WorldCover

Product Validation Report

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Applicable Documents

[AD 1] The General Clauses and Conditions for ESA Contracts (herein referred to as GCC), reference ESA/REG/002, rev. 2 not attached hereto but known to both Parties and available on http://emits.sso.esa.int/emits/owa/emits.main) “reference documentation” – “administrative documents”, as amended by the Draft Contract

[AD 2] The Statement of Work, ref. EOP-SD-SOW-2018-030, Issue 1, Revision 0, dated 15 November 2018;

[AD 3] The Standard Requirements for Management, Reporting, Meetings and Deliverables (rev 3: 2015-11) and its Annex A: Layout for Contract Closure Documentation (in its latest version)

[AD 4] The Contractor’s Proposal reference TAP/16974/060219, issue 1, Revision 0, dated 06/02/2019

Reference Documents

For clarity, all references used are in the text using the APA style. A bibliography is provided at the end of the document.

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
GWR	Geographically Weighted Regression
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 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 (http://worldcover2017.esa.int, 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 (GLC) 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%.

A crucial aspect for WorldCover was the involvement of several end-users active in different domains who provided primary input for all engineering aspects and followed the whole project workflow from design up to validation and uptake. Consequently, WorldCover intends to provide a substantial benefit to various user communities and expands the established GLC base of users and the development of novel services.

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 2020 product. The validation results include statistical accuracy assessment, map comparison, and spatial accuracy assessment.

1.3. Content of the document

This document is structured as follows:

- Section 2 details the methods for validating the WorldCover 2020 product. Here, the methods used for statistical accuracy assessments, map comparison, and spatial accuracy are detailed.
- Section 3 details the main results on validation of the WorldCover 2020 product, with details on qualitative map comparisons and statistical accuracy assessment.
- The observed limitations of the WorldCover 2020 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.

In this project, we performed the following steps to provide information on map quality, consistency, and fitness for use:

- **Statistical accuracy assessment** following Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) Land Product Validation (LPV) requirements.
- **Visual comparison** with other products
- **Spatial uncertainty** assessment.

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).

For comparison, we assessed visually two other 10m resolution GLC maps and a 100m resolution Copernicus GLC map. Spatial uncertainty assessment was carried out using more than 200 000 reference data locations. In the following subsection, we detail methods used to conduct the assessments towards the validation of the WorldCover 2020 product.

2.1. Statistical Accuracy Assessment

The statistical accuracy assessment of the WorldCover 2020 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 2020 product meets the requirements of the CEOS WGCV Validation Stage 3, while we also have capabilities to meet the Validation Stage 4 in case the product is updated (Table 1: CEOS WGCV stage 3 and 4 validation requirements http://lpvs.gsfc.nasa.gov/).

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 2020 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 (until 2019).
4. **A multi-purpose** validation data suitable for validating **10m land cover** maps, which allows the validation for WorldCover 2020 product.
5. A dataset containing high-quality **land cover elements** information **at 10m resolution** contributed and reviewed by more than 30 international and regional experts from around the world.
6. The 10m land cover element information fully corresponds to **Sentinel-2 10m 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 2020 product.

2.1.1. 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) allows to carry out a statistical accuracy assessment for each continent with a high level of precision (Tsendbazar et al. 2021). The spatial distribution of the validation sites and (sub)continent divisions are shown in Figure 1.

