Climate Change Initiative Extension (CCI+) Phase 2
New Essential Climate Variables (NEW ECVS)
High Resolution Land Cover ECV (HR_LandCover_cci)

Product Specification Document

(PSD)

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Changelog

Issue	Changes	Date
1.0	First issue	02/08/2024
1.1	Updated version according to CCI_HR LC _Ph2_Milestone1_RID-ESA.xlsx	11/09/2024

Detailed Change Record

Issue	RID	Description of discrepancy	Sections	Change
1.0	ESA-01	The Deliverable id should be D1.2	header	The id has been updated.
1.0	ESA-02	On the first bullet: The first one will generate products on clusters of Sentinel-2 tiles representative of each area of interest"	1.2	The criteria for selecting representative Sentinel-2 tiles for the first production are provided in the document, and the tiles will be chosen based on these outlined criteria.
1.0	ESA-03	On the 2nd activity could you please clarify if in terms of SAR and Optical data processing to obtain the meta products, the algorithm will be the same of Ph-1?	1.2	The SAR and Optical data processing will be the same of the products of the Phase 1. The improvements will be on the fusion and harmonization parts starting from the estimations of the class posterior probabilities of optical and SAR data and the related ancillary data derived in Phase 1
1.0	ESA-04	GIS shouldn't be "Geographic Information System"? LCCS should be "Land Cover Classification System"	1.5	The acronyms have been updated.
1.0	ESA-5	These are the very initial areas, the green areas have shrinked. It should be the same map as in the PVP (figure 1)	Figure 1	The figure is updated.
1.0	ESA-6	Would it make sens to also have a South box that would allow to cover Brazil entirely?	Figure 2	The document will be updated according to AI#8
1.0	ESA-7	The link https://www.unidata.ucar.edu/software/netcdf/documentation/NUG/data_type.html does not work "page not found"	2.3	The link has been updated.
1.0	ESA-8	The acronym CRG is not specified in the document, I guess it means Climate Research Group. Or is it a typo CRC?	3	The acronym stands for Climate Research Group and has been added to list of acronyms.
1.0	ESA-9	Regarding the sentence "Recent inputs provided by the Exeter University partner (S. Sitch) …" a reference to a paper or a document would be appreciated	3	The reference to recent inputs by Exeter is provided in URD. We provided cross reference in the document.
1.0	ESA-10	Please correct the sentence "The region of Tapajos in the Para state of Brazil is also of great interest since it is impacted by deforestation and forest degradation (Gatti et al., 2021) and will be the place of the next ESA Amazon experiment in 2025" with The region of Tapajos in the Para state of Brazil is also of great interest since it is impacted by	3	It is corrected.

		deforestation and forest degradation (Gatti et al., 2021) and will be the place of a foreseen ESA Amazon campaign in collaboration with INPE (BRA) in 2025.		
1.0	ESA-11	A link to the results of the questionnaire can be added to the document?	5	The results of the questionnaire can be founded in the dedicated document URD. Reference to URD will be added.
1.0	ESA-12	Regarding the CCI Prototype Africa as already mentioned during Phase-1, this map has been validated only over four Countries, using it could be risky.	Table 2	This dataset will be excluded in phase 2 due to its poor validation coverage and accuracy. The information of this dataset is remained but explanation was added to both PSD and PVP.

Contents

1 Introduction

1.1 Executive summary

Following the activities of user requirements updating according to Climate User Community and other users' consultations, the Consortium is working on defining HRLC products requirements. This document is organized based on the activities during Phase 1 and the first version of the URD [AD4] provided by the Climate Team. The document will be updated accordingly accounting for technical constraints such as main data sources available, spatial and temporal coverage, software and tools for quality control.

The first part of the document presents a preliminary user requirements for phase 2 (details are reported in URD [AD4]). The second part Requirements are also established for quality-related activities (independent validation and benchmarking) as described in the last section of the PVP document [AD5].

The HRLC Static and LCC Maps over the three large areas in South America, Africa and Siberia for recent years will be produced using Sentinel data, both optical and SAR. This allows for full compliancy with GCOS spatial requirement of 10m (i.e., high resolution multispectral). The historical LC and LCC products spanning temporal interval 1990-2019 will be reprocessed upon processing of Landsat imagery (all missions from 5 to 8) and ASAR, ERS, Sentinel-1 SAR data. The spatial requirement for historical products is compliant with GCOS requirements at 30m. For temporal resolution, it has to be noted that the in case of enough data available the yearly frequency is confirmed for LCC products, whereas LC maps is produced every 5 years. In case of not enough data, strategies has been designed to produce the LC and LCC maps by accounting for adjacent years and (please refer to [AD6]).

1.2 Purpose and scope

In the Product Specification Document (PSD) the climate user requirements described in the User Requirement Document (URD) [AD4] will be turned into a set of products specifications. All requirements, needs and suggestions coming from users' community consultations and other sources have been carefully analysed and considered. The result is a trade-off between user requirements and technical requirements which is described in detail in this document. Some pragmatic choices have been made when converting from user requirements to technical requirements. However, proper analysis and justification is given to support choices made, as indicated in the CCI HRLC project guidelines from the SoW [AD2].

