Product Validation Report

(D12-PVR)

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2.0	2022-10-25	All	Updated for the 2021 product and version 2.0 of the algorithm

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Acronyms and Abbreviations

AD	Applicable Document
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CGLS	Copernicus Global Land Service
ESA	European Space Agency
GLC	Global land cover
GOFC-GOLD	Global Observation of Forest Cover and Land Dynamics
IIASA	International Institute for Applied Systems Analysis
LCCS	Land Cover Classification System
LPV	Land Product Validation
MMU	Minimum Mapping Unit
PA	Producer Accuracy
PSU	Primary Sampling Unit
PVR	Product Validation Report
RB	Requirement Baseline
RD	Reference Document
SDGs	Sustainable Development Goals
SoW	Statement of Work
SSU	Secondary Sampling Unit
UA	User Accuracy
URD	User Requirement Document
UTM	Universal Transverse Mercator
VHR	Very High Resolution
WGCV	Working Group on Calibration and validation

1 Introduction

1.1 Project objectives and approach

In an ever-changing environment, the need for accurate, timely and high-resolution information on land use/land cover and its changes has increased tremendously. However, until now, regional or continental land cover maps either used low-resolution images (>100 m) as input or were based exclusively on high-resolution optical Earth observation data, such as Sentinel-2 or Landsat. The use of Synthetic Aperture Radar (SAR) data such as Sentinel-1 to produce large area land cover maps is still in its infancy.

For this purpose and inspired by the 2017 WorldCover conference (attended by more than 400 participants) the European Space Agency (ESA) initiated the WorldCover project. The key outcome of this project was the release in October 2021 of a freely accessible global land cover product at 10 m resolution for 2020 based on both Sentinel-1 and Sentinel-2 data, containing 11 land cover classes and independently validated with a global overall accuracy of 74.4%.

Following the positive feedback from the users, ESA decided to extend the WorldCover project and requested the WorldCover consortium to also produce a 2021 version of the product with even higher quality. This new WorldCover map for 2021 was released on 28 October 2022 and resulted in a global overall accuracy of 76.7%.

Since the **WorldCover maps for 2020 and 2021 were generated with different algorithm versions** (v100 and v200, respectively), changes between the maps should be treated with caution, as they include both changes in real land cover and changes due to the used algorithms.

1.2 Purpose of the document

The Product Validation Report (PVR) is a deliverable of contract N°4000128231/19/I-LG. The objective of this document is to describe the validation results of the WorldCover 2021 v200 product. The validation results include statistical accuracy assessment of the WorldCover 2021 v200 product and improvements as compared to the WorldCover 2020 v100 product.

1.3 Content of the document

This document is structured as follows:

- Section 2 details the methods for validating the WorldCover product. Here, the methods used for validation data update and statistical accuracy assessments are detailed.
- Section 3 details the main results on validation of the WorldCover 2021 v200 product, with details on qualitative comparisons with the previous release (WorldCover 2020 v100).
- The observed limitations of the WorldCover v200 product are included in Section 4.
- The final conclusions of the validation results are included in Section 5.

2 Methods

Validation is an intrinsic part of satellite-derived land product generation as it informs on the product quality, consistency and builds the product users' confidence in using the land product. In addition, validation should inform on the "fitness for use" to a variety of end-users that use land products. Information on these aspects of a map can be achieved through map validation assessments.

Here we performed the following steps to provide information on map quality, consistency, and fitness for use of the WorldCover 2021 v200 product.

- **Statistical accuracy assessment** following Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) Land Product Validation (LPV) requirements.
- **Qualitative comparison** with the WorldCover 2020 v100 product.

The statistical accuracy assessment aimed to provide information on the product accuracy using a statistically rigorous method which is based on independent validation data selected using probability sampling. Here we made use of the world's most advanced (CEOS-WGCV Stage 4) and multi-purpose independent GLC validation systems that have been developed, scientifically published (Tsendbazar et al. 2018), and operationally used and regularly updated as part of the Copernicus Global Land Service (CGLS) (Tsendbazar et al. 2021a).

For comparison, we assessed the WorldCover 2020 v100 visually. In the following subsection, we detail the methods used.

2.1 Statistical Accuracy Assessment

The statistical accuracy assessment of the WorldCover product follows closely the best practices guidelines for GLC validation supported by the international communities such as the Global Observation of Forest Cover and Land Dynamics (GOFC-GOLD) and the Committee on Earth Observation Satellites (CEOS).

The "validation" is defined according to the definition of the CEOS Working Group on Calibration and Validation (CEOS-WGCV):

"The process of assessing, by independent means, the quality of the data products derived from the system outputs"

The statistical accuracy assessment of the WorldCover map meets the requirements of the CEOS WGCV Validation Stage 3 and Stage 4 (Table 1).

Table 1: CEOS WGCV stage 3 and 4 validation requirements http://lpvs.gsfc.nasa.gov/

Stage 3	Uncertainties in the product and its associated structure are well-quantified from comparison with reference in situ and higher resolution airborne and satellite data. Uncertainties are characterized in a statistically robust way over multiple locations and time periods representing global conditions. The spatial and temporal consistency of the product and consistency with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature.
Stage 4	Validation results for stage 4 are systematically and operationally updated by independent actors for comparative assessment of existing products when new products are released and as the time-series expands.

The multi-purpose Global Land Cover Validation dataset developed for the Copernicus Global Land Service- Land Cover product (henceforth called CGLS-LC validation dataset) was used. The following characteristics of the CGLS-LC validation dataset made it suitable to assess statistically the WorldCover product meeting the requirements mentioned above:

1. A global stratification that is **independent** of any land cover maps and uses the Sentinel 2 Universal Transverse Mercator (UTM) grid as a geographic base
2. Globally more than **21 000** primary sampling units (PSUs) with each containing one hundred 10x10 m reference pixels, are suitable for assessing accuracy **per continent** (minimum of 3000 PSUs per continent).
3. **Stage 4 validation dataset**: the PSUs are updated every year by focusing on areas that went under change since 2015 as part of the CGLS.
4. **A multi-purpose** validation data suitable for validating **10 m land cover** maps, which allows the validation for WorldCover product.
5. A dataset containing high-quality **land cover elements** information **at 10 m resolution** contributed and reviewed by more than 30 international and regional experts from around the world.
6. The 10 m land cover element information fully corresponds to **Sentinel-2 10 m resolution** pixels and is collected on the **Geo-Wiki** reference data collection platform

The following subsections include a description of the CGLS-Validation data including a well-established method to estimate map accuracies with statistical rigorousness for validating the WorldCover product.

2.1.1 The CGLS-LC validation dataset

The CGLS-LC validation dataset is based on probability sampling to allow a design-based inference of map accuracies. The criterion of statistical probability sampling with known and non-zero inclusion probabilities was followed. The validation dataset is based on stratified random sampling, employing a global stratification (Olofsson et al. 2012). Globally there are 149 strata divided over seven (sub)continents. The validation dataset consists of 21 752 PSUs. The available PSUs per continent (minimum 3000 PSUs per continent) allow to carry out a statistical accuracy assessment for each continent with a high level of precision (Tsendbazar et al. 2021a). The spatial distribution of the validation sites and (sub)continent divisions are shown in Figure 1.

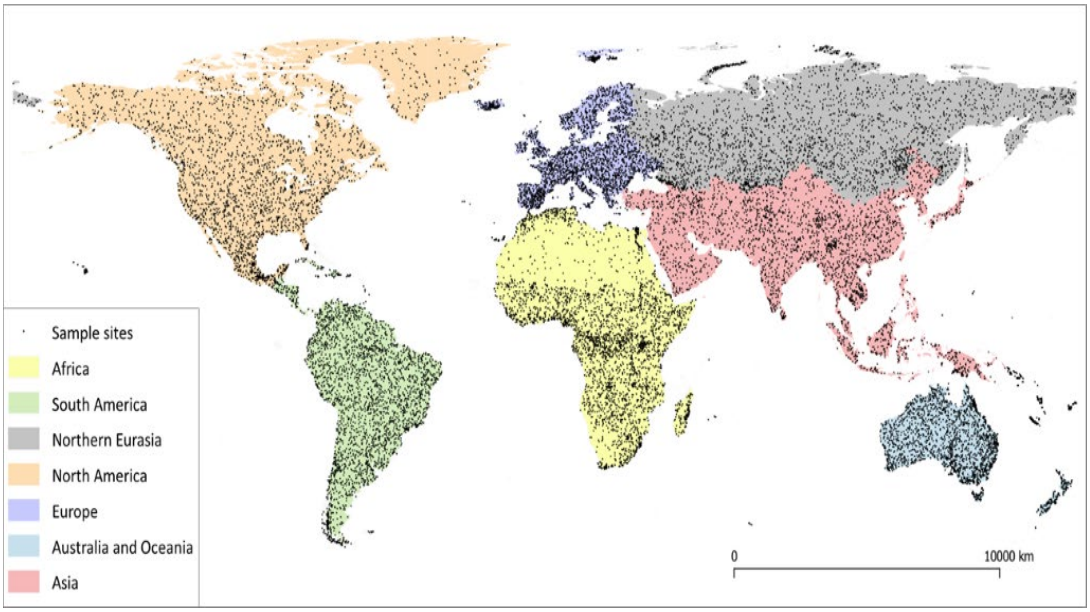

Figure 1: Spatial distribution of all validation sample sites for different (sub) continents

