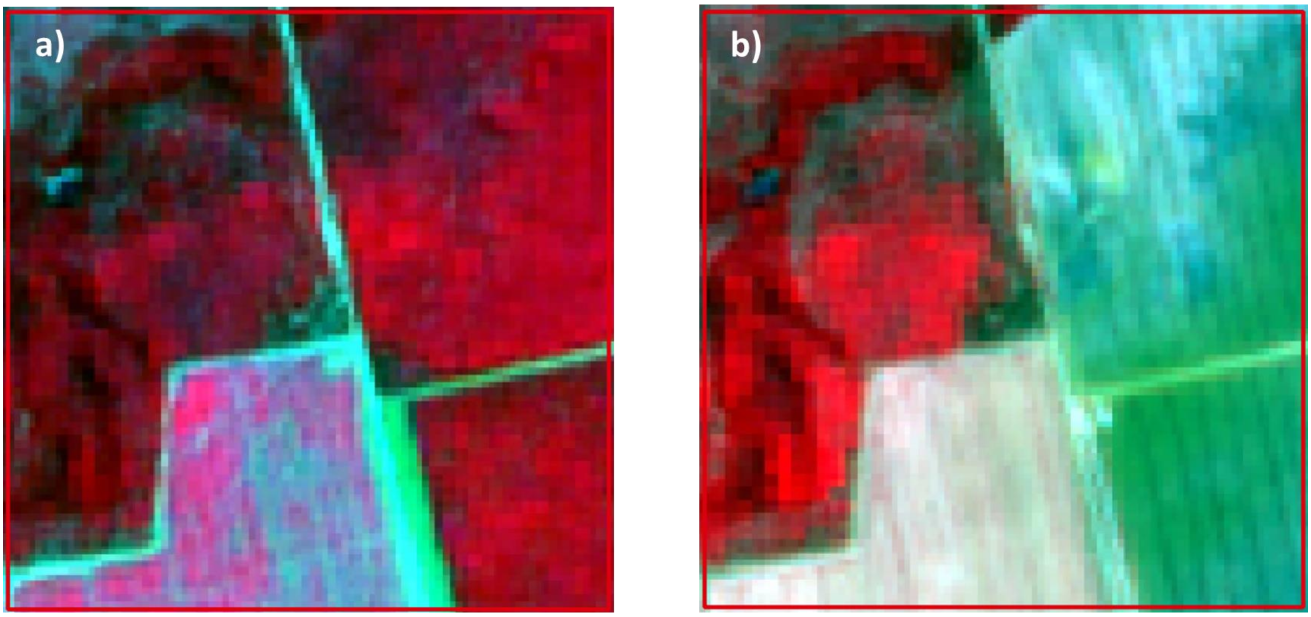

Figure 2-6: Major LC change from tree cover broadleaf evergreen to croplands between a) 24/06/2020 and b) 03/08/2021 in Brazil. (S2 imagery). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-7). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 32% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 21%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes. Looking at cumulative figures, it means that 61% of the SSU are covered by 2 or fewer LC types, 81% are covered by 3 or fewer LC types and 92% are covered by 4 or fewer LC types.

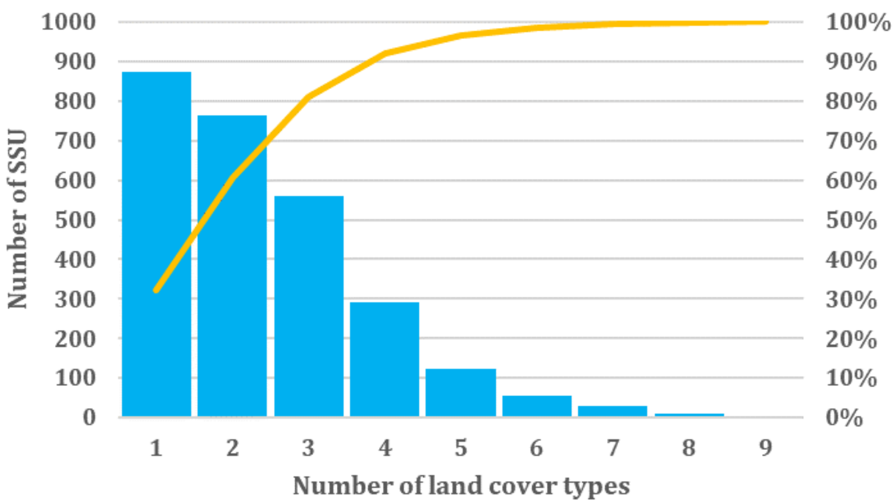

Figure 2-7: Distribution of the number of land cover classes per SSU.

2.3.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity thresholds. For the sake of the validation quality, only SSUs that were interpreted as “certain” by the LC experts were considered, corresponding to 78% of the SSUs. The results are summarized in Figure 2-8. With decreasing thresholds of homogeneity, overall accuracy slightly decreases. This is expected as the SSUs become more and more heterogeneous and more difficult to map.

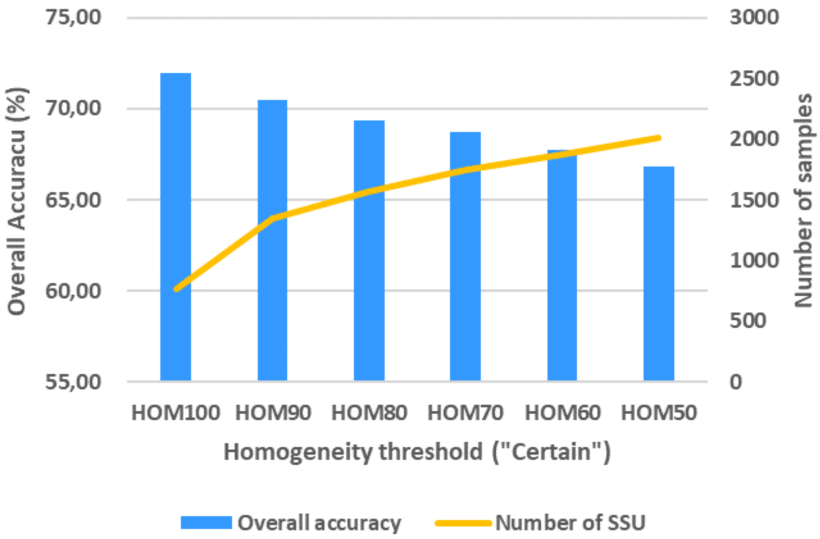

Figure 2-8: Overall accuracy values for 2021 depending on the “homogeneity” of the samples of the LC validation database that were interpreted as “certain”, (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the “certain” and “homogenous” at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-5 presents the confusion matrix calculated by comparing the 2021 LC map with the samples interpreted as both “certain” by the experts, and “homogenous” at 90%. Considering only the diagonal cells, the overall accuracy is 60.89%. When considering the cells off the diagonal that are thematically compatible from a LC typology perspective, the overall accuracy value is **70.48%** and corresponds to a Kappa of 0.69.

The “certain” and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 71.93% when considering the cells thematically compatible from a LC typology perspective (green and yellow cells). Table 2-4 summarizes those accuracy figures.

Table 2-4: LC map 2021 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	71.9
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	60.9
- considering thematically-close LC classes (yellow cells)	70.5

Table 2-5: Adjusted confusion matrix that considers the 2021 LC map and the "certain" and "homogenous 90" samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

		REFERENCE: LAND COVER VALIDATION DATASET																							
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. %**
PRODUCT: C3S LC 2021 MAP	**10**	120	30	0	0	2	1	0	0	0	0	0	5	13	0	2	0	0	1	0	1	0	0	175	**86**
	20	9	25	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	37	**92**
	30	8	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	18	**44**
	40	8	1	0	0	0	7	0	0	0	0	0	2	7	0	1	0	0	0	0	0	0	0	26	**62**
	50	3	0	0	0	197	14	3	0	2	0	0	3	1	0	0	0	0	0	0	0	0	0	223	**89**
	60	1	0	0	0	6	71	1	8	16	0	0	12	0	0	0	0	0	0	0	0	0	0	115	**76**
	70	0	0	0	0	9	3	52	2	16	0	0	2	0	0	4	0	0	0	0	1	0	0	89	**76**
	80	0	0	0	0	0	0	2	23	3	0	0	2	2	0	4	0	0	0	0	0	0	0	36	**72**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	3	0	0	0	8	10	2	1	0	0	0	5	5	0	2	0	0	1	0	0	0	0	37	**70**
	110	0	0	0	0	0	0	1	0	0	0	0	2	3	0	0	0	0	1	0	0	0	0	7	**43**
	120	7	0	0	0	7	19	2	1	0	0	0	105	22	0	8	0	0	0	0	1	0	0	172	**61**
	130	9	3	0	0	0	0	0	0	1	0	0	19	64	1	14	0	0	1	1	26	1	1	141	**45**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	23	0	0	0	0	12	0	0	88	**26**
	160	0	0	0	0	5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	12	0	0	0	0	59	0	0	77	**77**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	57	0	60	**95**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	175	60	0	0	238	131	64	36	53	0	0	183	152	6	72	1	0	10	4	100	59	1	1345	
	Prod. Acc. %	**78**	**92**	**N/A**	**N/A**	**86**	**67**	**84**	**67**	**96**	**N/A**	**N/A**	**61**	**49**	**33**	**32**	**0**	**N/A**	**40**	**75**	**59**	**97**	**0**		**70.48%**

2.4 Validation results: 2020

2.4.1 Validation database 2020

The validation database was updated with regards to the previous 2019 version to be representative of the year 2020. The validation database consists of a set of 2945 SSU that were interpreted by LC experts. Confidence levels remain the same as the SSU for 2016, 2017, 2018, and 2019 (section 2.8.1), with 78% of the SSU interpreted as certain.

The SSU in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 0.85% of the SSU were affected by at least one major change between 2019 and 2020. Their spatial distribution is shown in Figure 2-9

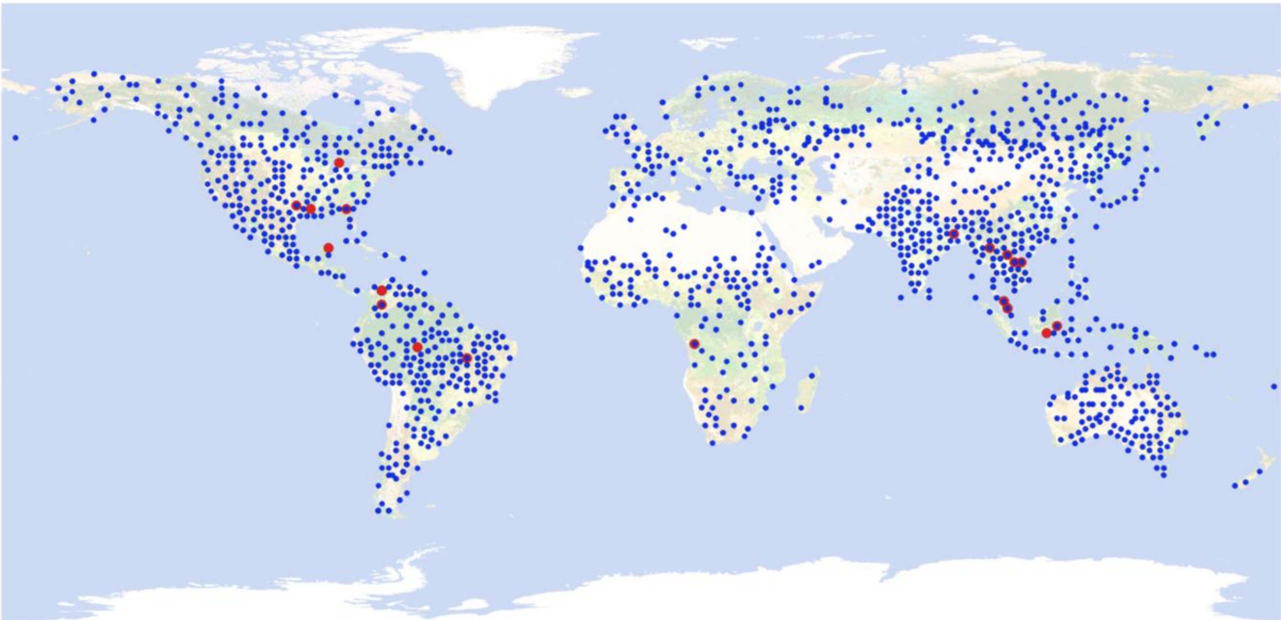

Figure 2-9: Presence of land cover change between 2019 and 2020 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-10 shows an example of major changes (i.e. >9ha) detected in USA between 2019 and 2020.