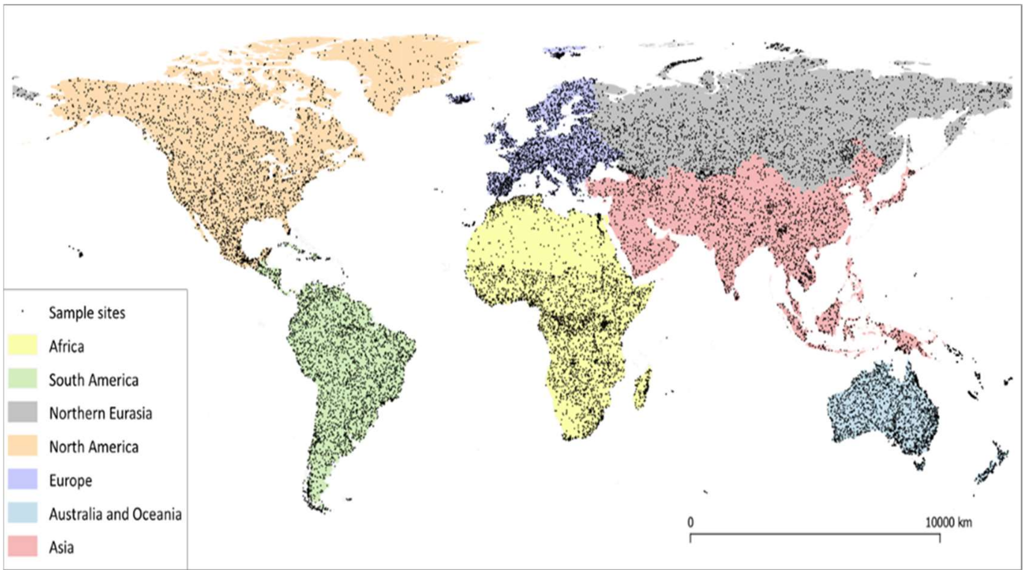

Figure 1: Spatial distribution of all validation sample sites for different (sub) continents

The CGLS-LC validation dataset is multi-purpose data compatible for validating maps with different resolutions and legends. Each PSU (covering an area of 100m × 100m) was divided into 10×10 small blocks (henceforth called SSU: secondary sampling unit). Since the reference land cover elements were collected at 10m × 10m SSU level, the dataset is compatible for assessing land cover maps with 10-100m resolutions. For the thematic representation, the generic land cover elements include trees (phenology and leaf types), shrubs, grass, crops, built-up areas, bare area, lichens/mosses, open water, snow & ice, and regularly flooded areas were recorded at each SSU. 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.

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. (2021).

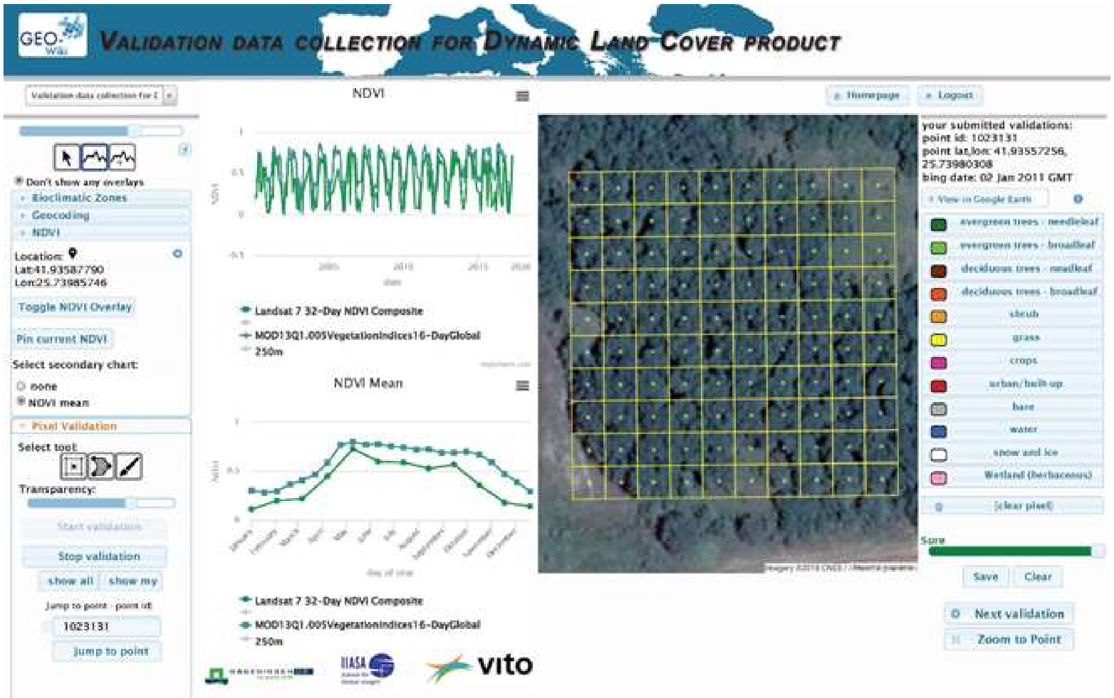

Figure 2: Screenshot of the Geo-Wiki based interface for validation data collection