The CGLS-LC validation dataset is multi-purpose data compatible for validating maps with different resolutions and legends. Each PSU (covering an area of 100 m × 100 m) was divided into 10×10 small blocks (henceforth called SSU: secondary sampling unit). Since the reference land cover elements were collected at 10 m × 10 m SSU level, the dataset is compatible for assessing land cover maps with 10-100 m resolutions. For the thematic representation, the generic land cover elements recorded at each SSU include trees (phenology and leaf types), shrubs, grass, crops, built-up areas, bare area, lichens/mosses, open water, snow & ice, and regularly flooded areas. The land cover elements were defined according to the United Nations Land Cover Classification System (LCCS) (Di Gregorio 2005). The validation data was collected using a dedicated web-interface through the Geo-Wiki platform (Fritz et al. 2011). The interface provided access to different remote sensing data and allowed labelling land cover (Figure 2). An example of labelling the land cover of SSUs within a PSU is provided in Figure 3.

The reference land cover was visually interpreted by 30 regional experts remotely (Table 1, Annex 1). All experts have experience in satellite-based land cover analysis and image interpretation. For **quality assurance**, all the interpretations were **reviewed** and improved where necessary (Tarko et al. 2021).

The validation dataset contains reference land cover information for the years 2015-2019. More detailed information on the validation data can be found in Tsendbazar et al. (2021a).

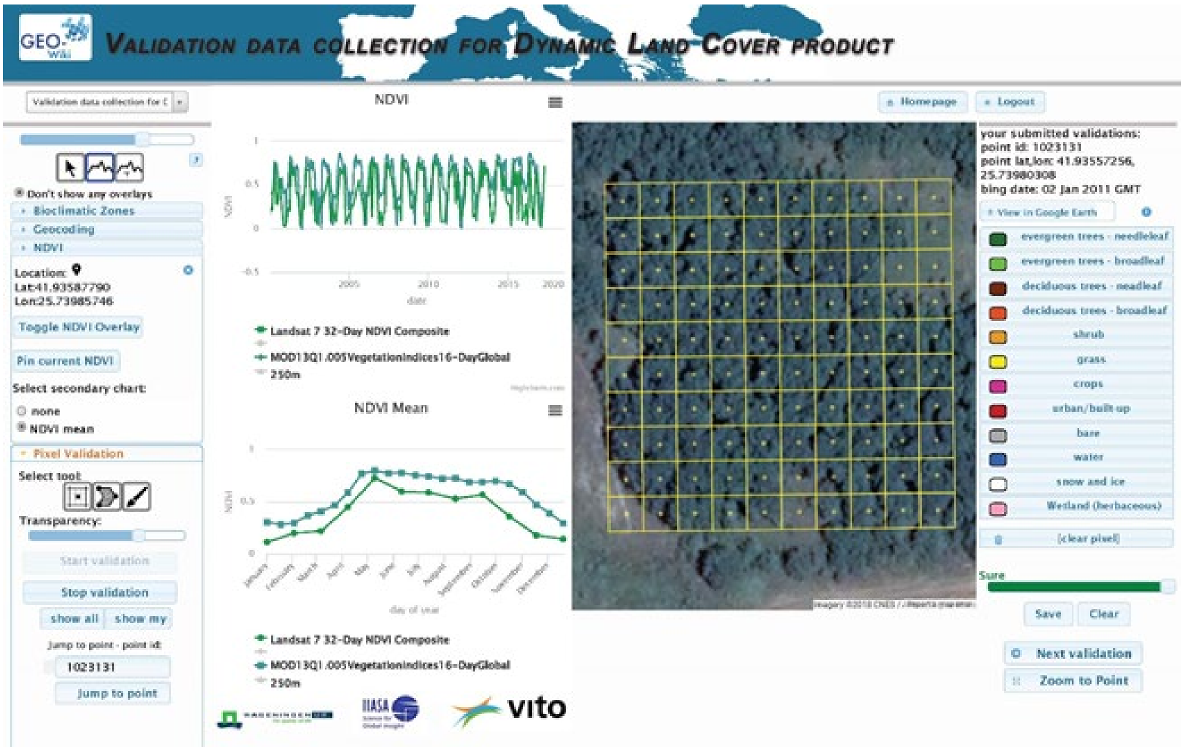

Figure 2: Screenshot of the Geo-Wiki based interface for validation data collection

Figure 3: A screenshot of an example sample interpretation (green – trees, orange – shrubs, yellow – grassland)

2.1.2 Adopting the CGLS Validation dataset for validating WorldCover 2021

To validate the WorldCover2020 v100 product, the CGLS-LC validation data for the reference year 2019 was updated with validation data for 2020 by revisiting 2860 validation points with a high possibility of change as well as a random subset (Tsendbazar et al. 2021b). For the reference year 2021, we further updated the validation dataset by revisiting a total of 4410 validation sites. Next to revisiting a random subset of 2200 validation sites (~10%), we have revisited about 2210 validation sites, aiming to target sites with high possibility of land cover change between 2020 and 2021. High possibility of land cover change sites were identified based on the BFAST Monitor change detection algorithm using Landsat 8 data (2015-2022) as well as change based on the WorldCover 2020 and 2021 (a preliminary version) maps. In addition, Sentinel-2 based NDVI and NDWI indices were calculated at the validation sites to flag validation sites to revisit for possible land cover change. Validation sites with inconsistent indices values with respect to their reference land cover labels were shortlisted. For example, validation sites with grass label having very low NDVI value for 2021 were included in the revision. Revision was done by an independent regional expert who contributed to the initial generation of the CGLS-LC validation data. In case of land cover change, the land cover information was updated.

Note that the CGLS-LC validation data is used as an independent validation dataset for the CGLS-LC mapping effort and to continue to support independent validation of maps, the dataset will not be released to the public.

The CGLS-LC validation dataset was collected by visual interpretation of VHR images. VHR images can have some level of geolocation errors which can result in shifts between VHR base maps. Figure 4 illustrates examples of shifts between the images sourced from Google map and Bing maps (Tsendbazar et al. 2021b). In case of such a shift, Google map locations were preferred for the CGLS-LC validation data collection. This was due to the larger availability of VHR maps in the Google map for recent years. However, in cases where no Google VHR images were available, Bing map and ESRI VHR images were used, supported by Sentinel-2 imagery. As the WorldCover products come at a high resolution (10 m), geolocation errors of these VHR images (e.g., Google map and Bing map) used for visual interpretation can have an impact on the obtained accuracy numbers.

To validate the WorldCover 2020 product, SSUs isolated in terms of land cover were excluded from the validation data to account for the possible impact of validation data ambiguity due to geolocation errors of the VHR images and labelling uncertainty in heterogeneous areas at high resolution (Tsendbazar et al. 2021b). This was done with the expectation that the impact of ambiguity would be less in a more homogeneous area (Gu and Congalton 2020). Therefore, SSUs having the same land cover type with at least two direct neighbours were included and the rest were not included in the validation. As a result, 1 935 650 SSUs across the world were used for the statistical accuracy estimation of the WorldCover 2020 product, while ~10% of the SSUs were excluded for this validation (Tsendbazar et al. 2021b). This approach however has a limitation in heterogeneous areas, being more biased towards homogeneous areas.