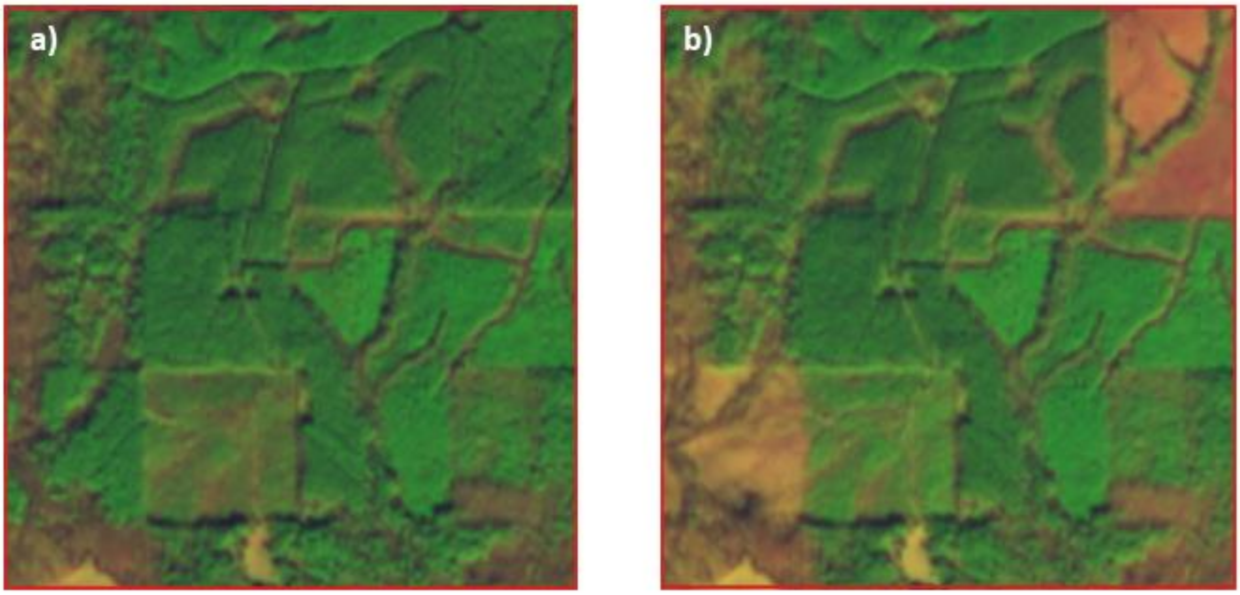

Figure 2-10: Major LC change from tree cover broadleaf evergreen to bare soil between a) 10/11/2019 and b) 04/11/2020 in USA. (S2 imagery). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-11). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 32% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 21%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes. Looking at cumulative figures, it means that 61% of the SSU are covered by 2 or less LC types, 81% are covered by 3 or less LC types and 92% are covered by 4 or less LC types.

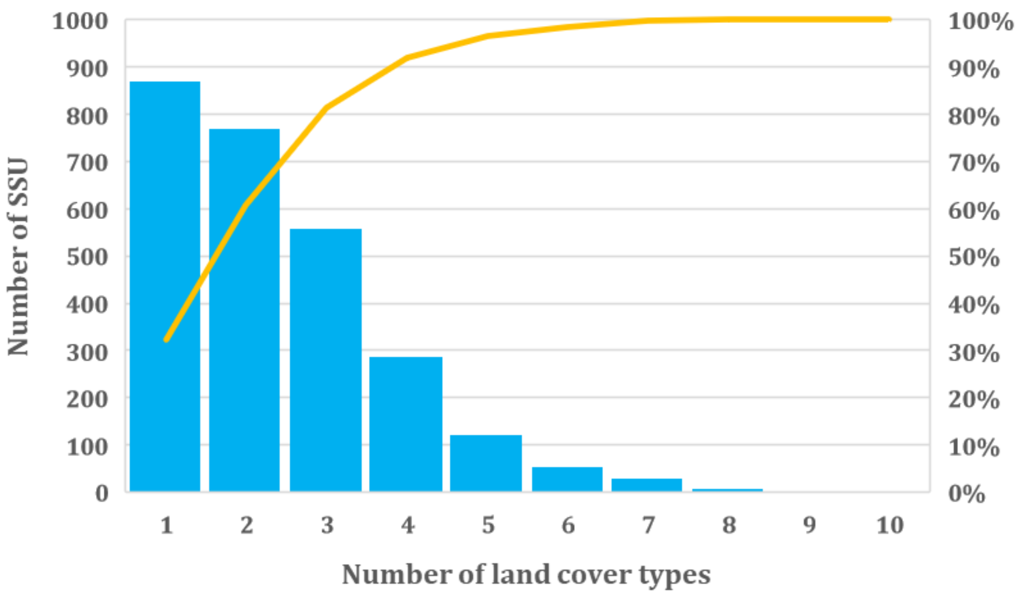

Figure 2-11: Distribution of the number of land cover classes per SSU.

2.4.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity thresholds. For the sake of the validation quality, only SSU that were interpreted as "certain" by the LC experts were considered which are corresponding to 78% of the SSU. The results are summarized in Figure 2-12. With decreasing thresholds of homogeneity, overall accuracy slightly decreases. This is clearly expected as the SSUs become more and more heterogeneous and more difficult to map.

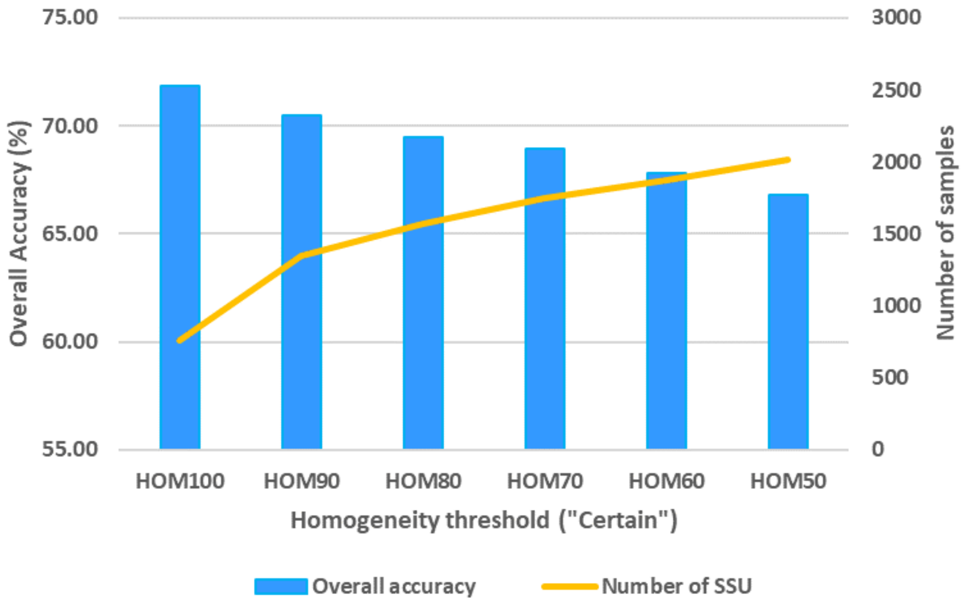

Figure 2-12: Overall accuracy values for 2020 depending on the "homogeneity" of the samples of the LC validation database that were interpreted as "certain", (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the "certain" and "homogenous" at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-7 presents the confusion matrix calculated by comparing the 2020 LC map with the samples interpreted as both "certain" by the experts, and "homogenous" at 90%. Considering only the diagonal cells, the overall accuracy is 60.86%. When considering the cells off-diagonal that are thematically compatible from a LC typology perspective, the overall accuracy value is **70.46%** and corresponds to a Kappa of 0.67.

The "certain" and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 71.86%, when considering the cells thematically compatible from a LC typology perspective (green and yellow cells). Table 2-6 summarizes those accuracy figures.

Table 2-6: LC map 2020 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	71.9
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	60.9
- considering thematically-close LC classes (yellow cells)	70.5

Table 2-7: Adjusted confusion matrix that considers the 2020 LC map and the "certain" and "homogenous 90" samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

		REFERENCE: LAND COVER VALIDATION DATASET																						
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. %**
PRODUCT: C3S LAND COVER 2020 MAP	**10**	119	30	0	0	2	1	0	0	0	0	0	5	14	0	2	0	0	1	0	1	0	0	175	**85**
	20	9	24	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	**94**
	30	8	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	18	**44**
	40	8	1	0	0	0	7	0	0	0	0	0	2	7	0	1	0	0	0	0	0	0	0	26	**62**
	50	3	0	0	0	197	14	3	0	2	0	0	3	1	0	0	0	0	0	0	0	0	0	223	**89**
	60	1	0	0	0	6	71	1	8	16	0	0	12	0	0	0	0	0	0	0	0	0	0	115	**76**
	70	0	0	0	0	10	3	53	2	16	0	0	2	0	0	4	0	0	0	0	0	0	0	90	**77**
	80	0	0	0	0	0	0	2	23	3	0	0	2	2	0	4	0	0	0	0	0	0	0	36	**72**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	3	0	0	0	8	10	2	1	0	0	0	5	5	0	2	0	0	1	0	0	0	0	37	**70**
	110	0	0	0	0	0	0	1	0	0	0	0	2	3	0	0	0	0	1	0	0	0	0	7	**43**
	120	7	0	0	0	7	19	2	1	0	0	0	105	22	0	8	0	0	0	0	1	0	0	172	**61**
	130	9	3	0	0	0	0	0	0	1	0	0	19	64	1	14	0	0	1	1	26	1	1	141	**45**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	23	0	0	0	0	12	0	0	88	**26**
	160	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	12	0	0	0	0	59	0	0	77	**77**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	57	0	60	**95**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	174	59	0	0	240	131	65	36	53	0	0	183	152	6	72	1	0	10	4	99	58	1	**1344**	
	Prod. Acc. %	**78**	**92**	**N/A**	**N/A**	**85**	**67**	**85**	**67**	**96**	**N/A**	**N/A**	**61**	**49**	**33**	**32**	**0**	**N/A**	**40**	**75**	**60**	**98**	**0**		**70.46%**

2.5 Validation results: 2019

2.5.1 Validation database 2019

The validation database was updated with regards to the previous 2018 version to be representative of the year 2019. The validation database consists of a set of 2945 SSU that were interpreted by LC experts. Confidence levels remain the same as the SSU for 2016, 2017 and 2018 (section 2.8.1) with 78% of the SSU interpreted as certain.

The SSU in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 1.2% of the SSU were affected by at least one major change between 2018 and 2019. Their spatial distribution is shown in Figure 2-13.

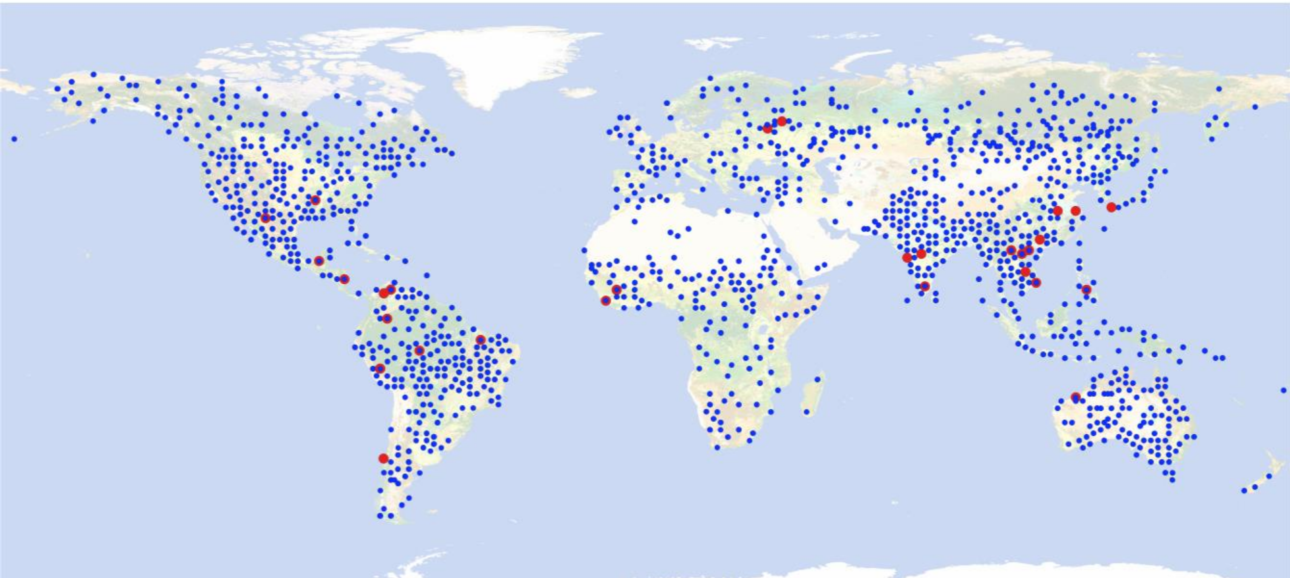

Figure 2-13: Presence of land cover change between 2018 and 2019 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-14 shows an example of major changes (i.e. >9ha) detected in Vietnam between 2018 and 2019.