The outcome of initial surveys of Climate users in the phase 2, CMUG, other CCI projects and potential users confirms the interest in relation to improved spatial resolution for the recent years of LC products and expansion of the area of the analysis [AD4]. To contribute to the understanding of the impact of spatial resolution in climate changes in key regions of the world, phase 2 will be focused on two cycles:

- The first one will generate products on clusters of Sentinel-2 tiles representative of each area of interest.
- The second one will extend the production to the full areas.

The criteria for selecting representative Sentinel-2 tiles for the first generation of products include identifying areas with the largest disagreement in Phase 1, prioritizing Fluxnet locations, covering a wide range of latitudes, including both coastal and inland regions with varying degrees of continentality, and ensuring representation across a variety of ecoregions (Figure 1).

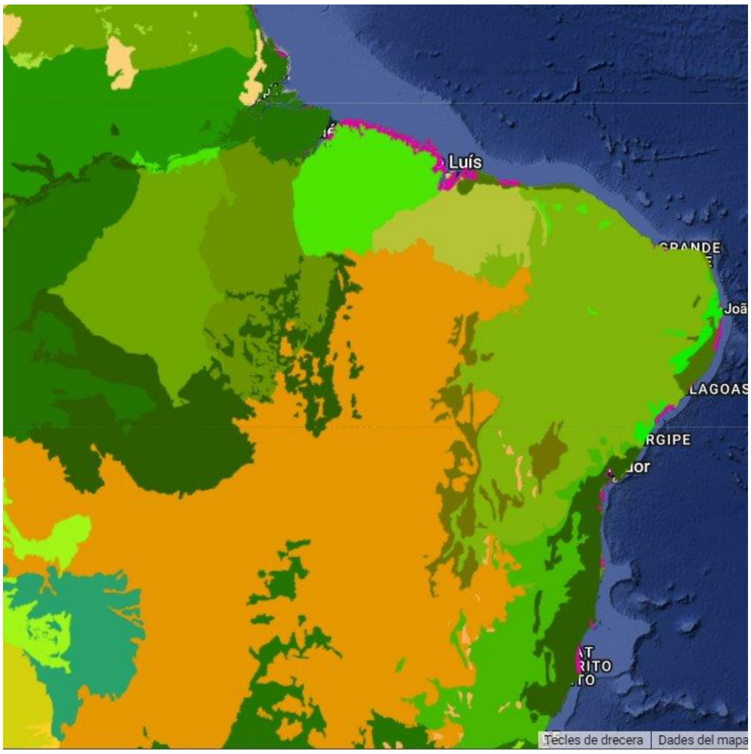

Figure 1. Criteria for first production of tiles selection.

The activities developed on different extensions of the two cycles are the same and can be summarized as follows:

1 Re-processed Phase 1 historical products: generation of an improved version of historical products of Phase 1 through improvement of the enhanced sensor decision fusion, spatial and temporal harmonization modules of the processing chain. The starting point of the re-processing will be the intermediate products (from hereafter called meta products) consisting of the pixel-wise class-posterior probabilities generated by the SAR and Optical processing chains during Phase 1. Therefore, the SAR and Optical processing chain will not be run again on the already produced areas and years, minimizing costs, and allowing the team to better focus on the temporal consistency and change detection reliability, as well as on the new area and years that will be produced.

2 Historical production on a new selected area: improved SAR and Optical processing chains will be defined and run on the new selected area in addition to the previously mentioned enhanced sensor decision fusion, spatial and temporal harmonization modules. Note that the same sensor decision fusion and the spatial and temporal harmonization modules will be used for both re-processing Phase 1 products and for generating new Phase 2 products to generate compatible and consistent products.

3 Historical (forward) production of year 2023/24 (TBD) for all the considered areas: Phase 2 will develop a different concept used for the historical production when considering the extension to years following 2019. In Phase 1, a backward approach was taken, producing static maps for 2019, and then proceeding backward for the historical production. Instead, Phase 2 will consider a forward approach to produce historical maps that extend forward in time after the static maps of 2019. The production of the year

2023 (or 2024) will be performed on the same historical areas considered in the backward approach. The backward and forward approaches will differ not only for the temporal direction, but also for the spatial resolution and data availability. Indeed, we can refer to the backward phase as the Landsat Era, characterized by the 30m spatial resolution and reduced data availability, and to the forward phase as the Sentinel Era, characterized by a 10m spatial resolution and a higher availability of satellite image data. This also leads to some differences in how the temporal correlation will be exploited, as in the Landsat Era more inconsistencies are expected in the meta products due to the use of different sensors and to lower data resolution, availability, and quality, requiring different levels of regularization between the two eras.

The CCI+ HRLC Phase 2 project will focus on the following main conceptual activities:

- Full exploitation of products of Phase 1 for climate activities;
- Generation of an improved version of historical products of Phase 1 through improvement of decision fusion, spatial and temporal harmonization modules of the processing chain;
- Generation of historical products between 1990 and 2023 (or 2024) for a new area through an improved version of the processing chain;
- Generation of new maps for the historical areas of Phase 1 for 2023 (or 2024);
- Validation of all products;
- Exploitation of all new products for climate activities.

This version of the document illustrate the current status of products in terms of their content, legend, spatial and temporal applicability, grids, projections and quality. The convention about the products' identification, format, structure, metadata and delivery. These aspects will be updated in the future issues according to evolutions.