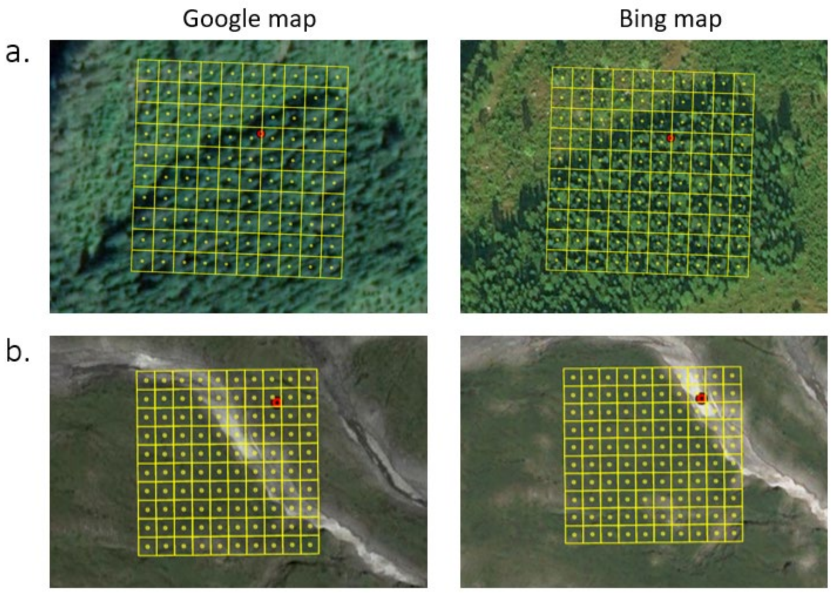

Figure 4: Snippets of validation data locations depicting shifts between the images sourced from Google map and Bing map (Tsendbazar et al. 2021b).

To validate the WorldCover 2021 product, we revised therefore the approach to deal with validation data ambiguity. We utilized information from the neighbouring SSUs as an alternative land cover label in addition to the reference label for the SSU itself. Making use of alternative or secondary labels from the surrounding area of the sample unit is a widely used method (Olofsson et al. 2014; Stehman et al. 2003; Wickham et al. 2021). This approach addresses possible reference label ambiguity and geolocation error, but all sample units are included in the validation; no sampling units are discarded. Similar to Stehman et al. (2003) and Wickham et al. (2021), next to the primary land cover label of a SSU, we used majority/modal land cover type from the surrounding neighbourhood (3x3) of the SSU. Therefore, the reference land cover is represented both by the primary and alternative labels in the validation dataset. Both the labels are compared with the mapped label. An example for identifying primary and alternative labels is included in Figure 5.

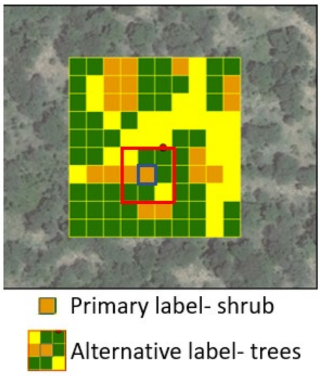

Figure 5: An example of primary and alternative validation labels

2.1.3 Accuracy estimation of the WorldCover product

For the accuracy estimation, we used a stratified one-stage cluster approach (Pengra et al. 2015). This cluster approach is suitable since multiple SSUs within the PSUs are used for the assessment. Calculation of inclusion probabilities for the PSUs and SSUs follows the methods described in Pengra et al. (2015) and Tsendbazar et al. (2018). Based on the estimation weight (the inverse of inclusion probability) per sampling unit, mapped and reference land cover types, a confusion matrix was constructed accounting for unequal sample inclusion probabilities (Stehman et al. 2003; Wickham et al. 2010). The estimation weights for each sample unit were available for this validation dataset.

Accuracy estimates, namely overall accuracies, class-specific accuracies, and their confidence intervals (at 95% confidence level) were calculated following the stratified one-stage cluster approach (Pengra et al. 2015; Stehman et al. 2003; Tsendbazar et al. 2018). Due to the limited number of validation sites, samples for the lichen/moss class were merged with the grass class in South America and Asia.

Next to global level accuracy estimates, the accuracy estimation was also done per continent (7 sub-continents) following the initial design of the validation dataset (Figure 1).

2.2 Qualitative Accuracy Assessment

For qualitative comparison, we compared the WorldCover 2021 v200 and 2020 v100 products visually with Google Earth VHR images as well as Sentinel-2 median composites accessed from the WorldCover viewer.

3 Results

3.1 Statistical Accuracy of the WorldCover 2021 v200 product

Overall accuracy estimates of the WorldCover 2021 v200 product can be found in Table 2. On a global scale, using 2.16 million SSUs at 21 624 PSU locations, the overall map accuracy was 76.7±0.5%.

In terms of class-specific accuracies, tree cover, snow/ice, cropland, water body, and bare/sparse vegetation classes had high accuracies. Grassland and built-up classes had moderate accuracies, while shrubs, wetlands, and moss/lichen classes had relatively lower accuracies globally.

In general, at the global scale, there was a slight underestimation of moss and lichen and bare class while a slight overestimation of trees was observed when comparing against the validation dataset. Shrubs, grassland, cropland, built-up and permanent water bodies classes were mapped with balanced user's and producer's accuracies.

Table 2: Confusion matrix (%) for the WorldCover 2021 v200 product at a global scale, corrected by sample inclusion probabilities.

	Tree cover	**Shrubland**	**Grassland**	**Cropland**	**Built-up**	**Bare / sparse veg**	**Snow and ice**	**Permanent water bodies**	**Herbaceous wetland**	**Mangroves**	**Moss and Lichen**	**Correct**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**26.2**	2.4	3.1	0.4	0.1	0.1		0.1	0.1	0.1	0.1	26.2	32.7	**80.0**	0.7
Shrubland	1.1	**3.9**	2.2	0.2	0.0	0.5		0.0	0.0	0.0	0.0	3.9	7.9	**49.1**	2.1
Grassland	0.9	1.5	**16.9**	1.2	0.1	1.7	0.0	0.1	0.4	0.0	0.8	16.9	23.4	**71.9**	1.0
Cropland	0.2	0.1	1.2	**7.4**	0.0	0.1		0.0	0.1	0.0		7.4	9.2	**80.6**	1.5
Built-up	0.0	0.0	0.1	0.0	**0.6**	0.1		0.0	0.0			0.6	0.8	**65.9**	3.3
Bare / sparse veg	0.0	0.2	0.7	0.1	0.0	**15.2**	0.0	0.0	0.0	0.0	0.3	15.2	16.5	**92.1**	0.9
Snow and ice			0.0			0.2	**2.3**	0.0			0.0	2.3	2.4	**93.0**	2.4
Permanent water bodies	0.0	0.0	0.0	0.0	0.0	0.1	0.0	**2.3**	0.1	0.0	0.1	2.3	2.6	**89.4**	1.8
Herbaceous wetland	0.0	0.1	0.5	0.0	0.0	0.0	0.0	0.1	**0.6**	0.0	0.5	0.6	1.8	**30.5**	4.3
Mangroves	0.0	0.0	0.0	0.0		0.0		0.0	0.0	**0.1**		0.1	0.1	**74.1**	13.2
Moss and Lichen	0.0	0.1	0.6			0.4	0.0	0.0	0.0		**1.4**	1.4	2.5	**57.5**	3.8
Correct	26.2	3.9	16.9	7.4	0.6	15.2	2.3	2.3	0.6	0.1	1.4				
Total	28.5	8.3	25.3	9.3	0.8	18.4	2.3	2.7	1.2	0.2	3.1				
Producer's accuracy	**91.9**	**46.9**	**66.7**	**79.3**	**73.2**	**82.5**	**99.1**	**86.4**	**44.6**	**46.2**	**46.4**			**76.7**	
Confidence interval ±	0.5	2.3	1.1	1.5	2.6	1.2	0.4	1.7	5.4	16.0	3.5				0.5

The accuracy of the WorldCover 2021 v200 product at the continental level is listed in Table 3. All continents had an overall accuracy above 72%. The overall accuracy was highest for Asia (82.1%) followed by South America, Europe, and Africa. The lower accuracy for Oceania could be due to high shrubland vs grassland and trees vs grassland confusions in the open woodlands of Australia. Similarly, high shrubland vs trees and grassland vs trees confusions in Siberian temperate tundra regions could explain the lower overall accuracy in Eurasia.