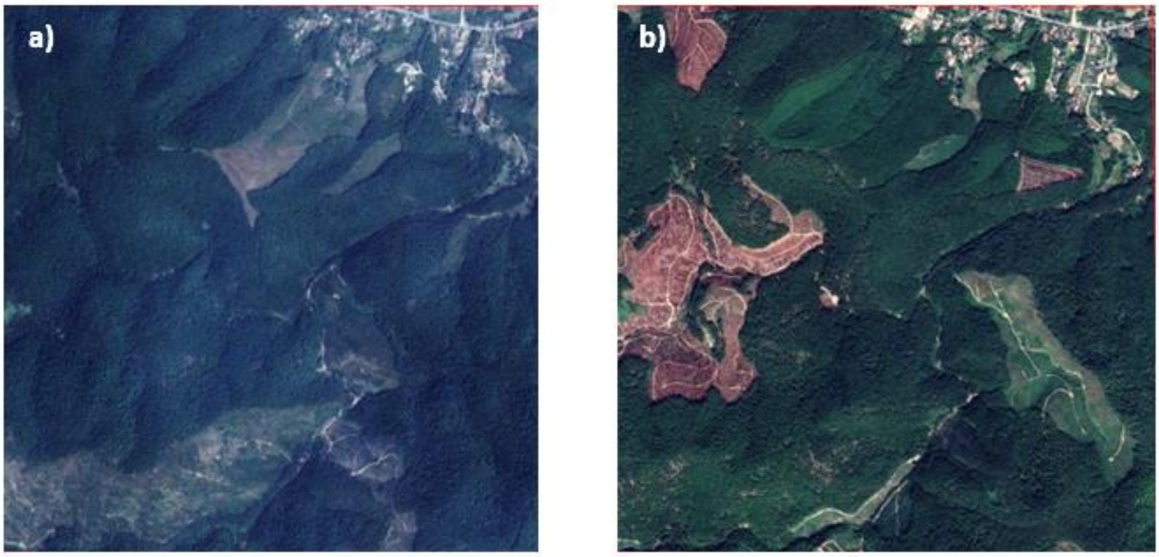

Figure 2-14: Major LC change from tree cover broadleaf evergreen to bare soil between a) 01/01/2018 and b) 08/11/2019 in Vietnam. (Google Earth imagery and historical timeline). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-15). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 32% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 21%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes. Looking at cumulative figures, it means that 60% of the SSU are covered by 2 or less LC types, 81% are covered by 3 or less LC types and 92% are covered by 4 or less LC types.

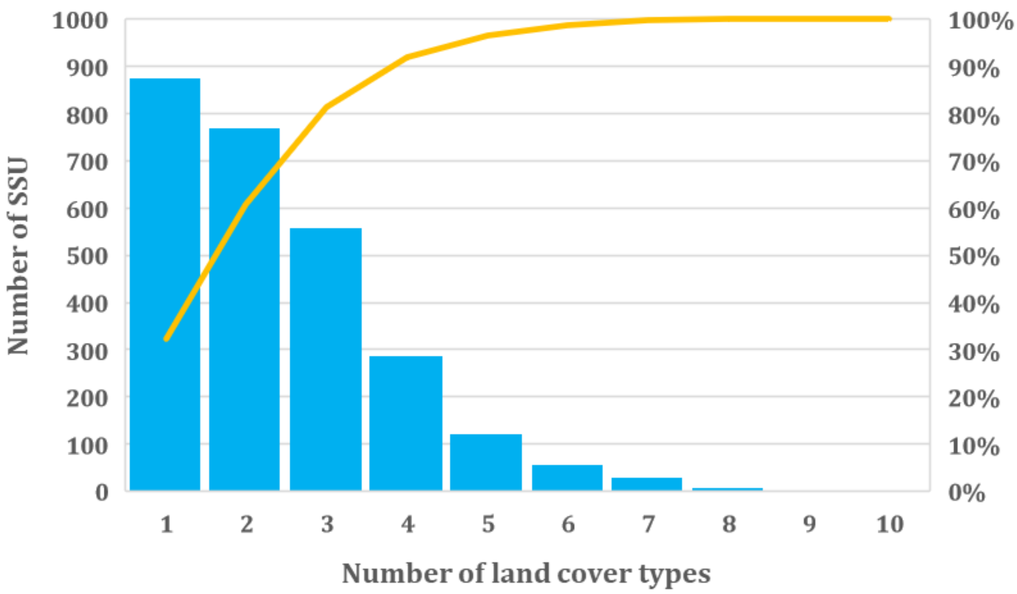

Figure 2-15: Distribution of the number of land cover classes per SSU.

2.5.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity thresholds. For the sake of the validation quality, only SSU that were interpreted as “certain” by the LC experts were considered which are corresponding to 78% of the SSU. The results are summarized in Figure 2-16. With decreasing thresholds of homogeneity, overall accuracy slightly decreases. This is clearly expected as the SSU becomes more and more heterogeneous and more difficult to map.

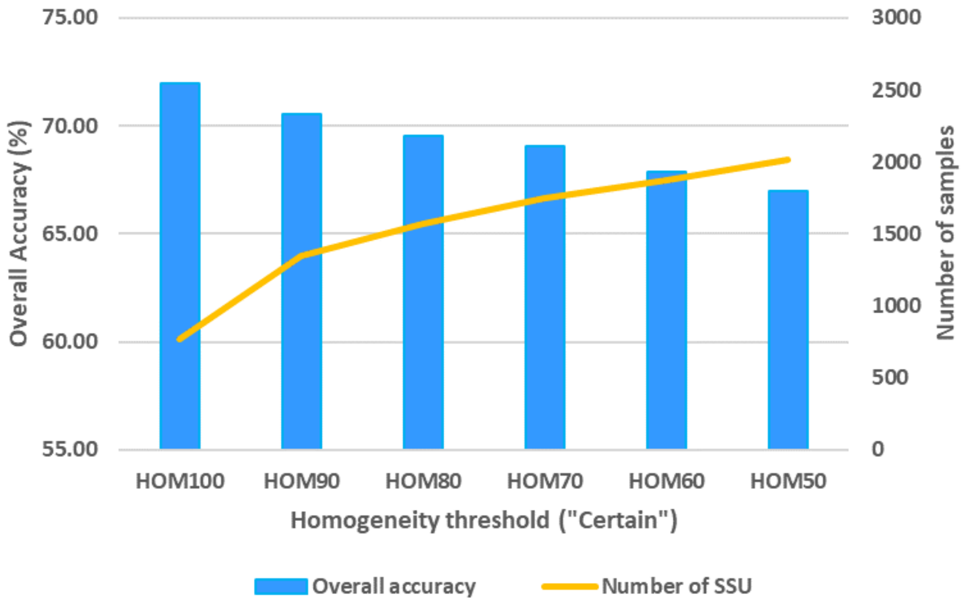

Figure 2-16: Overall accuracy values for 2019 depending on the “homogeneity” of the samples of the LC validation database that were interpreted as “certain”, (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the “certain” and “homogenous” at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-9 presents the confusion matrix calculated by comparing the 2019 LC map with the samples interpreted as both “certain” by the experts, and “homogenous” at 90%. Considering only the diagonal cells, the overall accuracy is 60.97%. When considering the cells off the diagonal that are clearly thematically compatible from a LC typology perspective, the overall accuracy value is **70.6%**, and corresponds to a Kappa of 0.67.

The “certain” and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 71.97%, when considering the cells clearly thematically compatible from a LC typology perspective (green and yellow cells). Table 2-8 summarizes those accuracy figures.

Table 2-8: LC map 2019 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	72.0
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	60.9
- considering thematically-close LC classes (yellow cells)	70.6

Table 2-9: Adjusted confusion matrix that considers the 2019 LC map and the “certain” and “homogenous 90” samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

		REFERENCE: LAND COVER VALIDATION DATASET																						
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. (%)**
PRODUCT: C3S LAND COVER 2017 MAP	**10**	119	30	0	0	2	1	0	0	0	0	0	5	14	0	2	0	0	1	0	1	0	0	175	**85**
	20	9	24	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	**94**
	30	8	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	18	**44**
	40	8	1	0	0	0	7	0	0	0	0	0	2	7	0	1	0	0	0	0	0	0	0	26	**62**
	50	3	0	0	0	198	14	3	0	2	0	0	3	1	0	0	0	0	0	0	0	0	0	224	**89**
	60	1	0	0	0	6	71	1	8	16	0	0	12	0	0	0	0	0	0	0	0	0	0	115	**76**
	70	0	0	0	0	10	3	53	2	16	0	0	2	0	0	4	0	0	0	0	0	0	0	90	**77**
	80	0	0	0	0	0	0	2	23	3	0	0	2	3	0	4	0	0	0	0	0	0	0	37	**70**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	3	0	0	0	8	10	2	1	0	0	0	5	5	0	2	0	0	1	0	0	0	0	37	**70**
	110	0	0	0	0	0	0	1	0	0	0	0	2	3	0	0	0	0	1	0	0	0	0	7	**43**
	120	7	0	0	0	7	19	2	1	0	0	0	105	21	0	8	0	0	0	0	1	0	0	171	**61**
	130	9	3	0	0	0	0	0	0	1	0	0	19	64	1	14	0	0	1	1	25	1	1	140	**46**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	23	0	0	0	0	12	0	0	88	**26**
	160	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	12	0	0	1	0	60	0	0	79	**76**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	57	0	59	**97**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	174	59	0	0	241	131	65	36	53	0	0	183	152	6	72	1	0	10	4	99	58	1	**1345**	
	Prod. Acc (%)	**78**	**92**	**N/A**	**N/A**	**85**	**67**	**85**	**67**	**96**	**N/A**	**N/A**	**61**	**49**	**33**	**32**	**0**	**N/A**	**40**	**75**	**61**	**98**	**0**		**70.56%**

2.6 Validation results: 2018

2.6.1 Validation database 2018

The validation database was updated with regards to the previous 2017 version to be representative of the year 2018. The validation database consists of a set of 2945 SSU that were interpreted by LC experts. Confidence levels remain the same as the SSU for 2016 and 2017 (section 2.8.1), with 78% of the SSU interpreted as certain.

The SSU in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 1.1% of the SSU were affected by at least one major change between 2017 and 2018. Their spatial distribution is shown in Figure 2-17.

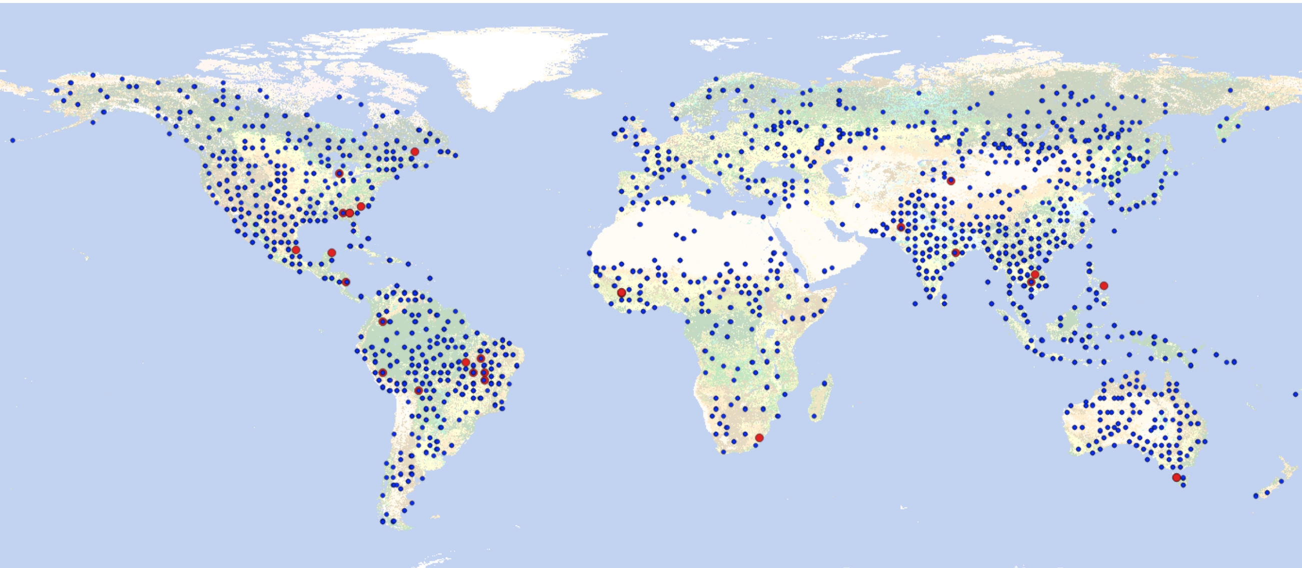

Figure 2-17: Presence of land cover change between 2017 and 2018 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-18 shows an example of major changes (i.e. >9ha) detected in Brazil between 2017 and 2018.