1.3 Applicable documents

Ref.	Title, Issue/Rev, Date, ID
[AD1]	CCI HR Technical Proposal, v1.1, 16/03/2018
[AD2]	CCI Extension (CCI+) Phase 1 – New ECVs – Statement of Work, v1.3, 22/08/2017, ESA-CCI-PRGM-EOPS-SW-17-0032
[AD3]	CCI_HRLC_Ph1-D1.1_URD, latest version
[AD4]	CCI_HRLC_Ph2-D1.1_URD, latest version
[AD5]	CCI_HRLC_Ph2-D2.1_PVP, latest version
[AD6]	CCI_HRLC_Ph1-D2.2_ATDB, latest version

1.4 Reference documents

Ref.	Title, Issue/Rev, Date, ID
[RD1]	The Global Climate Observing System: Implementation Needs, 01/10/2016, GCOS-200
[RD2]	CCI_HRLC_Ph1-D4.3_PUG, latest version

1.5 Acronyms and abbreviations

API Application Programming Interface

CCI Climate Change Initiative

CRC Climate Research Community

CRG Climate Research Group

CMUG Climate Modelling User Group

CREAF Centre de Recerca Ecològica i Aplicacions Forestals

ECV Essential Climate Variables

ESM Earth System Models

EVI Enhanced Vegetation Index

FTP File Transfer Protocol

GCOS Global Climate Observing System

GDPR General Data Protection Regulation

GIS Geographic Information System Geodata Information System

HR High Resolution

LAI Leaf Area Index

LC Land Cover

LCC Land Cover Change

LCCS Land Cover Classification System

LCML Land Cover Meta Language

LCZ Local Climate Zone

LSCE Laboratoire des Sciences du Climat et de l'Environnement

MR Medium Resolution

NDVI Normalized Difference Vegetation Index

PFT Plant Functional Type

RS Remote Sensing

SFT Surface Functional Type

SoW Statement of Work

URD User Requirements Document

VM Virtual meeting

WFS Web Feature Service

WMS Web Map Service

WP Work Package

2 Synthesis of user requirements

The user requirements concerning the products generated and the metadata associated are presented in the following sub-sections. Further details can be found in URD [AD3].

2.1 Key areas location

In summary, the geographical coordinates of the three regions in phase 1 are as the following:

Amazonia:

Static map: (24°S -9°N; 34°W - 62°W)

Historical LC and LCC map: (24°S - 12°S; 47°W - 62°W)

Sahel:

Static map: (0°N - 18.5°N; 18°W - 43.5°E),

Historical LC and LCC map: (4°N - 16°N; 27°E - 43.5°E)

Siberia:

Static map: (52°N - 79°N; 65°E - 142°E),

Historical LC and LCC map: (60°N - 74°N; 65°E - 86°E).

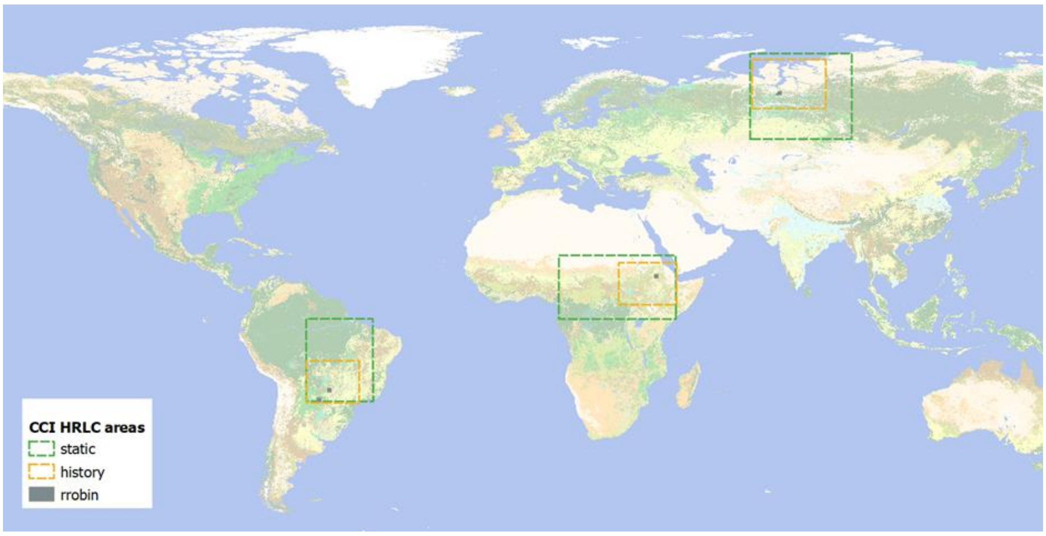

Figure 2. Final requirements for the location of the 3 study areas and Fluxnet sites.

The Amazonia area is expanded to the East and North-West side for HRLC10, HRLC30 and HRLCC30 considering Figure 3. We are fine tuning the actual extension on the basis of user requirements and engineering aspects.