Table 3: Overall accuracy for the WorldCover 2021 v200 product at the continental level and sample sites used (SSU- secondary sample units, PSU – primary sample units)

	Overall accuracy	**Total SSU**	**Total PSU**
Global	76.7 +/- 0.5	2,162,366	21,624
Africa	76.5 +/- 1.3	359,900	3,599
Europe	77.9 +/- 1.0	311,800	3,118
Eurasia	72.5 +/- 1.3	300,271	3,003
Asia	82.1 +/- 1.0	306,400	3,064
Oceania and Australia	72.5 +/- 1.3	296,100	2,961
North America	74.6 +/- 1.2	287,995	2,880
South America	77.9 +/- 1.1	299,900	2,999

The class-specific accuracies and the confusion matrices for each continent are listed in Tables A2.1-A2.7, Annex 2. Similar to the global scale accuracy, tree cover was mapped with high accuracy for most continents. For this class, the commission error (100-user's accuracy) tended to be higher than the omission error (100-producer's accuracy) for most continents except Africa. In Africa, the tree cover class was balanced in terms of user's and producer's accuracy.

Cropland class was mapped with higher accuracies for all the continents except Africa where this class tended to be under-represented. Mangroves class was mapped with moderate accuracies for continents in which this class has a presence.

Similar to the global level accuracy, permanent water bodies and snow/ice classes were mapped with higher accuracy, except for South America, where the snow/ice class had a higher confusion with bare/sparse vegetation class. Similarly, shrubs, herbaceous wetland, and moss and lichen classes showed lower class accuracies for all the continents consistent with the global level accuracy.

Bare /sparse vegetation class had varied accuracies among the continents. This can be mainly due to the differences in area coverage of this class in the continents. For example, this class had high accuracy in Africa and Asia which have significant coverage of bare/sparse vegetation. In contrast, in Europe where bare/sparse vegetation does not cover large areas, this class was mapped with lower accuracies.

3.2 Qualitative comparison of the WorldCover 2020 v100 and 2021 v200 product

The WorldCover 2021 v200 product has been visually compared with WorldCover 2020 v100. The legend of the WorldCover product is included in Figure 6.

Figure 6: The legend of the WorldCover product

Figure 7 depicts the visual comparison of five regions comparing the WorldCover 2020 v100 and WorldCover 2021 v200 maps. Figure 7-1 depicts the WorldCover product versions in the outskirts of Midland, Texas of the USA. WorldCover v100 previously overestimated cropland in the suburban areas significantly. In v200, the separation between cropland and grassland has been improved, with the backyards of houses correctly classified as grassland, based on the comparison with VHR images available in Google Earth. In this area, although slightly better compared to v100, v200 underestimates shrubland areas in the natural parks and open spaces. Improvements in characterizing shrublands in arid regions can further be demonstrated in Europe (Figure 7-2). In Andalusia, Spain, arid shrublands were previously mapped mostly as bare/sparse vegetation and grassland in WorldCover 2020 v100. In WorldCover 2021 v200, the shrubland are correctly mapped in better balance with bare/sparse vegetation class. In addition, forest borders match with what can be observed from the VHR image.

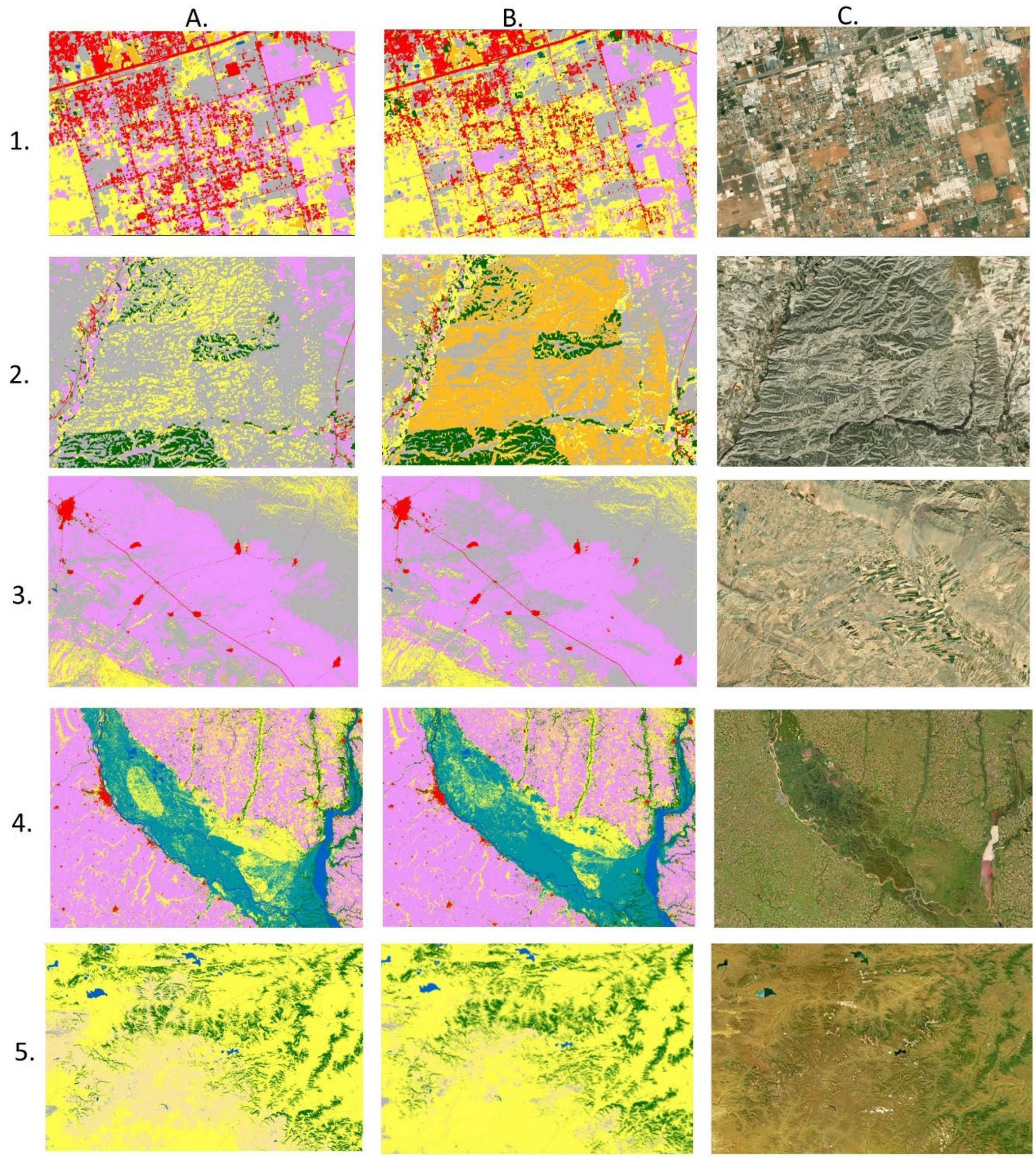

Figure 7: Comparison of WorldCover 2020 v100 (A) and WorldCover 2021 v200 (B) and VHR images available from the Google Earth (C). 1. Midland, Texas, the USA (Coordinates: 31.9510°N, 102.0457°W); 2. Andalusia, Spain (Coordinates:37.6877°N, 3.6986° W); 3. Near Fariman, Iran (Coordinates: 35.6369°N, 60.0684°E); 4. Parana River, Buenos Aires, Argentina (Coordinates: 33.0958°S, 60.3706°W); 5. Khangai mountains in Mongolia (Coordinates: 48.1886°N, 99.5896°E); see Figure 6 for legend.

Figure 7-3 compares the WorldCover product versions near Fariman, Iran. This area is mostly bare and sparsely vegetated but also has significant cropland areas. The WorldCover 2020 v100 overestimated cropland regions by including abandoned fields as croplands. However, cropland overestimation has been reduced in the WorldCover 2021 v200 version with mapping the non-cultivated areas as bare/sparse vegetation class. Improvements made in wetland areas can also be seen in Figure 7-4 which depicts the wetlands of Parana River of Argentina. Here, WorldCover 2020 v100 underestimated wetland class, but this has been improved in the WorldCover 2021 v200. Figure 7-5 depicts the Khangai mountains of Mongolia. This high altitude region (> 2000m above sea level) had an overestimation of lichen/moss class in the WorldCover 2020 v100. With the improvements in the WorldCover 2021 v200, the grasslands in the mountain steppes have been correctly characterized.