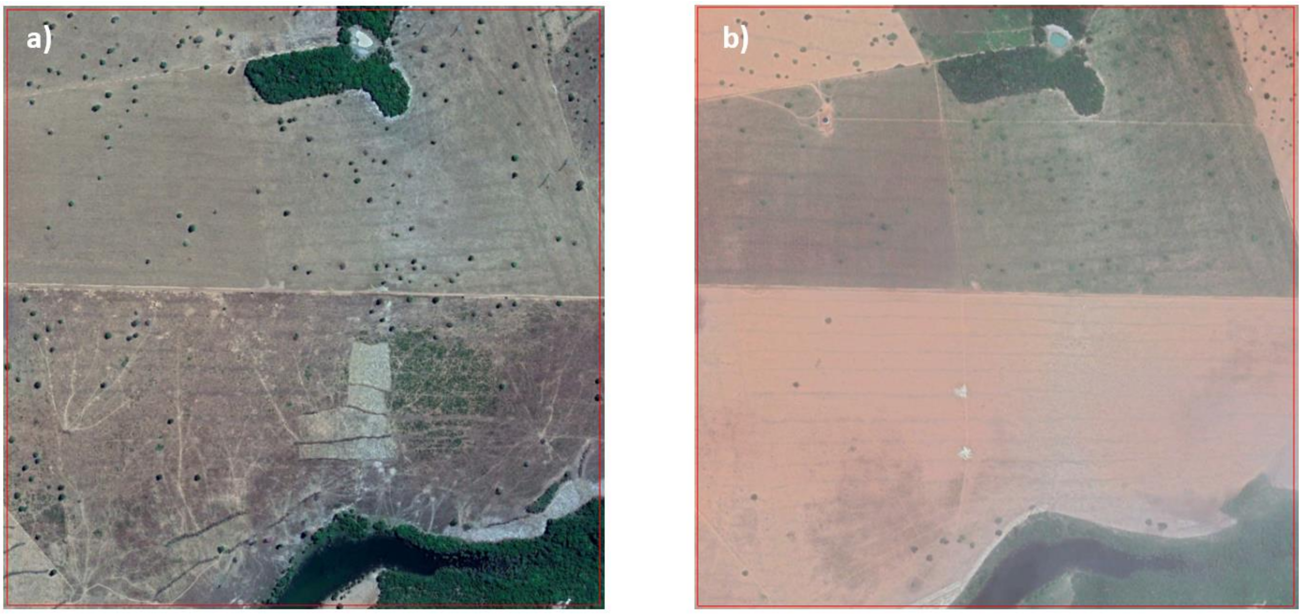

Figure 2-18: Major LC change from grassland to cropland between a) 18/07/2017 and b) 20/11/2018 in Brazil. (Google Earth imagery and historical timeline). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-19). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 33% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 20%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes. Looking at cumulative figures, it means that 61% of the SSU are covered by 2 or less LC types, 81% are covered by 3 or less LC types and 92% are covered by 4 or less LC types.

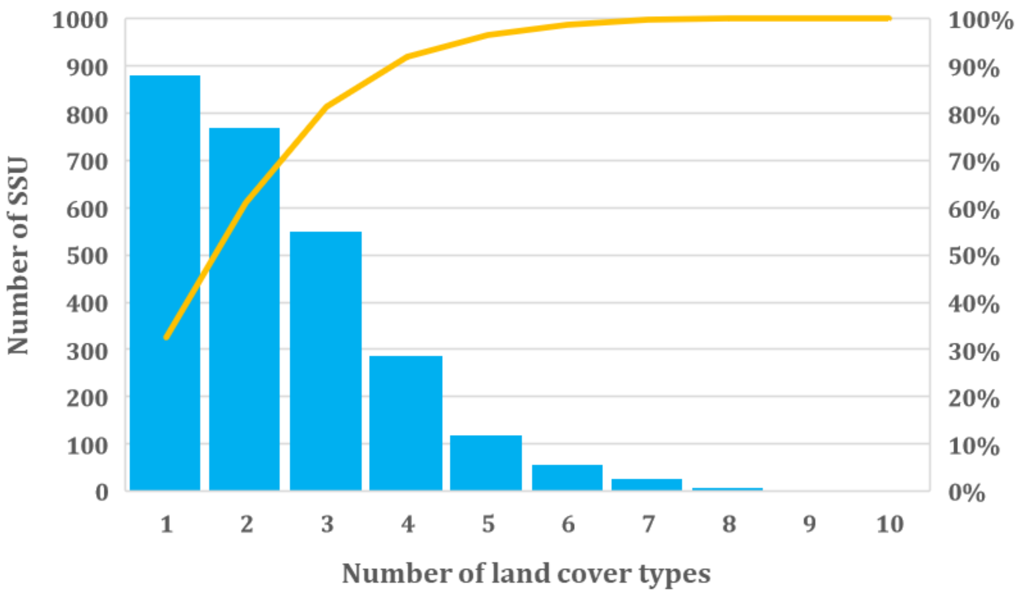

Figure 2-19: Distribution of the number of land cover classes per SSU.

2.6.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity thresholds. For the sake of the validation quality, only SSU that were interpreted as "certain" by the LC experts were considered which are corresponding to 78% of the SSU. The results are summarized in Figure 2-20. With decreasing thresholds of homogeneity, overall accuracy slightly decreases. This is clearly expected as the SSUs become more and more heterogeneous and more difficult to map.

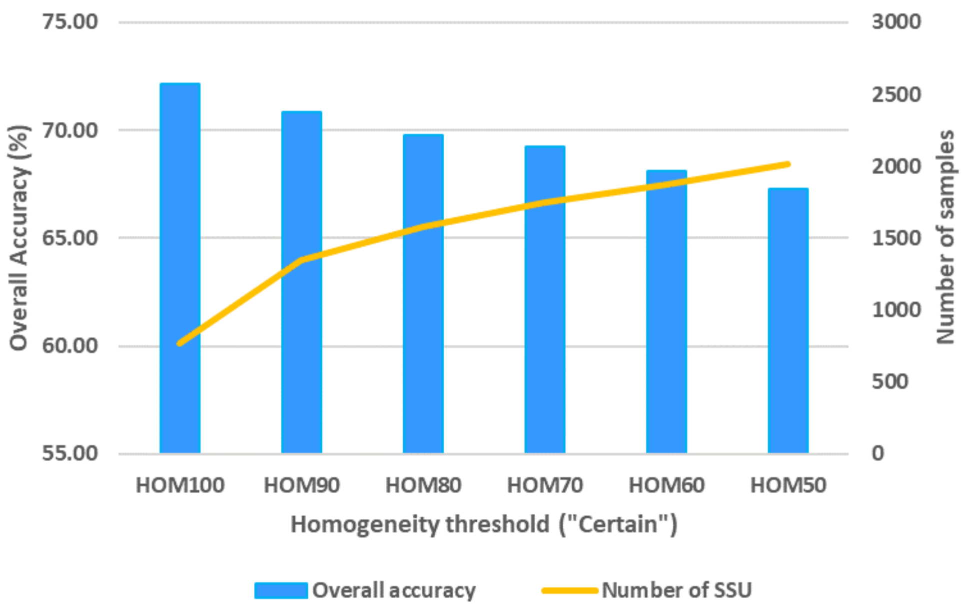

Figure 2-20: Overall accuracy values for 2018 depending on the "homogeneity" of the samples of the LC validation database that were interpreted as "certain", (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the "certain" and "homogenous" at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-11 presents the confusion matrix calculated by comparing the 2018 LC map with the samples interpreted as both "certain" by the experts, and "homogenous" at 90%. Considering only the diagonal cells, the overall accuracy is 60.88%. When considering the cells off the diagonal that are clearly thematically compatible from a LC typology perspective, the overall accuracy value is **70.8%**, and corresponds to a Kappa of 0.68.

The "certain" and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 72.2%, when considering the cells clearly thematically compatible from a LC typology perspective (green and yellow cells). Table 2-10 summarizes those accuracy figures.

Table 2-10: LC map 2018 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	72.2
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	60.9
- considering thematically-close LC classes (yellow cells)	70.8

Table 2-11: Adjusted confusion matrix that considers the 2018 LC map and the “certain” and “homogenous 90” samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

		REFERENCE: LAND COVER VALIDATION DATASET																						
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. (%)**
PRODUCT: C3S LAND COVER 2018 MAP	**10**	119	30	0	0	2	1	0	0	0	0	0	5	14	0	2	0	0	1	0	1	0	0	175	**85**
	20	9	24	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	**94**
	30	9	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	19	**47**
	40	8	1	0	0	0	7	0	0	0	0	0	3	7	0	0	0	0	0	0	0	0	0	26	**65**
	50	3	0	0	0	197	14	3	0	3	0	0	2	1	0	0	0	0	0	0	0	0	0	223	**90**
	60	1	0	0	0	6	71	1	8	16	0	0	13	0	0	0	0	0	0	0	0	0	0	116	**75**
	70	0	0	0	0	10	3	53	2	16	0	0	2	0	0	4	0	0	0	0	0	0	0	90	**77**
	80	0	0	0	0	0	0	3	23	3	0	0	2	3	0	4	0	0	0	0	0	0	0	38	**68**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	2	0	0	0	8	10	3	1	0	0	0	6	5	0	2	0	0	1	0	0	0	0	38	**74**
	110	0	0	0	0	0	0	1	0	0	0	0	2	3	0	0	0	0	1	0	0	0	0	7	**43**
	120	8	0	0	0	7	19	0	1	0	0	0	105	21	0	8	0	0	0	0	1	0	0	170	**62**
	130	8	3	0	0	0	0	0	0	1	0	0	19	64	1	14	0	0	1	1	25	1	1	139	**46**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	24	0	0	0	0	12	0	0	89	**27**
	160	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	12	0	0	1	0	60	0	0	79	**76**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	57	0	59	**97**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	174	59	0	0	240	131	65	36	54	0	0	185	152	6	72	1	0	10	4	99	58	1	**1347**	
	Prod. Acc (%)	**79**	**92**	**N/A**	**N/A**	**85**	**67**	**86**	**67**	**96**	**N/A**	**N/A**	**62**	**49**	**33**	**33**	**0**	**N/A**	**40**	**75**	**61**	**98**	**0**		**70.82%**

2.7 Validation results: 2017

2.7.1 Validation database 2017

The validation database was updated with regards to the previous 2016 version in order to be representative of the year 2017. The validation database consists of a set of 2945 SSU that were interpreted by LC experts. Confidence levels remain the same as the SSU for 2016 (section 2.8.1) with 78% of the SSU interpreted as certain.

The SSU in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 0.3% of the SSU were affected by at least one major change between 2016 and 2017. Their spatial distribution is shown in Figure 2-21.