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 the WorldCover 2020 product

We used the CGLS-LC validation data for the reference year 2019 as input for validating the WorldCover 2020 product. We then updated the validation data for 2020 by following the same revisiting procedure used in Tsendbazar et al. (2021). For this, we randomly revisited 10% of the 2019 validation dataset. Further, we used the BFAST Monitor change detection algorithm to identify validation sites with high possibility of land cover change between 2019 and 2020 (Verbesselt et al. 2010). In total, about 2860 sample sites were revisited and checked for land cover change. In case of a change in land cover since 2019, 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.

To assess the WorldCover 2020 product, we used the SSUs that have an area of 10x10m. All 100 SSUs within a PSU were considered for validating the WorldCover 2020 product. Thematically, the validation dataset is compatible with the legend of the WorldCover 2020 product other than the mangrove class. The validation dataset includes flooded trees and shrubs. We used these sample locations as the mangrove class. In addition, the sample sites that overlap with three mangrove products were visually checked to confirm the locations are indeed mangroves. These datasets are the Global distribution of Mangrove Forests (Giri et al. 2011), the Global Database of Continuous Mangrove Forest Cover for the 21st Century (Hamilton 2015), and the Global Mangrove Watch product (Bunting et al. 2018).

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. 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 10m resolution is considered a high resolution for land cover maps, possible geolocation errors between VHR images (e.g., Google map and Bing map) used for visual interpretation can have an impact on the accuracy of land cover products. In addition, Sentinel-1 and -2 imageries used to produce the WorldCover 2020 product have a geolocation error of approximately one pixel at 10m resolution (Clerc 2021). Therefore, there can be co-registration issues between the WorldCover 2020 product, and the validation data labels.

To account for the possible impact of geolocation errors of the VHR images used for validation data collection and the WorldCover 2020 product, we have filtered out the SSUs that are isolated in terms of land cover. Here, SSUs having the same land cover type with at least two direct neighbours were included and the rest were not included in the validation. In other words, if an SSU with urban land cover type is surrounded by one urban SSU and three trees SSUs as direct neighbours, the said SSU was not included in the validation. This filtering was done to reduce the impact of geolocation errors of VHR images on the validation, as the impact of the geolocation error would be less in a more homogeneous area in terms of land cover. However, considering the potential geolocation errors of the VHR images and the Sentinel-1 and 2 data, this is a conservative approach to deal with the geolocation error issue.

In total, **1 935 650 SSUs** across the world were used for the statistical accuracy estimation of the WorldCover 2020 product.

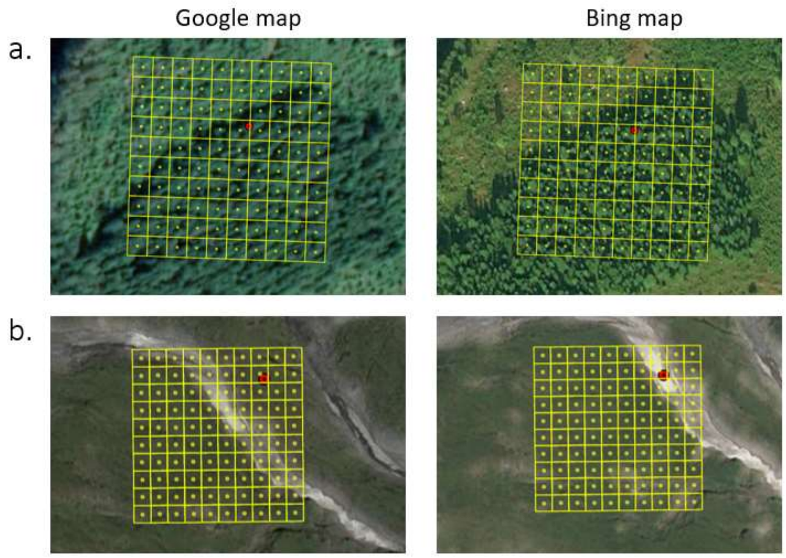

Figure 4. Snippets of validation data locations depicting shifts between the images sourced from Google map and Bing map.