Since the WorldCover v200 characterizes global land cover for the reference year of 2021, the dynamics of land cover in that year are depicted in this product. Figure 8 shows four examples of land cover for the year 2021. In Figure 8-1, forest clearings in Mato Grosso, Brazil are correctly depicted; The forest clearings occurred in the second half of 2020 around the centre west of area are included in the image snippet. Figure 8-2 depicts a relatively green summer in the transition zones of the Sahara Desert in Chad for the year 2021; Accordingly, increased grassland areas are captured in the WorldCover 2021 v200. Figure 8-3 shows the swampy marshlands of Ciénaga Grande de Santa Marta, Columbia; In 2021, this area has seen increased influence of flooding and accordingly, this is depicted as wetlands in the WorldCover 2021 v200 product. The seasonally flooded salt lakes, Sua-Pan of Botswana are shown in Figure 8-4; This area has also seen increased water dynamics in 2021 and accordingly, areas that were continuously flooded in 2021 were mapped correctly as water in the WorldCover 2021 v200, while the rest was mapped as bare/sparse vegetation since the flooding was temporary.

These examples showcase the up-to-date characterization of land cover by the WorldCover v200 product for the year 2021. **Note that the WorldCover v100 for 2020 and v200 for 2021 cannot be compared to identify changes in land cover. The difference in the versions are both due to the improvements made in the classification algorithm as well as the dynamics between the two years.**

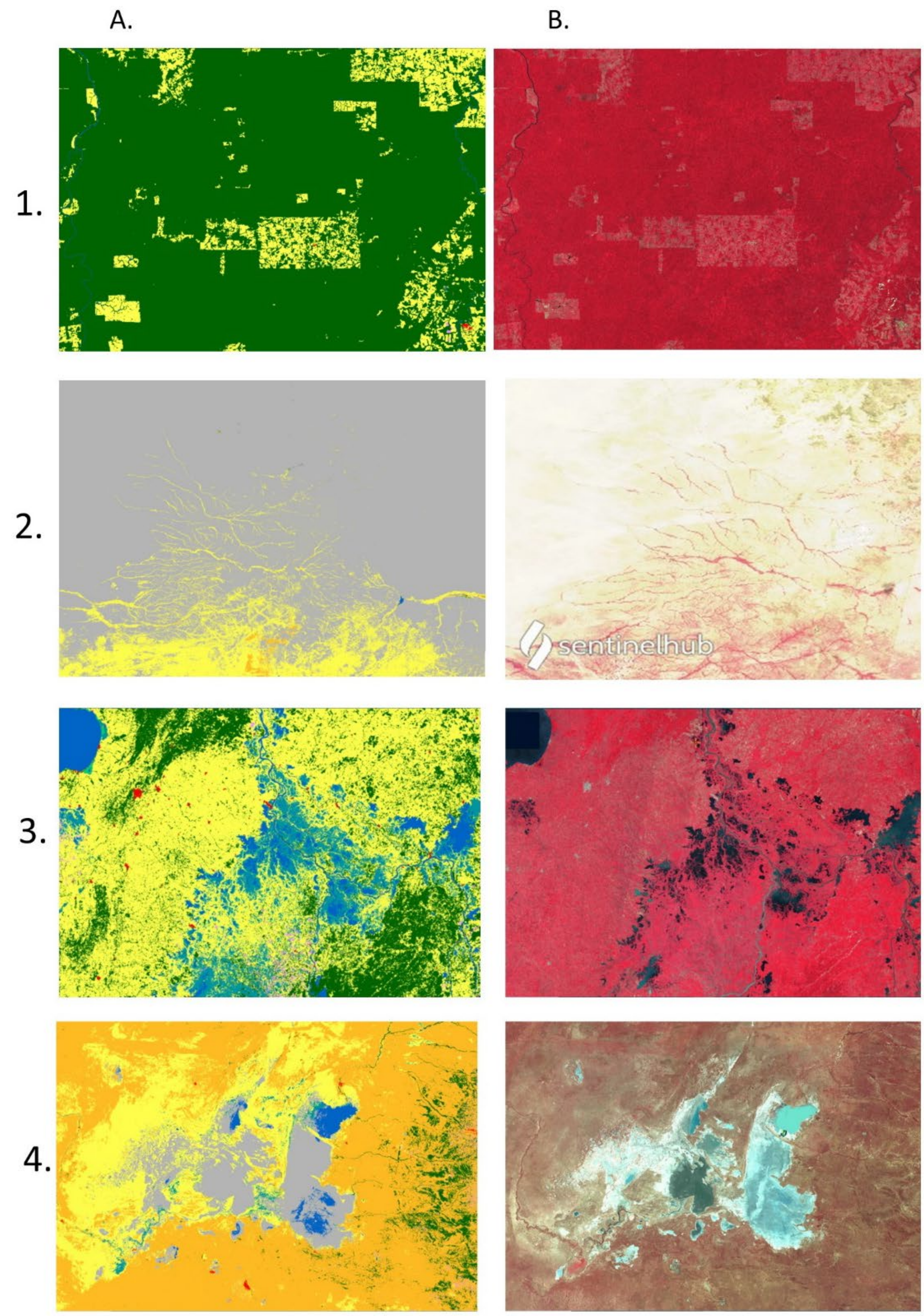

Figure 8: Comparison of the WorldCover 2021 v200 (A) and Sentinel 2 data (B). 1. Mato Grosso, Brazil (Coordinates: 9.9469°S, 59.8814°W); 2. Chad (Coordinates: 16.3122°N, 21.0947°E); 3. Columbia (Coordinates: 9.0344°N, 74.6195°W); 4. Sua-Pan, Botswana (Coordinates: 20.6461°S, 25.8411°E); 1, 3 & 4 show the false colour image of Sentinel 2 data of 2021 based on median composite; 2 shows a false colour image of Sentinel 2 data acquired on August 17 2021; see Figure 6 for legend.

4 Limitations

The statistical validation of the WorldCover 2021 v200 product and the qualitative comparison with the previous version v100 revealed improved quality of characterizing land cover at a global scale at 10 m resolution. However, there exist some limitations within this product which can be tackled in future mapping efforts.

As can be seen in Figure 9, there remain some anomalies in the WorldCover 2021 v200 product, although compared to WorldCover 2020 v100, considerably less. For example, a sharp divide between cropland and grassland was observed in an agricultural area of Nigeria (Figure 9A). Due to anomalies of the remote sensing data, sharp divides between grassland and lichen/moss class as well as artefacts not matching with the landscapes are visible near Russia and Mongolian border (Figure 9B). This area is generally wetlands, however, the wetland, grassland and lichen/moss transitions do not match with the landscapes that can be observed in VHR images.

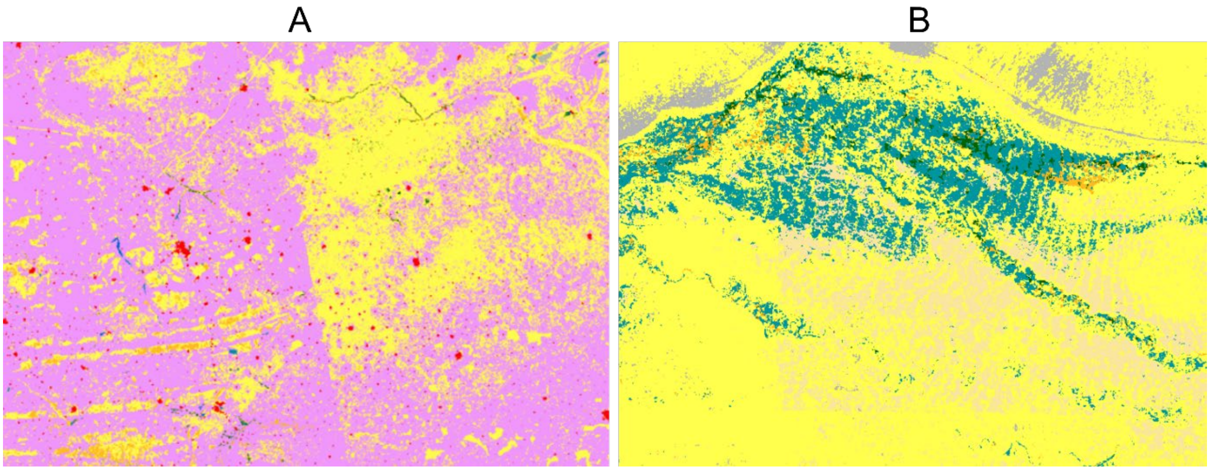

Figure 9: Examples of artefacts in the WorldCover 2021 v200 product. (A) Nigeria (Coordinates: 13.0691°N, 8.6240°E); (B) Russia (Coordinates: 50.6518°N, 94.0797°E); see Figure 6 for legend.