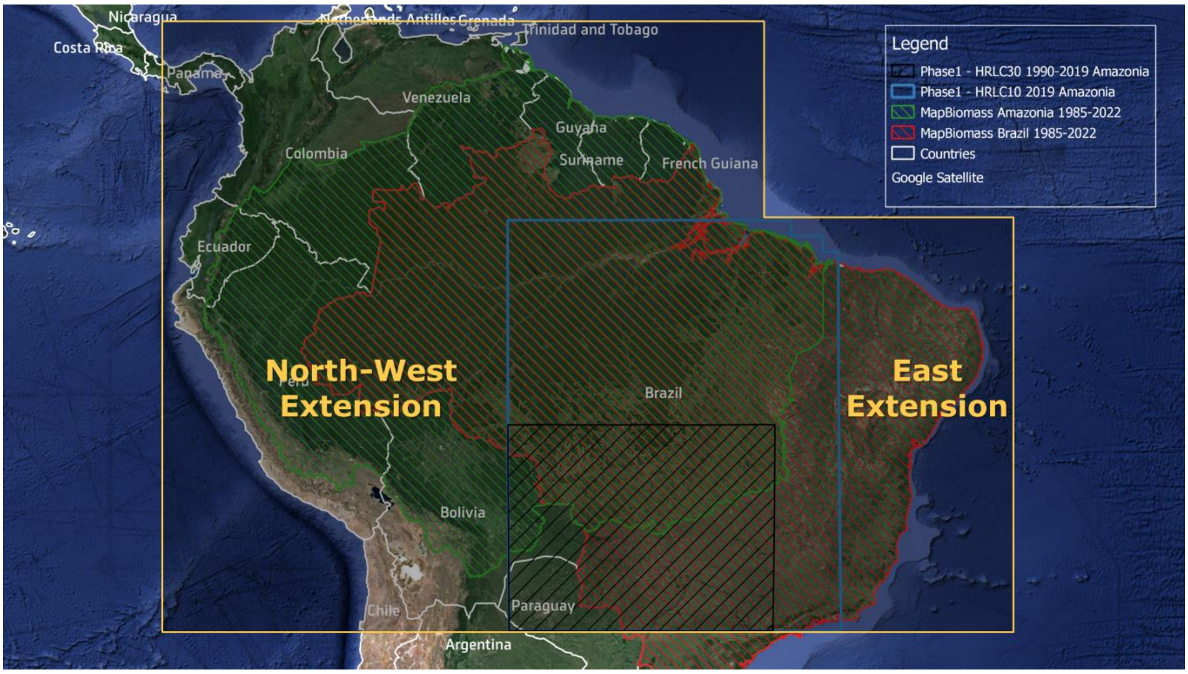

Figure 3. Amazonia area expansion to South America.

2.2 Coverage period

The coverage period is from 1990 – 2023 or 2024 and a forward approach is considered to produce historical maps that extend forward in time after the static maps of 2019. The production of the year 2023 (or 2024) will be performed on the same historical areas considered in the backward approach. We can refer to the backward phase as the Landsat Era, characterized by the 30m spatial resolution and reduced data availability, and to the forward phase as the Sentinel Era, characterized by a 10m spatial resolution and a higher availability of satellite image data (Figure 4). The 5-year mean LC maps are sufficient for climate studies if the changes are provided yearly. The consistency of the changes should be checked, along with the side products so that the climate modelling groups could assimilate coherently different sources of information on surface cover and surface state.

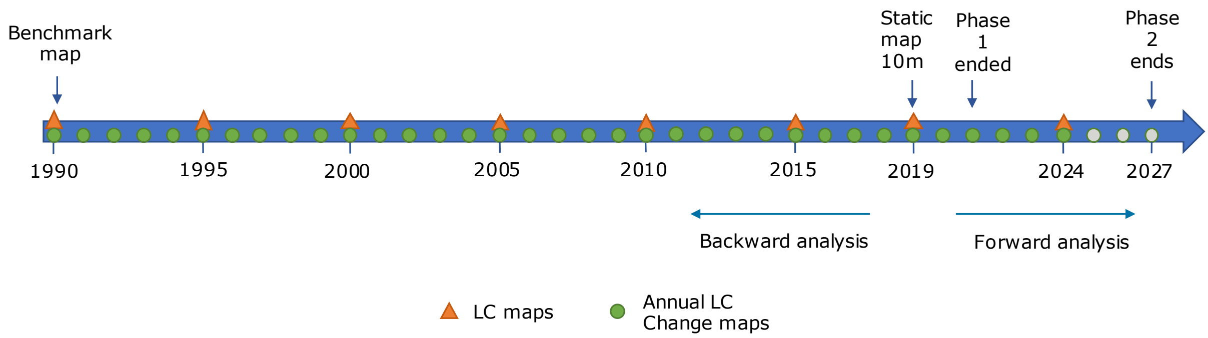

Figure 4. Time Line Analysis

2.3 Products format

The products will be available in two formats: i) GeoTIFF tiles following the Sentinel 2 MGRS tiling scheme, and ii) NetCDF mosaics.

This choice comes from important considerations implied by the average size of a HRLC product in phase 1:

GeoTIFF:

- Is portable but has not a strict way of storing metadata and there is not a common convention. Anyway, metadata can be added.
- Coordinates are derived by the context (top left pixel position, resolution in x and y).
- Has the concept band which is less general that a sub-dataset as it inherits from the file encoding (e.g. it does not support different types).

For this reason, as a general behaviour, the GeoTIFF cannot store different datatypes (e.g. int and float together) so it is impossible to store in the same file both a classification (e.g. integer 8 bit) and a posterior probability (e.g. float 32 bit) or at least a transformation has to be performed like converting the probability in an integer value from 0 to 100 discarding some of the precision.