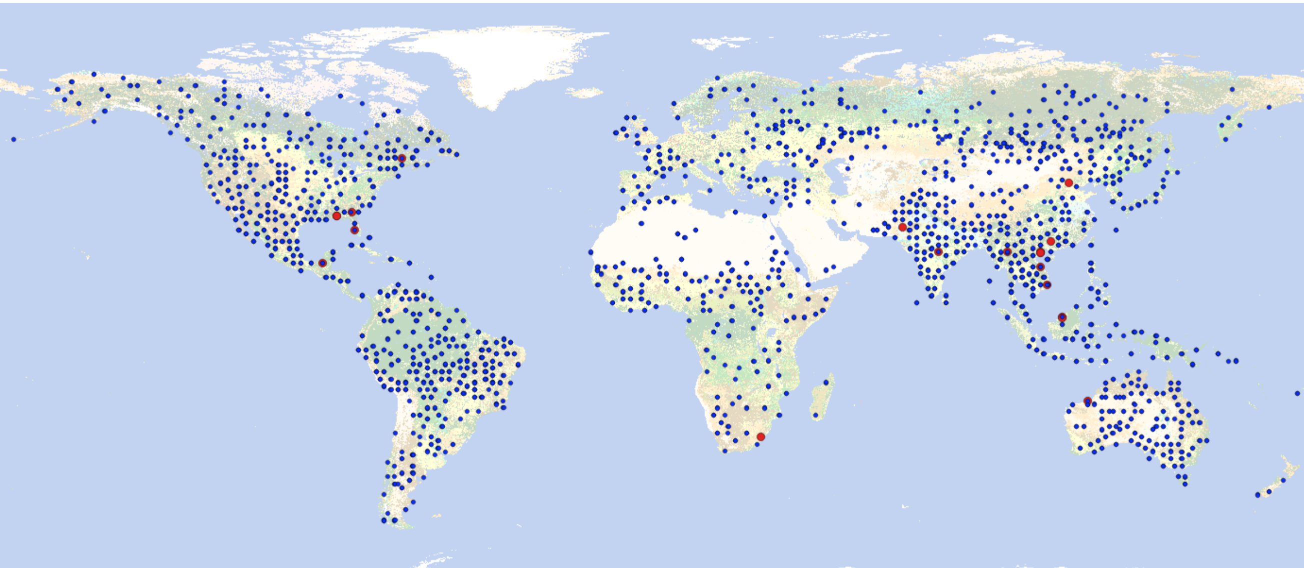

Figure 2-21: Presence of land cover change between 2016 and 2017 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-22 shows an example of major changes (i.e. >9 ha) detected in South Africa between 2016 and 2017.

Figure 2-22: Major LC change between a) 12/08/2016 and b) 01/11/2017 in South Africa. (Google Earth imagery and historical timeline). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-23). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 33% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 20%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes respectively. Looking at cumulative figures, it means that 61% of the SSU are covered by 2 or less LC types, 81% are covered by 3 or less LC types and 92% are covered by 4 or less LC types.

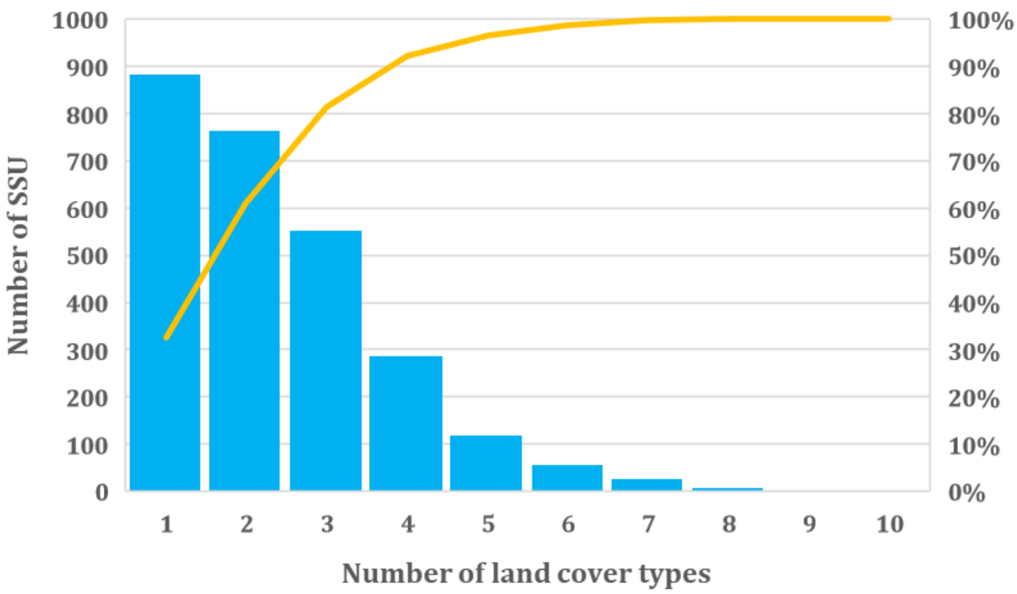

Figure 2-23: Distribution of the number of land cover classes per SSU.

2.7.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity thresholds. For the sake of the validation quality, only SSU that were interpreted as “certain” by the LC experts were considered, which are corresponding to 78% of the SSU. The results are summarized in Figure 2-24. With decreasing thresholds of homogeneity, overall accuracy slightly decreases. This is clearly expected as the SSUs become more and more heterogeneous and more difficult to map.

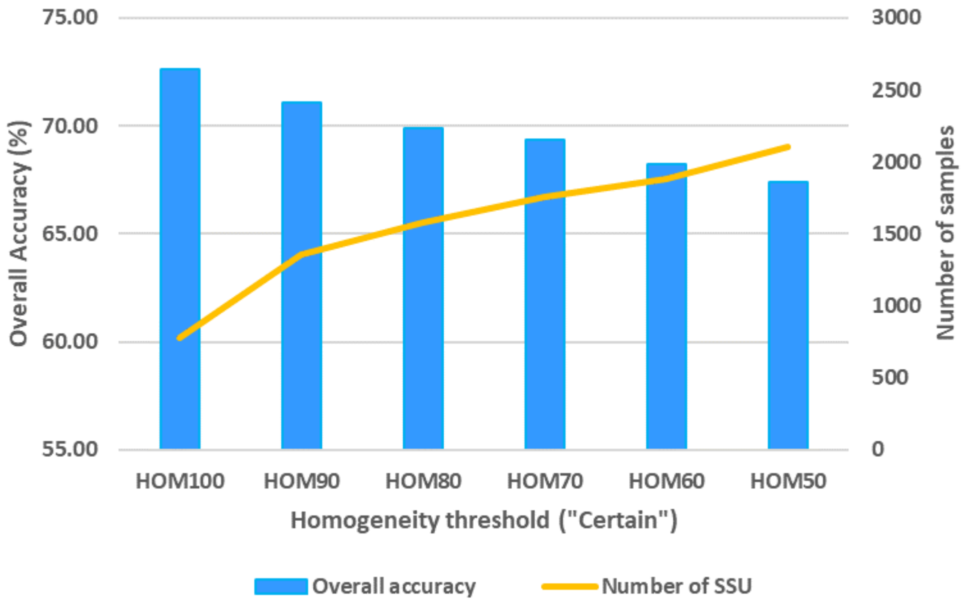

Figure 2-24: Overall accuracy values for 2017 depending on the “homogeneity” of the samples of the LC validation database that were interpreted as “certain”, (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the “certain” and “homogenous” at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-13 comparing the 2017 LC map with the samples interpreted as both “certain” by the experts, and “homogenous” at 90%. Considering only the diagonal cells, the overall accuracy is 61.2%. When considering the cells off the diagonal that are clearly thematically compatible from a LC typology perspective, the overall accuracy value is **71.1%** and corresponds to a Kappa of 0.68.

The “certain” and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 72.6%, when considering the cells clearly thematically compatible from a LC typology perspective (green and yellow cells). Table 2-12 summarizes those accuracy figures.

Table 2-12: LC map 2017 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	72.6
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	61.2
- considering thematically-close LC classes (yellow cells)	71.1

Table 2-13: Adjusted confusion matrix that considers the 2017 LC map and the "certain" and "homogenous 90" samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

		REFERENCE: LAND COVER VALIDATION DATASET																							
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. (%)**
PRODUCT: C3S LAND COVER 2017 MAP	**10**	121	30	0	0	2	1	0	0	0	0	0	5	14	0	2	0	0	1	0	1	0	0	177	**85**
	20	9	24	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	**94**
	30	9	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	19	**47**
	40	8	1	0	0	0	7	0	0	0	0	0	3	7	0	0	0	0	0	0	0	0	0	26	**65**
	50	3	0	0	0	199	15	3	0	3	0	0	2	1	0	0	0	0	0	0	0	0	0	226	**89**
	60	1	0	0	0	6	72	1	8	16	0	0	13	0	0	0	0	0	0	0	0	0	0	117	**75**
	70	0	0	0	0	10	3	54	2	16	0	0	2	0	0	4	0	0	0	0	0	0	0	91	**77**
	80	0	0	0	0	0	0	3	23	3	0	0	3	3	0	4	0	0	0	0	0	0	0	39	**67**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	2	0	0	0	8	10	3	1	0	0	0	6	5	0	2	0	0	1	0	0	0	0	38	**74**
	110	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	1	0	0	0	0	5	**60**
	120	8	0	0	0	7	19	0	1	0	0	0	105	21	0	8	0	0	0	0	1	0	0	170	**62**
	130	8	3	0	0	0	0	0	0	1	0	0	19	64	1	12	0	0	1	1	25	1	1	137	**47**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	25	0	0	0	0	11	0	0	89	**28**
	160	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	13	0	0	1	0	61	0	0	81	**75**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	57	0	59	**97**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	176	59	0	0	242	133	65	36	54	0	0	185	152	6	72	1	0	10	4	99	58	1	**1353**	
	Prod. Acc (%)	**79**	**92**	**N/A**	**N/A**	**86**	**67**	**88**	**67**	**96**	**N/A**	**N/A**	**62**	**49**	**33**	**35**	**0**	**N/A**	**40**	**75**	**62**	**98**	**0**		**71.10%**

2.8 Validation results: 2016

2.8.1 Validation Database 2016

The validation database was consolidated and updated with regards to the previous CCI LC version to be representative of the year 2016, and to include the full set of validation units worldwide, including those that were previously missing in South America. The validation database consists of a set of 2945 SSU that were interpreted by LC experts.

An analysis of the expert confidence levels found that 66% of the SSU were interpreted as certain, 30% as reasonable and 4% as doubtful. This identifies areas that are more difficult to interpret, but also that the evaluation of certainty is partly subjective and could sometimes be expert-dependent. For example, nearly all SSUs in India have been interpreted as reasonable, as can be seen in Figure 2-25. 90% of the SSUs interpreted by that expert were interpreted as reasonable. For the two experts that had a confidence level of ‘certain’ for less than 10% of their interpreted SSU, their ‘reasonable’ SSU were also interpreted as ‘certain’ by the LC team of this project.

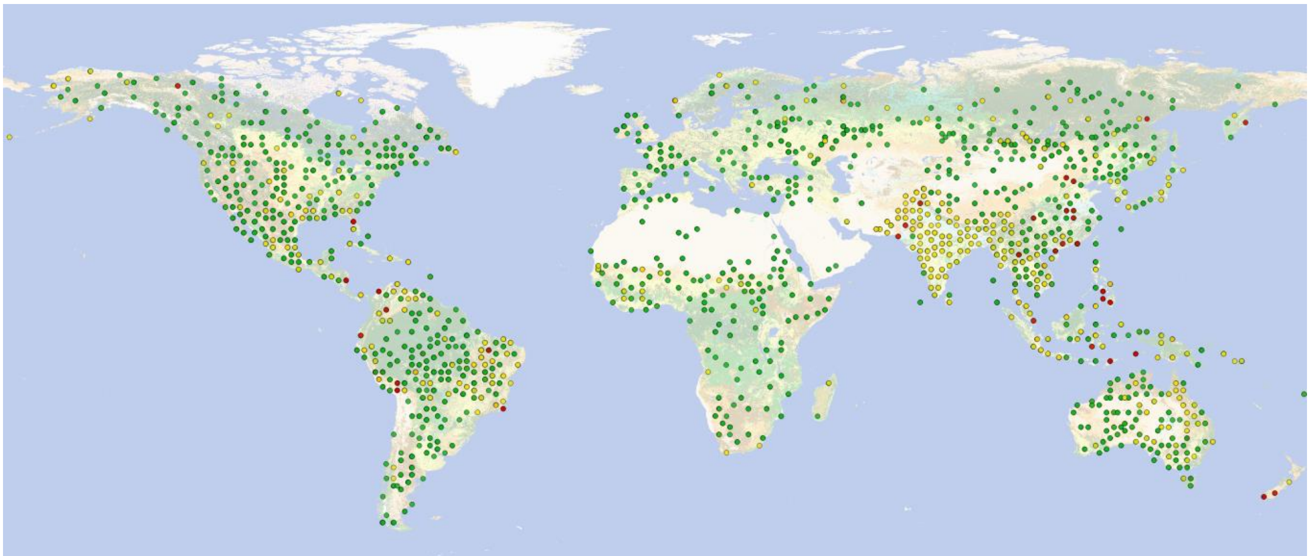

Figure 2-25: Samples included in the validation database associated with the level of certainty of their interpretation (green = certain, orange = reasonable, red = doubtful).

The consolidation steps increased the number of sample units used in the validation. The spatial distribution of the confidence levels in the consolidated validation database can be seen in Figure 2-26. 78% of the SSUs were as interpreted as certain, 19% as reasonable and 3% as doubtful.