Figure 10 demonstrates examples of areas that can be further improved in future mapping efforts. The WorldCover 2021 v200 tended to overestimate trees particularly in temperate regions such as Eurasia and Europe. This is illustrated in Figure 10-1 which shows in Sakha republic of Russia where a tundra landscape dominated by lichen/moss class is mostly mapped as trees. Although a closer look of the VHR image shows the presence of some trees, they are not dominant in these landscapes. Herbaceous wetlands is a challenging class to characterize accurately due to its high dynamics of flooding level. Figure 10-2 illustrates an example of wetland areas misclassified as cropland in North Eastern China. Similar misclassification of wetlands as cropland is also visible for example in the estuaries of Licungo river, Mozambique.

1

2

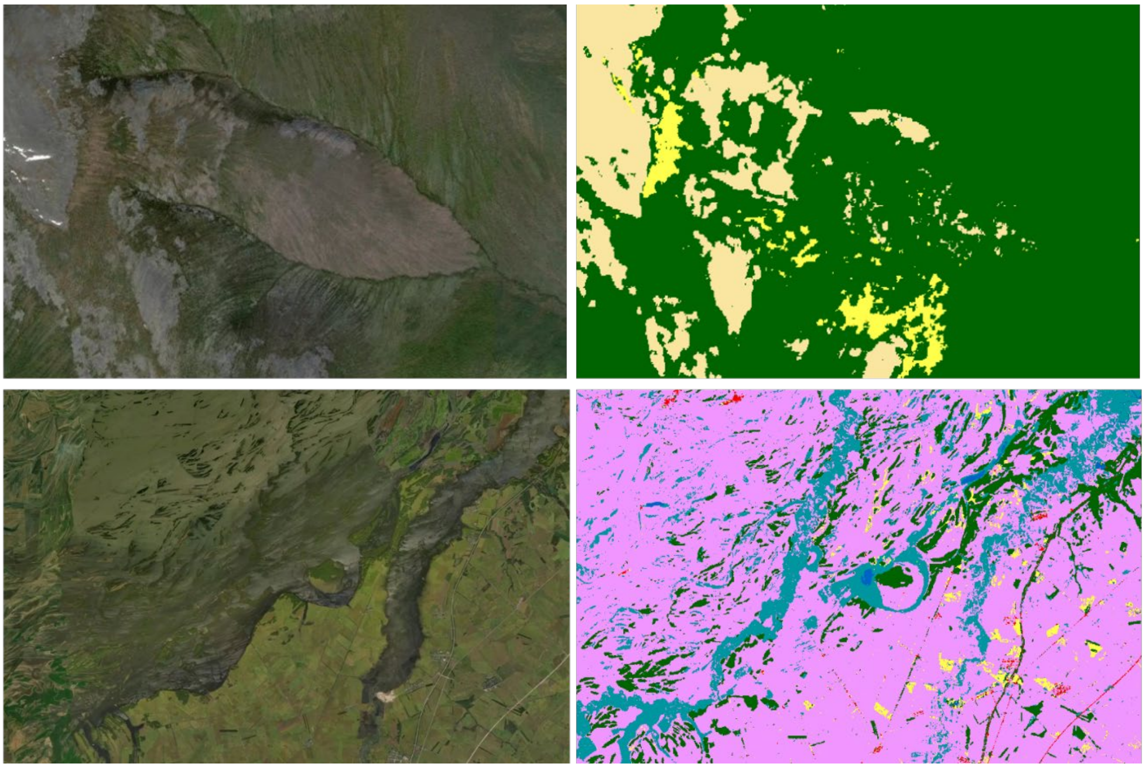

Figure 10: Examples of misclassification in the WorldCover 2021 v200 product. 1. Misclassification of trees (Coordinates: 68.1514°N, 132.1499°E); 2. Underestimation of wetlands caused by the mis-assigning of croplands (Coordinates: 48.1329°N, 134.1937°E); see Figure 6 for legend.

The validation of the WorldCover products was done at 10 m resolution. At this high resolution, the geolocation errors of VHR images used for validation data collection and the labelling uncertainties can influence the accuracy estimation (Figure 4). We used primary and secondary labels to deal with potential uncertainties in the validation data. In future efforts, the uncertainties of the validation data can be quantified and taken into consideration in the accuracy estimation (Foody 2013). The WorldCover 2021 v200 was validated using the CGLS-LC validation data by updating it to 2021. With this, the validation fulfils the requirement of Stage 4 validation by the CEOS LPV. Efficient way of keeping the validation dataset up-to-date can be further investigated to allow timely assessments of map products.

5 Conclusions

This document reports the validation process of the WorldCover 2021 v200 product by ESA. The validation was based on the CGLS-100 validation dataset, a statistical validation dataset developed as part of the Copernicus Global Land Service- Dynamic Land cover product. To validate the WorldCover 2021 v200 product, this validation dataset was updated to the year 2021 by revisiting a random subset of the dataset and the sample sites which have higher possibility of land cover change. This allowed to provide an independent and statistically-robust global and continental accuracy assessment at the time of the release of the WorldCover 2021 v200 map in October 2022.

Our 10 m resolution validation showed that the overall accuracy of the WorldCover 2021 v200 product is 76.7±0.5%. In terms of land cover types, tree cover, snow/ice, cropland, permanent water body, and bare/sparse vegetation classes had high accuracies, while shrubs, herbaceous wetland, and moss/lichen classes were mapped with relatively lower accuracies. Overall accuracies at the continental level are above 72%, with the highest accuracy of 82.1% for Asia.

Our visual comparison between the WorldCover 2021 v200 and WorldCover 2020 v100 further confirmed the improved depiction of arid areas and the delineation of cropland, bare/sparse vegetation, grassland and lichen moss classes. The WorldCover 2021 v200 map also depicted the dynamics that occurred in the year 2021 such as increase in vegetation, water/flooding influence and forest clearings. However, it is worth to note that the WorldCover v100 for 2020 and v200 for 2021 cannot be compared to identify changes in land cover. The difference in the versions are both due to the improvements made in the classification algorithm as well as the dynamics between the two years.

Overall, the WorldCover 2021 v200 product shows promising improvements in characterizing the World's land cover at 10 m resolution making use of Sentinel 1 and Sentinel 2 data for the year 2021. Users of the map are encouraged to make use of the statistical accuracy analysis at the global and continental level to best apply the WorldCover product for their purposes.

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Annex 1.

Table A1.1 List of regional experts that contributed to the validation data collection

	Continent	Regions	Experts and their degree	Affiliation
1	North America	Greenland and Canada	Alemu Gonsamo (PhD)	University of Toronto, Canada
2		Mexico	Luis Valderrama (PhD)	CONABIO, Mexico
3		USA	Yinan He (PhD student)	University of North Carolina, Charlotte, the USA
4	Asia	Centre	Konstantin Ivushkin (PhD student)	Wageningen University, The Netherlands
5		East	Hongrun Ju (PhD student)	IRSDE, Chinese Academy of Science, China
6		South	Hammad Gilani (PhD)	ICIMOD, Nepal and University of Illinois, the USA
7		South-East	Tony Widianto (MSc)	Regional Planning, R&D, Jawa-Timur, Indonesia
8		West	Ali Abkar (PhD)	Agriwatch, The Netherlands
9	Northern Eurasia	Eastern Russia (Siberia)	Eduard Batotsyrenov (MSc)	Baikal Institute of Nature Management, Russian Academy of Science, Russia
10		Kazakhstan	Tom Bewernick (MSc)	GIS consultant, The Netherlands
11		Mongolia	Sainbuyan (MSc)	Institute of Geography, Mongolian Academy of Science, Mongolia
12		Western Russia	Maria Shchepashchenko (PhD)	Russian Institute of Continuous Education in Forestry, Russia
	Oceania	Australia	Nirmala Liyanage (PhD)	University of Sydney, Australia
13		Australia	Bethany Melville (PhD)	University of Tasmania, Australia
14		New Zealand and Oceania	Vega Xu (PhD)	University of Canterbury, New Zealand
15	South America	Caribbean and North	Kenneth Jimenez (MSc)	University of Costa Rica, Costa Rica
		East	George Longhitano (MSc)	G Drones, Brazil
16		East	Gustavo Alckmin (PhD student)	Wageningen University, The Netherlands
17		South	Nicolas Mari (MSc)	RedLaTIF / Agencia de Extensión Rural Cruz del Eje, INTA, Argentina
18		West	Roberto Chavez (PhD)	Pontifical Catholic University of Valparaíso, Chile
19	Europe	East	Agnieszka Tarko (PhD student)	Wageningen University, The Netherlands
20		North	Paola Codipietro (MSc)	GIS consultant, Rome, Italy
21		South	Nadine Drigo (MSc)	Wageningen University, The Netherlands
22		West	Tim Jak (MSc)	Wageningen University, The Netherlands
23	Africa	East	Elias Buzayane (MSc)	HoLiN Training and Consultancy Services PLC, Ethiopia
24		West	Matt Herkt (PhD student)	Institute of Experimental Ecology, University of Ulm, Germany
25		South	Natasha Ribeiro (PhD)	Universidade Eduardo Mondlane, MIOMBO and GOFC-GOLD network
26		Centre	Andre Mazinga (BSc)	OSFAC, DRC
27		Centre	Ifo Suspence (PhD)	Marien Ngouabi University, Brazzaville, République du Congo.
28		West	Emmanuel Amoah Boakye (MSc)	WASCAL, Accra, Ghana

Annex 2.