For data types, please consider the following reference for tiles:

- "Band types of Byte, UInt16, Int16, UInt32, Int32, Float32, Float64, CInt16, CInt32, CFloat32 and CFloat64 are supported for reading and writing. Paletted images will return palette information associated with the band" from https://gdal.org/drivers/raster/gtiff.html

And for the mosaics:

- Data Type page from NetCDF official documentation: https://docs.unidata.ucar.edu/nug/current/md_types.html#data_type

In the case of any changes on the products format, it will be reported in the later version of the document.

3 Preliminary user requirements

A preliminary requirement that has been identified by the HRLC CRG concerns the location of the new products. Among the three case studies defined in task 5 for the products assessment, one concerns the development of a dedicated climate service for the monitoring of the Amazonian deforestation and the use of a regional climate model to model global carbon budget of the Amazonian ecosystem. The achievement of this task will require to extend the historical region to the North and to the West (the coordinates of the region have still to be specified by the CRG). Recent inputs (detailed information in [AD4]) provided by the Exeter University partner (S. Sitch) confirmed the interest of extending the historical region to the Rondonia and Pantanal regions to analyse land cover changes and fire activity over the last thirty years. The region of Tapajos in the Para state of Brazil is also of great interest since it is impacted by deforestation and forest degradation (Gatti et al., 2021) and will be the place of a foreseen ESA Amazon campaign in collaboration with INPE (BRA) in 2025. This experiment brings together a complete suite of observations and models in one of the specific critical zones currently regarded as tipping points of terrestrial emissions. It is foreseen to cover a region of around 100 x 100 km including a range of different types of land cover such as degraded land, agriculture, secondary and intact forests. It is also where the experimental sites of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) led by Brazil's National Institute for Space Research is located.

Besides, the region of Caatinga in the north-eastern part of Brazil is also of interest. Indeed, Caatinga is a seasonally dry tropical forest, one of the most threatened ecosystems in the world (Miles et al., 2006). This very heterogeneous region is not only threatened by various acute (e.g. forest loss) and chronic (*e*.g. overgrazing and firewood extraction) human disturbances, but also climate change (e.g. longer and more severe droughts) (Kulka et al., 2024; Rito et al., 2017). Being a highly heterogeneous region exposed to persistent disturbances makes this area an interesting case for evaluating the added value of HRLC maps. The same interest goes to the Gran Chaco tropical dry forest extending over Argentina, Paraguay, Bolivia and Brazil which is the second largest forest in South America after the Amazon. This region has been identified as a deforestation hotspot due to agricultural expansion (Baumann et al., 2022) and is prone to periodic fires used to deforest or as a practical management tool (San Martín et al., 2023) to promote crops and pastures production. Therefore, it is interesting to monitor the land cover in such regions over the historical period to detect impacts of drought variability as well as to monitor other natural and human disturbances. Additionally, it is of interest to better interpret MRLC data and Harpers's (Harper et al., 2023) PFTs dataset developed in the framework of the CCI-MRLC project, since important differences have been detected in PFT maps in these regions in terms of woody/grass partition leading to differences in the simulation of key land surface variables related to the water and energy cycles.

The same comparison of MRLC and Harper's PFTs maps highlighted some discrepancies in the woody/grass partition in other parts of the world and especially in the eastern Horn of Africa The CCI MRLC team would be interested to get HRLC maps over this region to confirm the added value of the Harper's PFT maps compared to the MRLC standard derived PFT maps. Additionally, the region faces more frequent droughts (Funk et al., 2008), while continued anthropogenic warming is likely to cause further drying in the Horn of Africa, emphasizing the need for improved simulations of the dynamics of the tropical hydrological cycle (Baxter et al., 2023). These studies suggest that climate models used to project future conditions in tropical dryland regions need better representation of land–atmosphere interactions on precipitation. Therefore, tropical dryland forests are complex and heterogeneous areas under constant pressure, leading to land cover changes. This makes them regions of great interest for climate studies and where the HRLC maps can be valuable for evaluating land–atmosphere interactions.

4 Advisory from Climate Research Community

Advisory from the CRC has been collected from two different sources. First, a direct invitation was sent to provide advisory feedback. Additionally, a questionnaire was prepared, comprising 24 questions across six topics: the selection of study regions, spatial resolution, product classification, usage of HRLC products, uncertainties and second-class products, and CCI products. The questionnaire can be accessed here: https://forms.gle/qzqZbhndN1FceXy77 .

On the other hand, direct interaction with attendees of the workshop organized during the EGU workshop was conducted using the Mentimeter (https://www.mentimeter.com) platform. The questionnaire was the same but adapted to the platform's format. A total of 22 answers were collected.

5 Synthesis

Both preliminary user requirements and results of the questionnaire (can be founded in [AD4]) indicate interest in extending the Amazonian region for the monitoring of deforestation or forest degradation and land cover changes impacts. The suggestions vary, proposing extensions to the North, West, East, and the entire Amazon. A preliminary analysis of the other existing products in this region, show that the extension of the HRLC maps will bring an added value because of the use of a common legend better adapted to climate modelling and consistency in the data processing. Besides, as suggested in section 2, results of the questionnaire also confirm the community's interest in dryland regions such as Caatinga (to the East of the current HRLC region) or Gran Chaco and savanna-like ecosystems such as Cerrado already included in the static HRLC map. Similarly, tropical drylands ecosystems from eastern Horn of Africa represent an interesting region to be included in the historical HRLC maps since it is a heterogeneous region exposed to persistent natural and anthropic pressure.