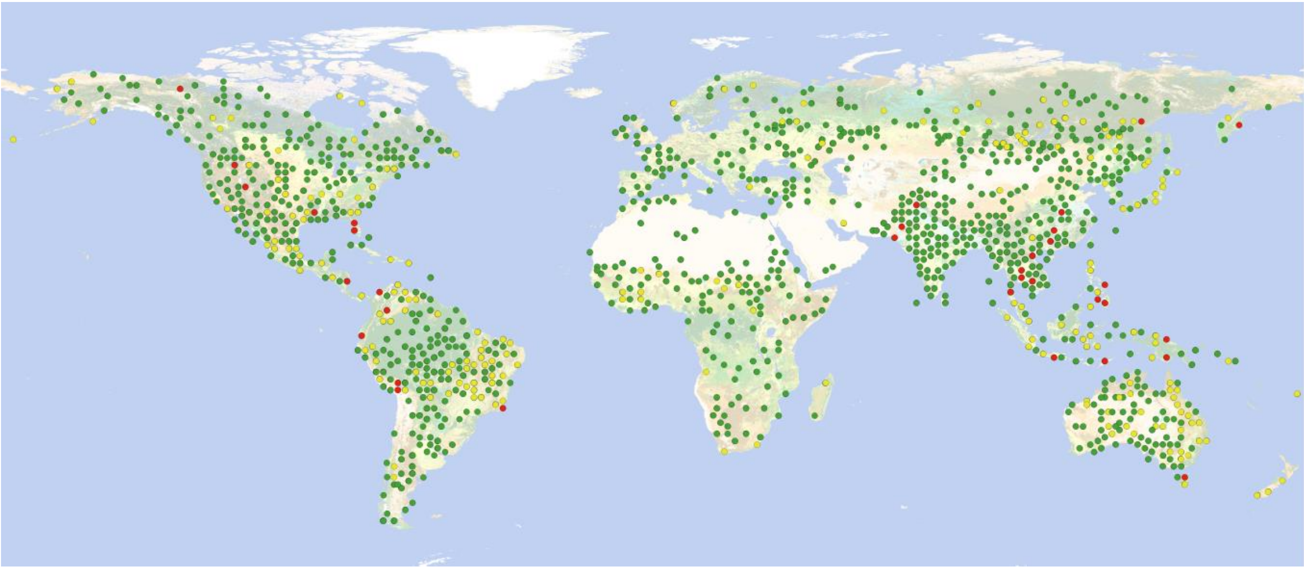

Figure 2-26: Samples included in the consolidated validation database associated with the level of certainty of their interpretation (green = certain, orange = reasonable, red = doubtful).

The SSUs in which major change occurred were identified. Then, a new LC was reinterpreted by experts. 4.6% of the SSU were affected by at least one major change between 2010 and 2016. Their spatial distribution is shown in Figure 2-27.

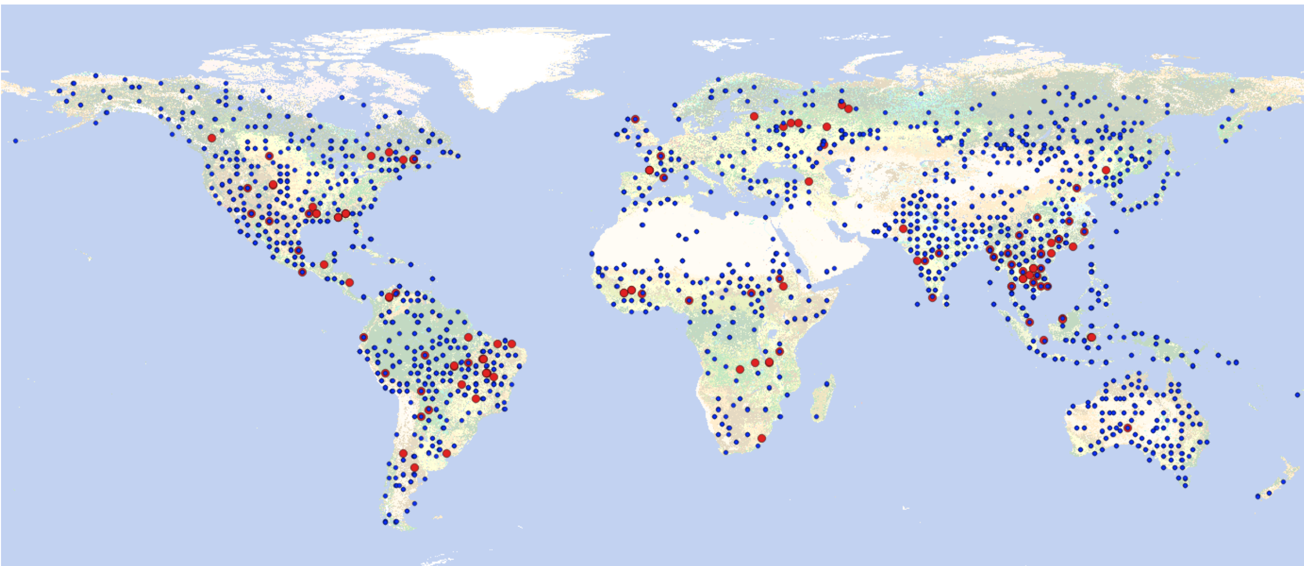

Figure 2-27: Presence of land cover change between 2010 and 2016 within the samples included in the LC validation database (blue = no change, red = change).

Figure 2-28 and Figure 2-29 show examples of major changes (i.e. >9 ha) detected in France and Argentina between 2010 and 2016.

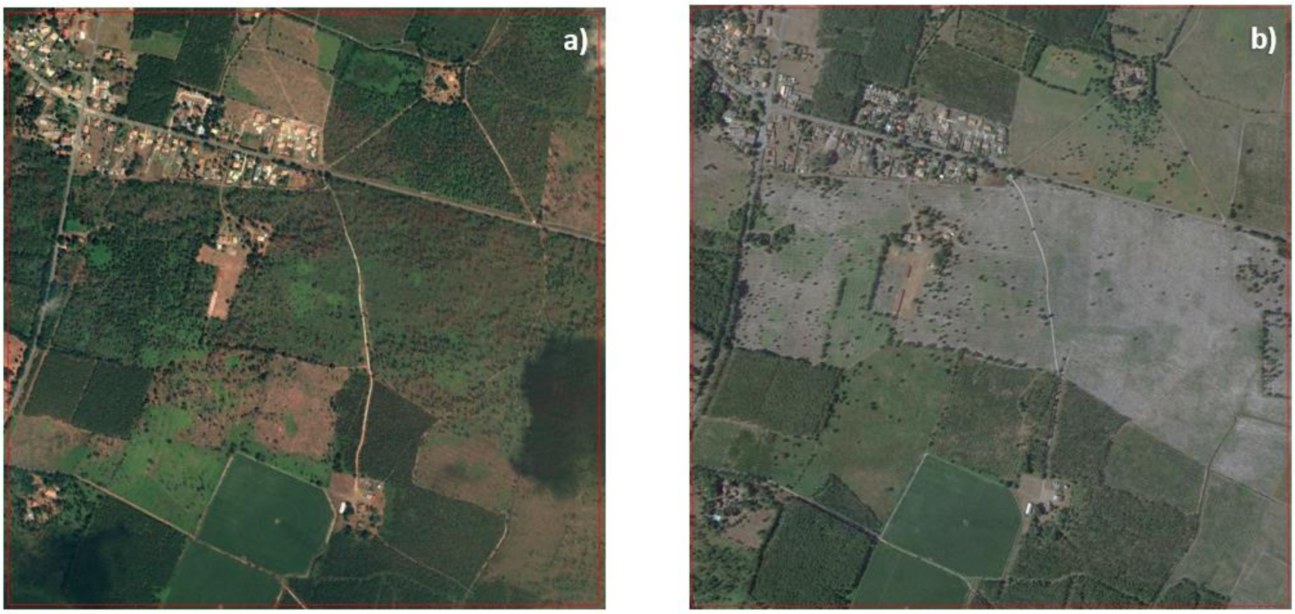

Figure 2-28: Major LC change between a) 28/07/2010 and b) 10/08/2016 in France. (Google Earth imagery and historical timeline). The red border outlines the SSU (~81ha).

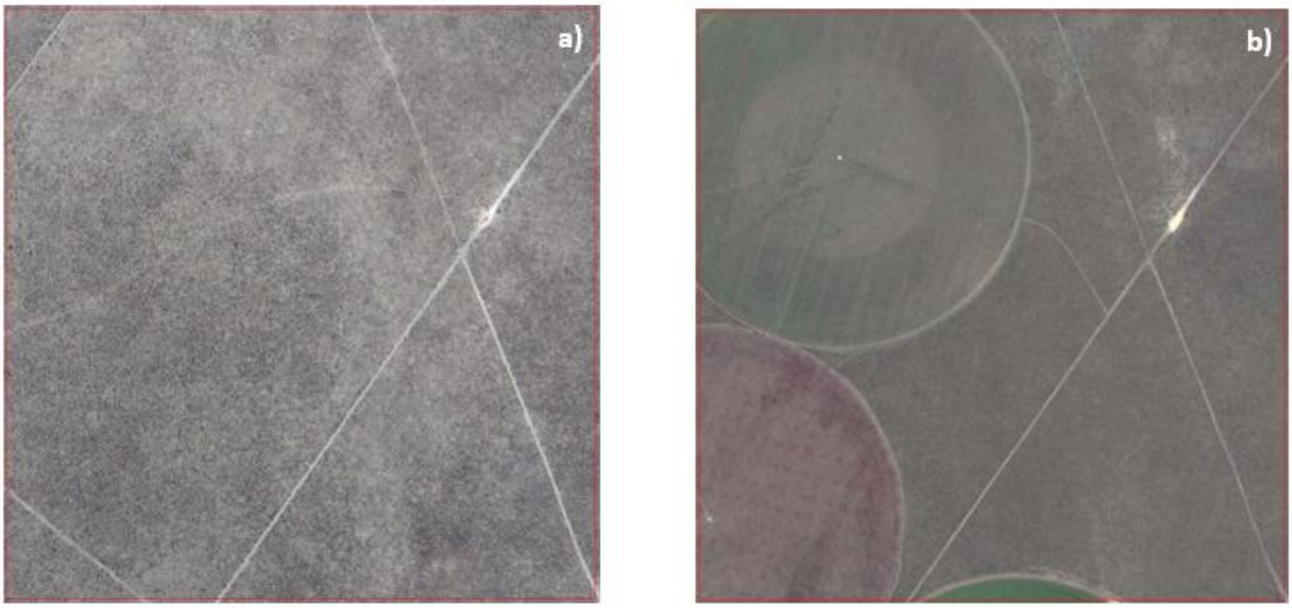

Figure 2-29: Major LC change between a) 04/02/2010 and b) 08/03/2016 in Argentina. (Google Earth imagery and historical timeline). The red border outlines the SSU (~81ha).

The homogeneity of the SSU was evaluated by looking at the number of LC classes by SSU (Figure 2-30). The SSUs were covered by a minimum of 1 and a maximum of 9 LC classes. 33% of the SSU are fully homogenous i.e. covered by just a single LC class. 28%, 21%, and 11% of the SSU are respectively covered by 2, 3 and 4 different LC classes respectively. Looking at cumulative figures, it means that 61% of the SSU are covered by 2 or less LC types, 82% are covered by 3 or less LC types and 93% are covered by 4 or less LC types.

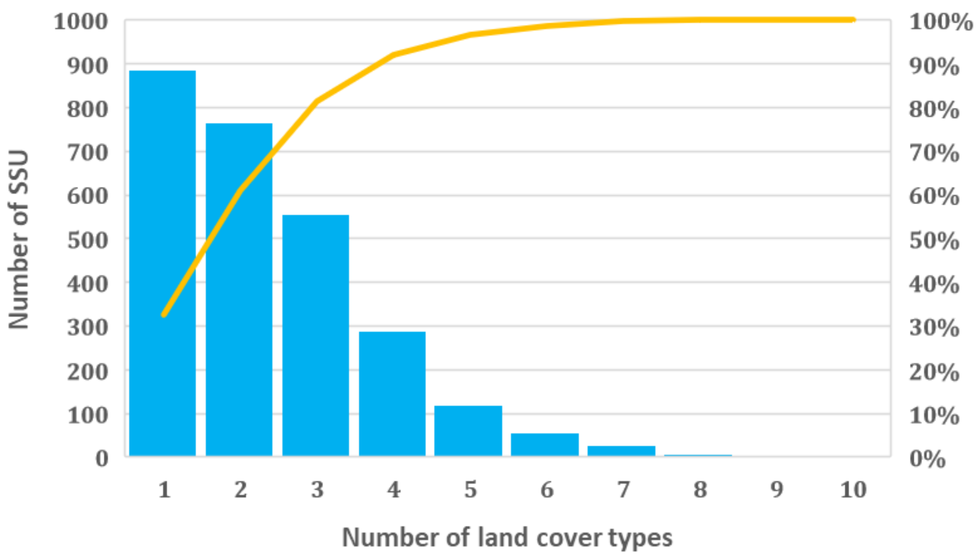

Figure 2-30: Distribution of the number of land cover classes per SSU

2.8.2 Accuracy results

Overall accuracies were derived for different sets of validation samples defined according to the homogeneity threshold. For the sake of the validation quality, only SSU that were interpreted as "certain" by the LC experts were considered, which are corresponding to 78% of the SSU. The results are summarized in Figure 2-31. With decreasing thresholds of homogeneity, the number of SSU used in the validation increases, but overall accuracy slightly decreases. This is clearly expected as the SSUs become more and more heterogeneous and more difficult to map.