Table A2.1 Confusion matrix (%) for the WorldCover 2021 v200 product for Africa, corrected by sample inclusion probabilities.

	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse veg	Permanent water bodies	Herbaceous wetland	Mangroves	Correct	Total	User's accuracy	Confidence interval ±
Tree cover	**15.8**	1.5	1.8	0.4	0.0	0.0	0.0	0.1	0.1	15.8	19.7	**80.3**	2.0
Shrubland	2.9	**8.9**	5.1	0.6	0.0	0.8	0.0	0.1	0.0	8.9	18.4	**48.5**	3.5
Grassland	0.7	1.3	**15.2**	1.9	0.0	1.9	0.0	0.4	0.0	15.2	21.5	**70.7**	3.0
Cropland	0.2	0.3	1.1	**4.5**	0.0	0.2	0.0	0.1	0.0	4.5	6.3	**71.3**	4.7
Built-up	0.1	0.0	0.2	0.0	**0.4**	0.2	0.0			0.4	0.9	**47.1**	9.7
Bare / sparse veg	0.0	0.2	0.7	0.1	0.0	**29.8**	0.0	0.0		29.8	30.9	**96.6**	1.4
Permanent water bodies	0.0	0.0	0.0	0.0	0.0	0.1	**1.2**	0.0	0.0	1.2	1.3	**91.0**	2.8
Herbaceous wetland	0.0	0.0	0.2	0.1		0.0	0.0	**0.6**	0.0	0.6	0.9	**63.3**	14.4
Mangroves	0.0	0.0	0.0			0.0	0.0	0.0	**0.1**	0.1	0.2	**74.5**	13.8
Correct	15.8	8.9	15.2	4.5	0.4	29.8	1.2	0.6	0.1				
Total	19.8	12.2	24.2	7.6	0.5	32.9	1.3	1.2	0.2				
Producer's accuracy	**80.1**	**73.1**	**62.7**	**58.9**	**84.0**	**90.6**	**91.5**	**45.7**	**56.0**			**76.6**	
Confidence interval ±	2.0	3.6	3.1	4.9	5.3	2.2	4.6	12.9	27.1				1.3

Table A2.2 Confusion matrix (%) for the WorldCover 2021 v200 product for Europe, corrected by sample inclusion probabilities.

	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse veg	Snow and ice	Permanent water bodies	Herbaceous wetland	Moss and Lichen	Correct	Total	User's accuracy	Confidence interval ±
Tree cover	**32.4**	2.2	4.7	0.8	0.5	0.3		0.1	0.1	0.0	32.4	41.0	**79.1**	1.4
Shrubland	0.2	**0.5**	0.5	0.0	0.0	0.1		0.0	0.0	0.0	0.5	1.3	**36.4**	8.0
Grassland	1.3	1.1	**17.0**	3.6	0.2	0.6		0.1	0.3	0.5	17.0	24.5	**69.2**	2.5
Cropland	0.2	0.2	1.8	**21.4**	0.1	0.1		0.0	0.0		21.4	23.8	**89.9**	1.7
Built-up	0.1	0.0	0.2	0.1	**2.0**	0.1		0.0	0.0		2.0	2.4	**81.6**	2.9
Bare / sparse veg	0.0	0.0	0.1	0.1	0.0	**0.7**	0.0	0.0	0.0	0.1	0.7	1.1	**67.7**	9.2
Snow and ice						0.1	**0.7**	0.0		0.0	0.7	0.8	**81.0**	7.0

	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse veg	Snow and ice	Permanent water bodies	Herbaceous wetland	Moss and Lichen	Correct	Total	User's accuracy	Confidence interval ±
Permanent water bodies	0.0	0.0	0.0		0.0	0.1	0.0	**2.4**	0.0	0.0	2.4	2.5	**95.1**	1.8
Herbaceous wetland	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	**0.3**	0.0	0.3	0.7	**39.1**	12.5
Moss and Lichen	0.0	0.0	0.6			0.5	0.0	0.0	0.0	**0.6**	0.6	1.8	**33.9**	10.1
Correct	32.4	0.5	17.0	21.4	2.0	0.7	0.7	2.4	0.3	0.6				
Total	34.2	4.1	25.2	26.0	2.8	2.6	0.7	2.7	0.6	1.2				
Producer's accuracy	**94.9**	**11.5**	**67.5**	**82.3**	**71.2**	**28.0**	**93.4**	**89.5**	**41.7**	**51.6**			**78.0**	
Confidence interval ±	0.7	3.6	2.2	2.1	3.2	4.9	3.9	3.1	11.5	12.1				1.0

Table A2.3 Confusion matrix (%) for the WorldCover 2021 v200 product for Eurasia, corrected by sample inclusion probabilities.

	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse veg	Snow and ice	Permanent water bodies	Herbaceous wetland	Moss and Lichen	Correct	Total	User's accuracy	Confidence interval ±
Tree cover	**33.6**	4.2	5.2	0.1	0.0	0.1		0.2	0.1	0.4	33.6	43.9	**76.6**	1.9
Shrubland	0.1	**0.6**	0.3		0.0	0.1		0.0	0.0	0.0	0.6	1.2	**52.2**	11.2
Grassland	0.6	1.1	**21.4**	0.6	0.0	1.6		0.1	0.5	1.8	21.4	27.7	**77.2**	2.2
Cropland	0.0	0.0	1.2	**4.7**	0.0	0.1		0.0	0.0		4.7	5.9	**79.0**	5.6
Built-up	0.0	0.0	0.1	0.0	**0.1**	0.0		0.0			0.1	0.2	**57.4**	7.7
Bare / sparse veg	0.0	0.0	0.4	0.0	0.0	**4.0**	0.0	0.0	0.0	0.2	4.0	4.6	**86.1**	3.5
Snow and ice			0.0			0.1	**0.2**	0.0		0.0	0.2	0.3	**78.6**	24.0
Permanent water bodies	0.0	0.0	0.0		0.0	0.1		**3.4**	0.1	0.1	3.4	3.7	**93.0**	2.9
Herbaceous wetland	0.1	0.3	2.1	0.0		0.0		0.2	**1.4**	1.7	1.4	6.0	**23.7**	5.7
Moss and Lichen	0.2	0.3	2.1			0.9	0.0	0.0	0.1	**3.0**	3.0	6.5	**46.3**	6.1
Correct	33.6	0.6	21.4	4.7	0.1	4.0	0.2	3.4	1.4	3.0				
Total	34.7	6.7	32.7	5.4	0.2	6.9	0.2	3.9	2.2	7.2				
Producer's accuracy	**97.0**	**9.7**	**65.4**	**86.6**	**72.0**	**57.9**	**98.7**	**86.6**	**64.3**	**41.9**			**72.5**	
Confidence interval ±	0.7	3.2	2.3	4.9	8.2	5.0	1.6	3.5	9.4	5.9				1.3

Table A2.4 Confusion matrix (%) for the WorldCover 2021 v200 product for Asia, corrected by sample inclusion probabilities.