6 Independent Validation Process

6.1 Static LC maps quantitative accuracy assessment

6.1.1 Sampling designs

The sampling scheme, tailored to each type of CCI HR LC static product, needs to address the issue of rare classes with a strong impact on the climate system (urban areas, wetlands, etc.) in the CCI HR LC static maps.

Following these requirements, three aspects of the sampling design will be addressed: the number of sample plots, their size and the way they are selected from the total population.

Given the time needed for sample photo-interpretation, the construction of the validation database started before the product generation. The number of samples is also constrained by the time for interpreting the data. The GlobCover/CCI MRLC validation exercise showed that experts can interpret between 30 and 50 sample plots per day. Finally, the availability and quality of VHR resolution imagery, the certainty of the LC photo-interpreter and the heterogeneity of the landscape constrain the sample size (details are reported in [AD5]).

In order to find an optimal sample distribution that seeks a balance between the number of samples that can be photo-interpolated and precise confidence intervals per class, we preferred an intermediate distribution between proportional and equal. This optimal allocation allows us to set a minimum number of samples for the minority classes, i.e. 40, and to redistribute the remaining points proportionally among the remaining classes. A large number of points are thus retained in the majority classes, maintaining accurate confidence intervals (CIs) while significantly improving the CIs of the minority classes. A set of 1827, 1878, and 1540 samples will be collected for Siberia, Amazonia, and Africa.

6.1.2 Response design

6.1.2.1 Choice of the sample spatial unit

It is unwise to match the size of the validation sample unit to the spatial resolution of the product to validate for the following reasons:

- Geo-location accuracy of the information. The absolute positional accuracy of the LC product is targeted to a 1/3 pixel dimension;
- S2 time series may result in radiometric information coming from a few adjacent pixels;
- Therefore, sample plots of 3×3 pixels were interpreted for the validation of each CCI HR LC product. This results in 30 m x 30 m sample plots for the validation of the CCI HR LC static maps.

6.1.2.2 Labelling protocol

For each sampling unit, a set of attributes is recorded systematically. Table 1 present an optimum attribute table designed for the validation of the static CCI HR LC. The information is collected in order to test two response designs.

Table 1. The information included in the static validation databases for each validation sample plot.

Field name	Details
Sample ID	Unique identifier
Lat / Long	Centre coordinates of the observational unit to interpret
Central_Class	The class ID of the LC legend of the central pixel of the sample plot.

Field name	Details
Central_Class_Homogeneity	How many pixels in the window are of a similar label as the pixel central
Window_Class	The class ID of the LC legend of the majority of the 3x3 plot
Window_Class_Homogeneity	How many pixels form the majority
Level of certainty	Level of certainty (certain, reasonable, doubtful) associated with the interpretation of the expert
Comments	Comments given by the expert to explain/detail its interpretation (e.g. for indication of why the labelling was not successful, or to give the local name used for the concerned LC type)

Although error-free validation databases do not exist, a rigorous validation protocol is a prerequisite to building it as close as possible to "ground truth". First, the legend of the LC classes should be described exhaustively and be well understood by the interpreter. The ground, as visible on the VHR imagery, can be spatially complex and include a mixture of classes within the sampling spatial unit. A graphical validation interface is a valuable tool to gather evidence that effectively helps the interpreter converge towards the best guess.

6.2 Land cover historic and change maps quantitative accuracy assessment

6.2.1 Reference data sources

The use of the GEE Time Series Explorer allows easy access to a wide range of high and VHR reference images. Landsat vegetation index profiles can be extracted with GEE for the period 2000-2024 The tool offers false colour date-specific images. To compensate for the lack of data between 1990 and 2000, the USGS Global Visualization Viewer (GloVis) can be used to validate change by accessing Landsat images and the Global Land Survey (GLS). The GLS was derived from a geodetically accurate, orthorectified global land dataset of Landsat TM (30 m × 30 m) and Enhanced Thematic Mapper (ETM+) (30 m × 30 m) satellite imagery with global coverage. The GLS datasets have the advantage of standardised wall-to-wall imagery available annually. Although it is recommended to rely on a higher spatial resolution than the product to be validated to avoid geolocation problems as much as possible, GLS annual mosaics can be used complementarily with date-specific images to determine whether a change has occurred with annual accuracy.

6.2.2 Sampling design

Considering the specificities of change validation, the sampling should be random and stratified in space to ensure a significant representation of the areas known to experience high rates of change (Khorram, 1999) . Systematic access to Landsat data from 1992 to the present through the Google Earth, Collect Earth and Glovis interfaces allows us not to stratify over time.

Two criteria guided the generation of the "change" and "no change" stratification layers:

- A priori knowledge of change locations, determined by the PCC values from CCI HR LC historic maps, is used to define stratification and expected user accuracies for each stratum. This approach aims to translate the increasing reliability in change detection, progressing from low-priority changes to high-priority changes and then to stable areas.
- To reduce the uncertainty related to the geolocation issues between the validation footprints and the CCI HR LC products, we applied an erosion buffer of 1 pixel on the union of each change observed in the full period. This means that only hot spots of changes of at least 0.81 ha were attributed to the "change"

stratum.