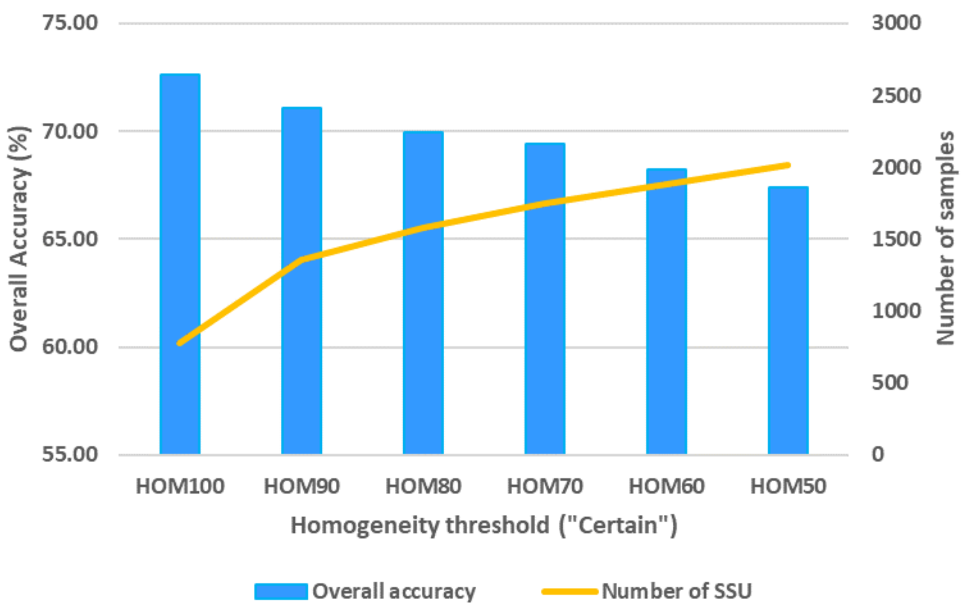

Figure 2-31: Overall accuracy values for 2016 depending on the "homogeneity" of the samples of the LC validation database that were interpreted as "certain", (HOM100 to HOM50 meaning the homogeneity, defined based on a threshold of the area covered by the dominant LC class, this threshold varying from 100 – 50%).

The selection of the “certain” and “homogenous” at 90% SSU (i.e. made of a single LC class covering at least 90% of the area of the validation unit) was found appropriate for accuracy assessment while retaining a large number of SSU.

Table 2-15 presents the confusion matrix calculated by comparing the 2016 LC map with the samples interpreted as both “certain” by the experts, and “homogenous” at 90%. Considering only the diagonal cells, the overall accuracy is 61.2%. When considering the cells off the diagonal that are clearly thematically compatible from a LC typology perspective, the overall accuracy value is **71.1%** and corresponds to a Kappa of 0.68.

The “certain” and fully homogenous SSU, i.e. made of a single LC class, provide an overall accuracy level of 72.6%, when considering the cells clearly thematically compatible from a LC typology perspective (green and yellow cells). Table 2-14 those accuracy figures.

Table 2-14: LC map 2016 overall accuracy figures (%)

Response design	Overall Accuracy (%)
Certain and homogeneous samples at 100%	72.6
Certain and homogeneous samples at 90%	
- 22 LCCS LC classes	61.2
- considering thematically-close LC classes (yellow cells)	71.1

Table 2-15: Adjusted confusion matrix that considers the 2016 LC map and the “certain” and “homogenous 90” samples of the validation unit i.e. made of a single LC class covering at least 90% of the area of the validation unit. Green cells mark diagonal cells, while yellow cells represent other samples that also mark a clear agreement between the product and the reference based on the LC class definition. The values 0…220 are the land cover class values as shown in Table 1-2.

	REFERENCE: LAND COVER VALIDATION DATASET																							
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**SUM**	**User Acc. (%)**
PRODUCT: C3S LAND COVER 2016 MAP	**10**	121	30	0	0	2	1	0	0	0	0	0	5	14	0	2	0	0	1	0	1	0	0	177	**85**
	20	9	24	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	**94**
	30	9	0	0	0	4	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	19	**47**
	40	8	1	0	0	0	7	0	0	0	0	0	3	7	0	0	0	0	0	0	0	0	0	26	**65**
	50	3	0	0	0	199	15	3	0	3	0	0	2	1	0	0	0	0	0	0	0	0	0	226	**89**
	60	1	0	0	0	6	72	1	8	16	0	0	13	0	0	0	0	0	0	0	0	0	0	117	**75**
	70	0	0	0	0	10	3	53	2	16	0	0	2	0	0	4	0	0	0	0	0	0	0	90	**77**
	80	0	0	0	0	0	0	3	23	3	0	0	3	3	0	4	0	0	0	0	0	0	0	39	**67**
	90	0	0	0	0	0	2	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**78**
	100	2	0	0	0	8	10	3	1	0	0	0	6	5	0	2	0	0	1	0	0	0	0	38	**74**
	110	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	1	0	0	0	0	5	**60**
	120	8	0	0	0	7	19	0	1	0	0	0	105	21	0	8	0	0	0	0	1	0	0	170	**62**
	130	8	3	0	0	0	0	0	0	1	0	0	19	64	1	12	0	0	1	1	25	1	1	137	**47**
	140	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	3	**67**
	150	5	0	0	0	0	0	0	0	0	0	0	23	22	3	25	0	0	0	0	11	0	0	89	**28**
	160	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	**0**
	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	**0**
	180	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	1	0	4	0	0	0	0	12	**33**
	190	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	**75**
	200	2	0	0	0	0	0	0	0	0	0	0	1	3	0	13	0	0	1	0	61	0	0	81	**75**
	210	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	57	0	59	**97**
	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**N/A**
	SUM	176	59	0	0	242	133	64	36	54	0	0	185	152	6	72	1	0	10	4	99	58	1	**1352**	
	Prod. Acc (%)	**79**	**92**	**N/A**	**N/A**	**86**	**67**	**88**	**67**	**96**	**N/A**	**N/A**	**62**	**49**	**33**	**35**	**0**	**N/A**	**40**	**75**	**62**	**98**	**0**		**71.08%**

2.9 Concluding remarks

- ***Classification accuracy in the light of producer and user accuracy values***

The producer and user accuracy values give more information about the accuracy of specific thematic classes.

Considering the confusion matrices for 2016, 2017, 2018, 2019, 2020, 2021 and 2022 the highest user accuracy values are found for the classes of rainfed cropland (class value 10: 85-86%), irrigated cropland (class value 20: 92-94%), four of the tree cover classes (class values 50: 89-90%; 60: 75-76%; 70: 76-77% and 90: 78%), urban (class value 190: 75%), bare areas (class value 200: 75-77%) and water bodies (class value 210: 95-97%). This is not surprising for classes such as bare areas and water bodies, as these classes tend to be homogenous, unambiguous, and recognizable. The high user accuracy for the cropland classes is an additional positive result. Tolerating the compatibility between thematic classes, two of the mosaic classes (class values 40 and 100) have surprisingly reasonable accuracy values, considering that the inclusion of a mix of LC in these classes can be a source of mapping errors.

Conversely, lower user accuracy values are found for mosaic cropland / natural vegetation (class value 30), grassland (class value 130), sparse vegetation (class value 150) and flooded vegetation cover (class values 160, 170 and 180).

From a producer perspective, water bodies, croplands, and all types of forests are the best mapped with PAs of 97% (class 210), 78% (class 10), and 92% (class 20) and ranging from 86% (class 50) to 96% (class 90), respectively. On the one hand, we tend to largely omit grasslands (class 130), sparse vegetation (class 150), bare areas (class 200), and flooded shrub or herbaceous vegetation. On the other hand, classes such as sparse vegetation, shrubland, grassland, and flooded natural vegetation can be affected by errors. For the shrubland, grassland and sparse vegetation classes there are major sources of disagreement between the LC experts and the LC map products, as well as between the sparse vegetation and grassland classes with the bare ground classes. Natural gradients of shrubland – grassland – sparse vegetation – bare areas appear as a continuum on the ground and are difficult to map in categorical classes. Similarly, they are also difficult to be interpreted by the validation experts.

- ***Not possible to validate the changes properly***

The sampling design underlying the building of the LC validation database is not relevant for validating LC changes. Indeed, at a global scale, LC change represents a few percent of the total area and is thus not well rendered in classical validation approaches. The methodology and sampling design to validate LC change will be revisited within the ESA CCI Medium Resolution Land Cover (MRLC[1]) project to enable robust accuracy figures, representative of LC change to be provided.

Independently of what can be validated, it is nevertheless known that the set of annual LC maps do not capture all changes that have occurred between the 22 LC classes defined in Table 1-2. This limitation is inherent to the methodology developed to detect the change in a consistent way over years [RD-3]. The different shortcomings related to the change detection method are highlighted here:

- *Not all possible changes between the 22 LC classes are captured in the dataset*

The 22 LCCS land cover classes are indeed grouped into the 6 Intergovernmental Panel on Climate Change (IPCC) land categories, with the consideration of the subcategories shrubland, sparse vegetation, bare area and water (forming the "Other" IPCC main land category). Consequently, any change occurring between LCCS classes being part of the same IPCC land category is not captured by the LC dataset. More precisely, the LC dataset does not provide information on:

- the conversions between rainfed (class values 10, 11 and 12) and irrigated agriculture (class value 20). As a result, agriculture intensification through irrigation will not be detected as a change;
- the conversion between forest classes (e.g. conversion of broadleaved to mixed forests, flooded forest dewatering, or salinization of a forest flooded with freshwater);
- the conversion between sparse vegetation (class value 150) and lichens and mosses (class value 140);
- the conversion between a "pure"[2] class and a mosaic class (e.g. forest degradation characterized by the evolution of a pure forest (class values 50 to 90) to a mosaic of natural vegetation (class values 100 and 110); cropland intensification characterized by the conversion of a mosaic of cropland and natural vegetation (class values 30 and 40) to a rainfed or irrigated cropland (class values 10 to 20); forest regeneration characterized a mosaic of natural vegetation (class values 100 and 110) to a pure forest (class values 50 to 90).
- the conversion between "level 2" or "regional" classes (details can be found in [RD-2]), whatever the IPCC land category. This corresponds to any dynamics specific to herbaceous vs woody cropland (class values 11 and 12), to the density of the forests (depicted in level 2 of the forest classes 61, 62, 71, 72, 81, and 82), to the phenology of the shrubland (class values 121 and 122), to the type of the sparse vegetation (class values 151, 152, 153) or the type of bare area (class values 201 and 202).

- *Change delineated at 300 m based on hot spots of change detected at 1 km*

All annual LC maps are delivered at 300 m spatial resolution, but it should be noted that the change detection is performed at 1 km spatial resolution, based on the AVHRR (Advanced Very High-Resolution Spectrometer), SPOT-VGT (Satellite Pour l'Observation de la Terre – Vegetation), PROBA-V and S3-OLCI missions. This means that only land cover changes visible at 1 km resolution are detected. These hot spots of change and their surroundings (up to 5 km) are then further delineated at 300 m thanks to the availability of the 300 m MERIS (Medium Resolution Imaging Spectrometer), PROBA-V, and S3-OLCI time series. As a result, several cases of change omissions are observed in the annual LC maps. First, changes of low intensity and/or surface much below 1 km² is not detected. Second, changes are not delineated at 300 m if they do not occur in the surroundings of a hot spot of change detected at 1 km²- in other words, if the change occurs at a distance greater than 5 km away from the 1 km² change hot spot.

- *Changes along the coastlines and of permanent snow and ice class are not included in the LC products*

Changes along the coastlines are not captured with a change detection algorithm based on 1 km observations. Yet, an exception is made for changes related to the Saudi Arabian manmade islands.
In addition, the permanent snow and ice (class value 220) relies solely on a static version of the Randolph Glaciers Inventory[3] [RGI Consortium, 2015 and Pfeffer et al. 2015] and thus remains constant over time during the full period.