	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse veg	Snow and ice	Permanent water bodies	Herbaceous wetland	Mangroves	Correct	Total	User's accuracy	Confidence interval ±
Tree cover	**24.6**	1.6	2.4	1.0	0.2	0.2		0.1	0.1	0.1	24.6	30.3	**81.3**	1.8
Shrubland	0.2	**0.4**	0.6	0.1	0.0	0.2		0.0	0.0	0.0	0.4	1.5	**24.4**	7.7
Grassland	0.8	0.9	**11.1**	1.0	0.1	1.8	0.0	0.1	0.2	0.0	11.1	16.0	**69.4**	2.9
Cropland	0.6	0.2	1.4	**12.1**	0.1	0.3		0.1	0.3	0.0	12.1	15.0	**80.6**	2.8
Built-up	0.1	0.0	0.1	0.1	**1.1**	0.2		0.0	0.0		1.1	1.6	**68.0**	4.0
Bare / sparse veg	0.0	0.3	1.5	0.2	0.1	**30.3**	0.0	0.0	0.0		30.3	32.4	**93.5**	1.1
Snow and ice			0.0			0.0	**0.4**				0.4	0.4	**90.0**	4.2
Permanent water bodies	0.0	0.0	0.0	0.0	0.0	0.2	0.0	**1.9**	0.1	0.0	1.9	2.3	**83.4**	6.2
Herbaceous wetland	0.0	0.0	0.1	0.1		0.0		0.0	**0.1**	0.0	0.1	0.3	**35.2**	22.0
Mangroves	0.0	0.0	0.0			0.0		0.0	0.0	**0.1**	0.1	0.2	**76.7**	28.1
Correct	24.6	0.4	11.1	12.1	1.1	30.3	0.4	1.9	0.1	0.1				
Total	26.3	3.4	17.1	14.7	1.5	33.3	0.4	2.3	0.8	0.2				
Producer's accuracy	**93.4**	**10.8**	**64.8**	**82.7**	**71.6**	**91.0**	**93.9**	**82.1**	**12.9**	**63.4**			**82.1**	
Confidence interval ±	1.0	4.1	3.0	2.5	5.0	1.2	4.9	5.2	9.5	35.8				1.0

Table A2.5 Confusion matrix (%) for the WorldCover 2021 v200 product for Oceania & Australia, corrected by sample inclusion probabilities.

	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse veg	Snow and ice	Permanent water	Herbaceous wetland	Mangroves	Correct	Total	User's accuracy	Confidence interval ±
Tree cover	**14.0**	2.1	5.4	0.0	0.0	0.2		0.0	0.0	0.0	14.0	21.9	**64.1**	2.5
Shrubland	1.1	**7.5**	6.2	0.0	0.0	1.1		0.0	0.0		7.5	15.9	**47.1**	3.6
Grassland	0.8	2.0	**43.2**	0.6	0.0	5.1		0.0	0.2	0.0	43.2	52.0	**83.2**	1.5
Cropland	0.0	0.0	0.8	**3.2**	0.0	0.0		0.0			3.2	4.1	**79.5**	6.7
Built-up	0.0	0.0	0.0		**0.1**	0.0		0.0			0.1	0.1	**82.3**	10.0
Bare / sparse veg	0.0	0.1	1.3	0.0	0.0	**4.1**		0.0	0.0		4.1	5.5	**74.3**	4.8
Snow and ice			0.0			0.0						0.1		0.0
Permanent water bodies	0.0	0.0	0.0			0.0		**0.3**	0.0	0.0	0.3	0.3	**86.9**	6.7

Herbaceous wetland	0.0	0.0	0.1	0.0	0.0	0.1		0.0	**0.01**	0.0	0.0	0.2	**5.1**	5.8
Mangroves	0.0	0.0	0.0	0.0		0.0		0.0	0.0	**0.1**	0.1	0.1	**77.5**	21.6
Correct	14.0	7.5	43.2	3.2	0.1	4.1		0.3	0.0	0.1				
Total	16.0	11.7	56.9	3.8	0.2	10.7		0.3	0.2	0.1				
Producer's accuracy	**87.6**	**63.8**	**75.9**	**84.6**	**65.8**	**38.2**		**77.0**	**3.6**	**81.9**			**72.5**	
Confidence interval ±	1.9	4.1	1.8	5.2	14.1	4.6		13.4	3.4	19.4				1.3

Table A2.6 Confusion matrix (%) for the WorldCover 2021 v200 product for North America, corrected by sample inclusion probabilities.

	Tree cover	**Shrubland**	**Grassland**	**Cropland**	**Built-up**	**Bare / sparse veg**	**Snow and ice**	**Permanent water bodies**	**Herbaceous wetland**	**Mangroves**	**Moss and Lichen**	**Correct**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**24.4**	2.2	2.8	0.1	0.1	0.2		0.1	0.1	0.0	0.3	24.4	30.3	**80.6**	2.0
Shrubland	1.0	**3.2**	1.5	0.0	0.0	0.5		0.0	0.0	0.0	0.1	3.2	6.2	**51.0**	4.5
Grassland	1.1	2.2	**12.7**	0.8	0.1	0.5		0.2	0.3	0.0	2.5	12.7	20.3	**62.4**	3.0
Cropland	0.0	0.0	0.7	**6.8**	0.0	0.1		0.0	0.0			6.8	7.6	**88.8**	3.1
Built-up	0.0	0.0	0.1	0.0	**0.5**	0.0		0.0	0.0			0.5	0.7	**72.9**	5.1
Bare / sparse veg	0.0	0.3	0.4	0.0	0.0	**4.6**	0.0	0.1			1.3	4.6	6.7	**68.4**	4.6
Snow and ice						0.7	**12.0**	0.0			0.1	12.0	12.7	**93.8**	2.5
Permanent water bodies	0.0	0.0	0.1			0.1		**4.6**	0.1		0.2	4.6	5.1	**90.0**	3.1
Herbaceous wetland	0.0	0.1	0.4	0.0		0.0		0.2	**0.5**		1.1	0.5	2.3	**23.2**	7.7
Mangroves								0.0		**0.01**		0.0	0.0	**86.1**	25.3
Moss and Lichen	0.1	0.1	1.2			1.2	0.0	0.1	0.0		**5.3**	5.3	8.0	**67.0**	4.9
Correct	24.4	3.2	12.7	6.8	0.5	4.6	12.0	4.6	0.5	0.0	5.3				
Total	26.7	8.1	19.8	7.8	0.7	7.8	12.0	5.2	1.0	0.0	10.9				
Producer's accuracy	**91.6**	**39.3**	**64.0**	**87.5**	**70.1**	**59.0**	**99.8**	**87.9**	**51.5**	**54.3**	**48.9**			**74.6**	
Confidence interval ±	1.4	4.6	2.9	3.1	5.7	4.8	0.2	2.7	13.9	42.4	4.5				1.2

Table A2.7 Confusion matrix (%) for the WorldCover 2021 v200 product for South America, corrected by sample inclusion probabilities.

	Tree cover	**Shrubland**	**Grassland**	**Cropland**	**Built-up**	**Bare / sparse veg**	**Snow and ice**	**Permanent water bodies**	**Herbaceous wetland**	**Mangroves**	**Correct**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**42.4**	3.8	2.6	0.4	0.0	0.2		0.1	0.1	0.1	42.4	49.7	**85.2**	1.4
Shrubland	1.1	**5.2**	2.0	0.1	0.0	0.7		0.0	0.0	0.0	5.2	9.2	**57.1**	4.1
Grassland	0.9	2.1	**16.7**	1.1	0.0	2.0	0.0	0.1	0.9	0.1	16.7	23.9	**69.9**	2.5
Cropland	0.1	0.1	1.7	**6.3**	0.0	0.1		0.0	0.1		6.3	8.3	**75.6**	4.6
Built-up	0.0	0.0	0.0	0.0	**0.3**	0.0		0.0			0.3	0.4	**75.5**	6.9
Bare / sparse veg	0.0	0.1	0.2		0.0	**5.0**	0.1	0.0	0.0	0.0	5.0	5.4	**92.5**	2.5
Snow and ice			0.0			0.0	**0.2**				0.2	0.2	**85.1**	8.1
Permanent water bodies	0.0	0.0	0.0	0.0		0.1	0.0	**1.3**	0.1	0.0	1.3	1.5	**85.8**	5.5
Herbaceous wetland	0.1	0.1	0.5	0.0	0.0	0.0		0.0	**0.6**	0.1	0.6	1.4	**43.0**	12.1
Mangroves	0.0	0.0	0.0			0.0		0.0	0.0	**0.1**	0.1	0.1	**66.2**	33.2
Correct	42.4	5.2	16.7	6.3	0.3	5.0	0.2	1.3	0.6	0.1				
Total	44.7	11.4	23.7	7.7	0.4	8.1	0.2	1.6	1.8	0.4				
Producer's accuracy	**94.9**	**46.0**	**70.3**	**81.1**	**74.6**	**61.3**	**69.7**	**81.4**	**33.5**	**21.9**			**77.9**	
Confidence interval ±	0.8	4.0	2.5	4.3	8.4	4.8	20.5	4.7	9.8	18.6				1.1