The number of samples selected per stratum is chosen according to Eq. 1 and the evaluation of the time available for the validation exercise. Table 2 provides an example of the values selected per stratum based on the hypothesis that the stratum remaining stable in time is more accurately mapped than the strata (PCC= 1, PCC = 2) experiencing change. Equal allocation is chosen, allowing 306 samples to be distributed in each stratum, for a total of 918 samples per study area. Confidence intervals (CI) for this allocation remain below 5%, and the margin of error $S(\hat{O})$ for overall accuracy is 1%. The current Wi values are assumptions and will be updated once the extent of the historical CCI HR LC maps has been validated.

Table 2. The number of samples per stratum for the evaluation of the CCI HR LC historic LC maps, based on Wi set as an example. Ui is the user accuracy estimated a priori, S(Ô) is the standard error on overall accuracy, z is equal to 1. 96 for a 95% confidence interval, Si is the standard deviation of stratum i, $S_i = \sqrt{U_i(1 - U_i)}$, Wi is the proportion of the class, 'n' is the total number of validation samples, the 'Equal' and 'Prop' columns correspond to equal or proportional allocations to classes, and the associated confidence intervals (CI).

Label	Ui	S(Ô)	z (95% CI)	Si	Wi	n	Equal	CI	Prop	CI
PCC=1	75%			0.43	2%		306	5%	18	20%
PCC=2	85%	0.01	1.96	0.36	1%	918	306	4%	9	23%
No Change	90%			0.30	97%		306	3%	892	2%

6.2.3 Response design

Choice of the sample spatial unit.

It is unwise to match the size of the validation sample unit to the spatial resolution of the product to validate for the following reasons:

- Geo-location accuracy of the information. The absolute positional accuracy of the LC product is targeted to a 1/3 pixel dimension;
- Landsat time series may result in radiometric information coming from a few adjacent pixels;

Therefore, sample plots of 3×3 pixels were interpreted for the validation of each CCI HR LC product. This results in 90 m x 90 m for the validation of the CCI HR LC historical and LCC maps.

6.2.4 Labelling protocol

For each sampling unit, a set of attributes is systematically recorded. Table 3 shows an optimal attribute table designed for the validation of CCI HR LC historic and LCC maps. The information is collected to test two response design, i.e. either the central pixel is well classified, or the majority of the 3x3 window is well classified.

Table 3. The information included in the historical validation database for each validation sample plot.

Field name	Details
Sample ID	Unique identifier
Lat / Long	Centre coordinates of the observational unit to interpret
Central_LC_Start	The LC legend class ID of the sample plot center pixel at the start of the period
Central_LC_Start_Homogeneity	How many pixels in the window are of a similar label as the pixel central at the start of the period
Central_LC_End	The LC legend class ID of the sample plot center pixel at the end of the period.
Central_LC_End_Homogeneity	How many pixels in the window are of a similar label as the pixel central at the end of the period
Central_LC_Change	Presence/absence of LC change observed at the central pixel of the sample

Field name	Details
	plot (if applicable). Change is defined as a LC transition from one year to the other, confirmed for at least one year. Seasonal variations of the LC are not considered a change. Multiple LC changes in the period can be recorded in the field “comments”.
Central_Year_Change	Year when LC change was observed (if the field Central LC change was filled). This field is completed for each LC change observed in the previous field.
Level of certainty	Level of certainty (certain, reasonable, doubtful) associated with the interpretation of the expert
Comments	Comments given by the expert to explain/detail its interpretation (e.g. for indication of why the labelling was not successful, or to give the potential change phenomenon observed on the VHR imagery)

6.3 Benchmarking with other existing products

The data collected during Phase 1 were mostly global and regional HR LC because these datasets are of global interest, and usually available online or upon request with few local HR LC that have been collected upon contacting national mapping authorities. Currently in Phase 2 (as for June 2024), a similar trend is observed where mainly new global datasets were released in the recent few years. Notably, the objectives of the scholars and/or organizations producing HR LC are currently more focused on time-series and/or LC change products. This fact is mainly due to the longer time spans of the ongoing NASA’s Landsat and ESA’s Sentinel mission, as well as the availability of powerful computing cloud services (e.g., Google Earth Engine, Microsoft Planetary Computer, etc.).

All of the newly collected and recently released HR LC products have global coverage, where the only current exception is GLanCE V001 as the data owners released only partial products covering Europe, North and South America with the intention of releasing the rest of the continents. Table 4 shows the newly collected HR LCs as well as the HR LCs collected during Phase 1, which are indicated in the “Phase 1 Dataset” column. In the cases where the dataset series used in Phase 1 have new releases, then new versions are marked in red colour font.

For the dynamic datasets the following notation for the year of the products is used below in the table:

- When maps are produced for distinct years, the years are separated with comma. For example, “1985,1990” would mean that there is a single map for the 1985 and one for 1990.
- When maps are produced for a period of years, the contained period will be noted with dash between the start and end period. For example, “2000-2005” would mean that there is a single map produced for the period between year 2000 and 2005.
- When maps are produced for a period of years at a certain time-step, the notation will be again using a dash sign between the start and end period, but in brackets will be clarified the time-step period. For example, “2000-2005 (for every year)” would mean that there are maps produced for each year in the period between the year 2000 and 2005.