3 Application(s) specific assessments

3.1 Visual Quality Assessment of the 2016 - 2022 LC map series

Figures 3-1 and 3-2 present extracts of the 2016, 2017, 2018, 2019, 2020, 2021, and 2022 LC products. This presentation is done, through snapshots and visual comparison with the previous version of the LC map for 2015 and Google Earth high-resolution imagery in various regions of the world.

Figure 3-1 and Figure 3-2 illustrate the good agreement that exists between 2016, 2017, 2018, 2019, 2020, 2021 and 2022 LC maps, PROBA-V, and S3-OLCI imagery. The high thematic detail present in the global LC maps is also illustrated in these figures. In addition, the ability to map evolving LC changes is illustrated.

Figure 3-1 gives examples of changes from forest to cropland in Belarus, and from forest to grassland as shown on the LC 2022 map. Figure 3-2 gives an example of cropland expansion in DRC. Additional qualitative assessments can be found in the PUG [RD-2].

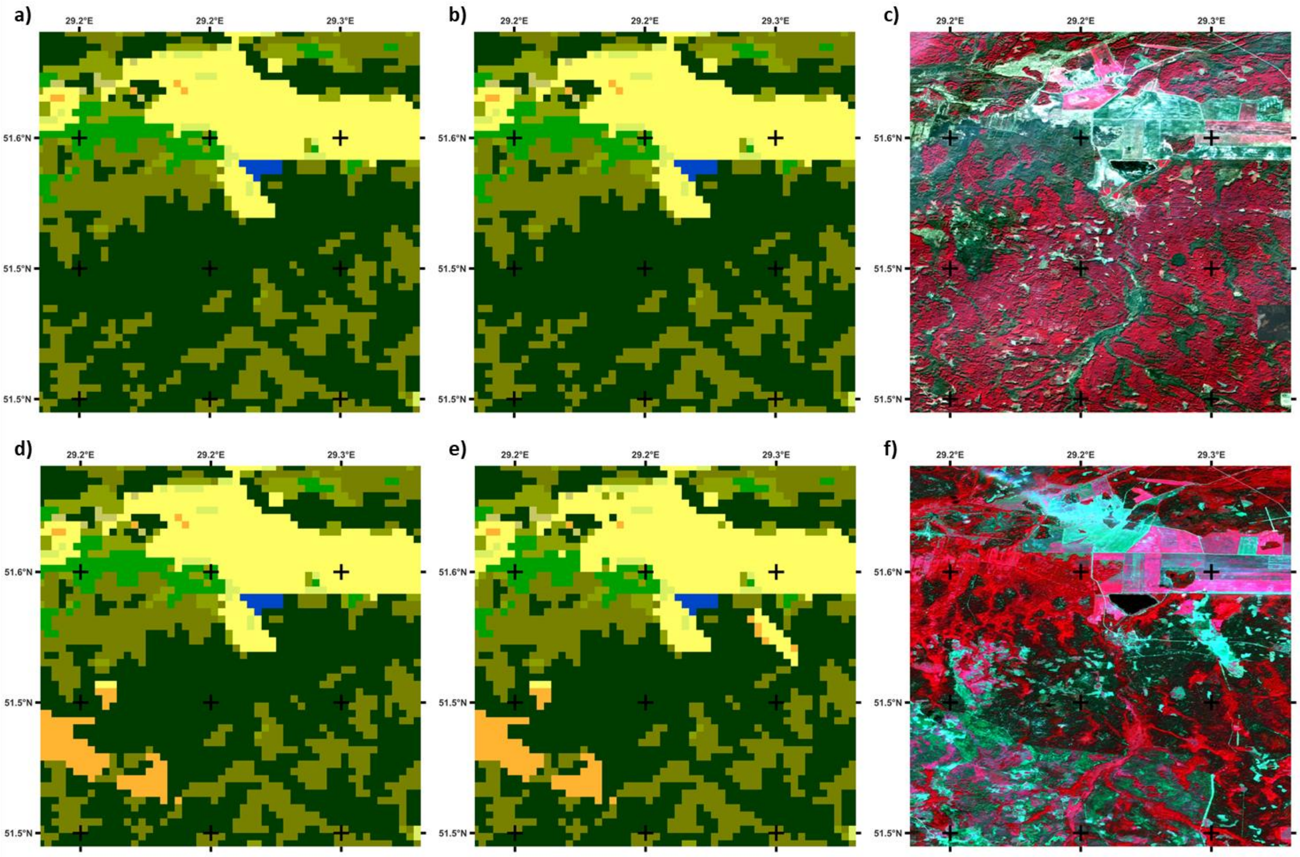

Figure 3-1: Example of the detection of the conversion of forests to grassland and crops in Belarus, in 2021 and 2022 respectively. a) the 2019 LC map, b) the 2020 LC map, d) the 2021 LC map, e) the 2022 LC map, c) 2019 S2 imagery and f) 2022 S2 imagery.

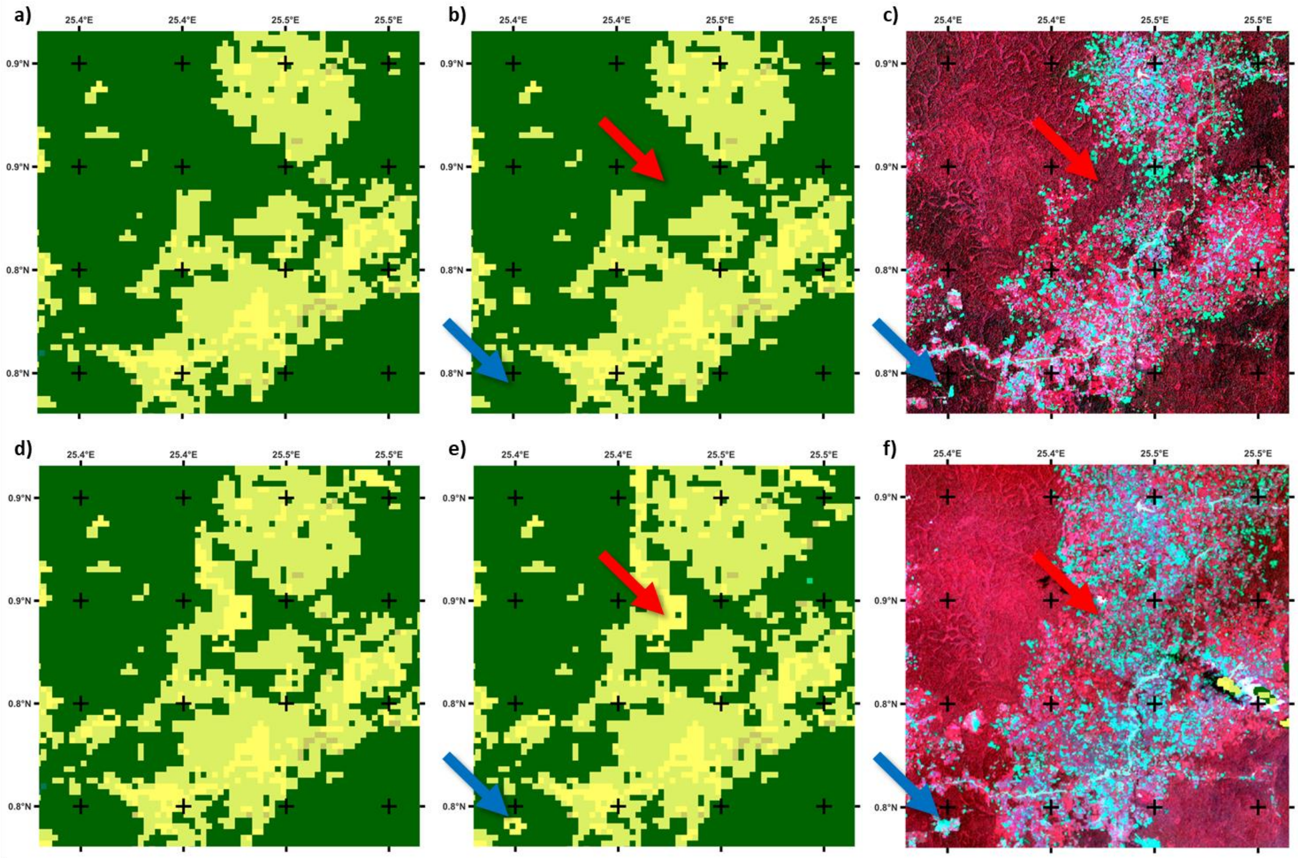

Figure 3-2: Cropland expansion in DRC in a) the 2019 LC map, b) the 2020 LC map, d) the 2021 LC map, e) the 2022 LC map, c) 2019 Landsat imagery and f) 2022 Landsat imagery. The red and blue arrows give a clearer view of the areas of change.

4 Compliance with user requirements

The 2016 - 2022 LC products are a continuation of the generation of successive LC state products consistent over time. As a result of the CCI user requirement analysis, several product requirements **were identified, as outlined in** Table 4-1 (see also TRGAD LC - RD-4)**. These requirements are transferable and applicable in the** C3S LC data set.

Features of the 2016 - 2022 LC products confirm compliance with the user requirements. The products are the most recent LC maps on a global scale and complement a long series of annual LC products. They use 22 thematic classes defined in the LCCS nomenclature and can be converted to Plant Functional Types distribution for climate models. The overall accuracy for 2016, 2017, 2018, 2019, 2020, 2021 and 2022 LC products is estimated at 71.1%, 71.1%, 70.8%, 70.6%, 70.5%, 70.5% and 70.3% respectively, based on an independent dataset. While the 2016 - 2022 LC products have not reached the target accuracy of 90-95%, they have slightly better accuracy than previous datasets. Compared to Globcover 2005 and 2009, the real improvement brought by this dataset is its spatio-temporal consistency. The overall accuracy of the global LC map Globcover 2009 is 70.7% based on 1484 homogenous sample sites, including classes thematically compatible from a LC typology perspective [Bontemps et al., 2011]. This accuracy cannot be directly compared to any similar products, as no other global LC map for recent years exists with both this spatial resolution and the thematic detail of 22 LC classes over such a time-period.

Table 4-1: Threshold (minimum) and target (optimal) requirements identified for LC products in the User Requirements Survey carried out in the CCI LC project Phases I and II. Green tick-marks indicate fulfilled requirements, red x marks indicate requirements not yet achieved. [ESA, 2015].

	Threshold req. Phase 1	**Target req. Phase 1**	**Threshold req. Phase 2**	**Target req. Phase 2**
	COVERAGE AND SAMPLING			
Geographic Coverage	Global ✓	Global ✓ with regional and local specific legend ✓	Global ✓ with regional specific legend ✓	Global ✓ with regional specific legend ✓
Temporal sampling	Best/stable map and regular updates ✓	Monthly data on vegetation dynamics and change ✗	5-10 year epoch maps with monthly vegetation dynamics (NDVI) ✓	1-year epoch maps. Monthly data on vegetation dynamics (NDVI) ✓
Temporal extent	1-2 years, most recent ✓	1990 (or earlier)-present ✗	1990 (or earlier) - present ✓	1980 (or earlier) - present ✗
	RESOLUTION			
Horizontal Resolution	1000 m ✓	30 m ✗	300 m ✓ with regional 30 m products ✗	30 m ✗

	Threshold req. Phase 1		Target req. Phase 1		Threshold req. Phase 2		Target req. Phase 2	
Vertical Resolution	–		–					
	ERROR/UNCERTAINTY							
Precision	Thematic LC detail sufficient to meet current modeling user needs	✓	Thematic LC detail sufficient to meet future model needs	✗	Thematic LC detail (incl. conversion tables to PFT for climatic regions) sufficient to meet current and future model needs, incl. key land IPCC changes	✓	Thematic LC detail (incl. conversion tables to PFT for climatic regions and traits) sufficient to meet current and future model needs, incl. LC changes and management	✗
Accuracy	Higher accuracy than existing datasets	✓	Errors less than 5-10% either per class or as overall accuracy	✗	Higher accuracy than existing datasets of the same period length	✓	Errors less than 5-10% either per class or as overall accuracy	✗
Stability	Higher stability than existing datasets	✓	Errors less than 5-10% either per class or as overall accuracy	✗	Higher stability than existing datasets	✓	Errors less than 5-10% either per class or as overall accuracy	✗
Error Characte-ristics	Independent one-time accuracy assessment	✓	Operational and independent multi-date validation	✗	Independent multi-date validation	✓	Operational and independent multi-date validation	✓

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