Table 4. Existing HR LC for benchmarking

Name of LC map	Producer	Resolution	Year	Spatial coverage	Phase 1 Dataset
GFC* (European Commission. Joint Research Centre., 2024)	JRC	10 m	2020	Global	No
GLC_FCS30/D*(Zhang	Aerospace Information Research	30 m	1985,1990,1995,	Global	No

Name of LC map	Producer	Resolution	Year	Spatial coverage	Phase 1 Dataset
et al., 2021),(Xiao Zhang et al., 2024)	Institute, Chinese Academy of Sciences		2000-2022 (map for every year)		
GISD30* (Zhang et al., 2022)	Aerospace Information Research Institute, Chinese Academy of Sciences	30 m	1985–2020	Global	No
GWL_FCS30/D**(Zhang et al., 2023), (X. Zhang et al., 2024)	Aerospace Information Research Institute, Chinese Academy of Sciences	30 m	2000-2022 (map for every year)	Global	No
Dynamic World* (Brown et al., 2022)	World Resources Institute Google	10 m	From 27/06/2015	Global	No
LULC Annual v2* (Karra et al., 2021)	Impact Observatory, Microsoft, and Esri	10 m	2017-2023 (map for every year)	Global	No
WorldCover*(Zanaga et al., 2021) (Zanaga et al., 2022)	ESA	10 m	2020,2021	Global	No
GHS-BUILT-S R2023A* (European Commission. Joint Research Centre., 2023) (Pesaresi and Politis, 2023)	JRC	10 m	2018	Global	No
GLanCE V001* (Arevalo et al., 2022),(Friedl et al., 2022)	BU/EE/NASA ES/USGS EROS	30 m	2001-2019 (map for every year)	Global (currently available Europe, North & South America)	No
MapBiomas Collection 10m Beta*	SEEG and Climate Observatory	10m	2016-2022 (map for every year)	Regional Brazilian Amazon	No
GL30 **(Chen et al., 2015),(Jun et al., 2014),(Chen et al., 2017)	NGCC	30 m	2000, 2010,2017	Global	Yes
FROM-GLC(Gong et al., 2013),(Li et al., 2017),(Gong et al., 2019)	Tsinghua University	30 m	2010, 2015,2017	Global	Yes
GUF ***	DLR	12 m	2011	Global	Yes
GHS BU S1 *(Corbane et al., 2017),(Joint Research Centre (European Commission) et al., 2019)	JRC	20 m	2016	Global	Yes
GHS BU LDS (Corbane et al., 2017),(Joint Research Centre (European Commission) et al., 2019)	JRC	38 m	1990, 2000, 2014	Global	Yes
GSW Yearly History* (Pekel et al., 2016)	JRC	30 m	1984-2021 (map for every year)	Global	Yes
FNF * (Shimada et al., 2014)	JAXA-EORC	25 m	2007 - 2010 (map for every year) 2017 - 2020 (map for every year)	Global	Yes
Tree canopy cover * (Hansen et al., 2013)	Hansen/UMD/Google/USGS/NASA	30 m	2000 - 2023	Global	Yes

Name of LC map	Producer	Resolution	Year	Spatial coverage	Phase 1 Dataset
WSF*(Marconcini et al., 2020), (Marconcini et al., 2021)	DLR	10 m	2015, 2019	Global	Yes
TerraClass * (Almeida et al., 2016)	INPE and EMBRAPA	30 m	2004, 2008, 2010, 2012, 2014	Regional Brazilian Amazon	Yes
MapBiomas Collection 8*	SEEG and Climate Observatory	30m	1985 - 2022 (map for every year)	Regional Brazilian Amazon	Yes
ESA-DUE-GlobPermafrost* (Bartsch et al., 2019)	ESA-DUE-GlobPermafrost	20 m	2016-2018 (map for period)	Regional Siberia	Yes
CCI Prototype Africa* (Lesiv et al., n.d.)	CCI Land Cover team	20 m	2016	Regional Africa	Yes
AUE*	NYU Urban Expansion Program	30 m	1984-2015 some years	Cities in Nigeria, Brazil, Uganda, Sudan, Ghana, Mali,	Yes

*Freely available

**Available upon agreement

*** Freely available upon request for non-commercial and scientific purpose

Most of the HR LC products gathered in Phase 2 are multitemporal, providing maps mainly on a yearly basis, except the Dynamic World, which provides LC classification for each available Sentinel-2 scene with a cloud cover ≤35% starting from 27/06/2015. Another exception is the GISD30 dataset, which provides a map with temporal coverage from 1985 to 2020, using different pixel values to represent different year periods.

Some HR LCs from Phase 1 (including GSW Yearly History, FNF, Tree Canopy Cover, and MapBiomas) have been updated to cover a larger spatial extent. Additionally, MapBiomas has introduced a new collection with a 10-meter resolution, called MapBiomas Collection 10m Beta (for detailed information see [AD5]).

The CCI Prototype Africa dataset used in Phase 1 will be excluded due to its limited validation across countries and its low overall accuracy in three out of the four countries where it was tested.

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