2.1.3. Accuracy estimation of the WorldCover 2020 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).

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. Comparison of GLC maps

2.2.1. GLC products used for comparison

Two available GLC products at 10m were selected for comparison with the WorldCover 2020 product. These are FROM-GLC10 for 2017 and ESRI 2020 GLC maps.

(1) The FROM-GLC10 is a 10m GLC map for the reference year 2017, produced by Tsinghua University, China (Gong et al. 2019). Training data consisted of 340 000 sample units located at around 93 000 sites worldwide. Random Forest algorithm was used to classify Sentinel-2 images acquired in 2017. FROM-GLC10 provides 10 generic land cover classes consisting of cropland, forest, grassland, shrubland, wetland, water, tundra, impervious, barren, and snow/ice. The map has a reported overall accuracy of 72.76% based on an independent

validation dataset consisting of 140 000 sample units at over 33 000 locations. The land cover class definition of this product is included in Table 2.

(2) Esri 2020 Land Cover is a 10 class global land use/land cover map for the year 2020 at 10m resolution (ESRI 2021). This product was recently produced by ESRI in collaboration with Microsoft's Planetary Computer and scaled using Microsoft Azure Batch. The map was produced using Sentinel-2 images acquired in 2020. A deep learning model was trained using 5 billion hand-labelled Sentinel-2 pixels at over 20 000 sites distributed over the world. The map depicts different land use and land cover classes, namely water, trees, grass, flooded vegetation, crops, scrub, built area, bare, and snow/ice class. Using the validation set, the map has a reported overall accuracy of 86% for 8 land cover classes (excluding snow/ice and clouded areas). The land use and land cover class definition of this product is included in Table 3.

Table 2. Definition of land cover types in FROM-GLC10 product that is based on FROM-GLC30 legend (Gong et al. 2013)

Classes	Code	Description
Cropland	10	Land that has clear traits of intensive human activity. It varies from bare field, seeding, crop growing to harvesting. Fruit trees are classified into forests. Pasture could be transitional from croplands to natural grasslands. Lands for rice cultivation, arable and tillage lands, greenhouse farming.
Forest	20	Trees observable in the landscape from the images. Parcels planted with fruit trees or shrubs: single or mixed fruit species, fruit trees associated with permanently grassed surfaces. Tree cover percentage classification to >15% and tree height classification to >3 m
Grasslands	30	Grasslands for grazing as well as natural grasslands. Herbaceous cover percentage classification >15%
Shrublands	40	Shrub cover identifiable in the image. Has a texture finer than tree canopies but coarser than grasslands. With height between 0.3-5m and cover percentage >15%.
Wetlands	50	Marshlands with distinctively high reflectivity in the NIR band. Low relief areas with perched bogs, playas, and patholes may also be included. Forested wetland is not included. Aquatic and hydrophytic herbaceous plants.
Waterbodies	60	All inland waterbodies. Patches of fish ponds are included in this category. Natural or dammed water bodies, natural or artificial water-courses serving as water drainage channels and salinity water
Tundra	70	Located at high mountains above tree line and high latitude regions with low height vegetation. The growing season is between 1 and 2 months. Dominated by low shrubs, grasses, lichens, and mosses at the background as well as various sedges and forbs.
Impervious	80	Primarily based on artificial cover such as asphalt, concrete, sand and stone, bricks, glasses, and other cover materials. Impervious road cover with high albedo materials as well as Impervious roof tops covered by low albedo materials (e.g. asphalts, black shingles).
Barren Land	90	Lands not covered by vegetation or vegetation is hardly observable but dominated by exposed soil, sand, gravel, and rock backgrounds. Dry salt flats occurring on the flat floored bottoms of interior desert basins; Sandy areas composed primarily of dunes; gravel land and bare rocks; other types of land not covered by vegetation such as lake/river bottoms in dry season.
Snow and ice	100	Distributed in the polar areas and high mountains. Lands under perennial or non-perennial ice or snow cover.

Table 3. Land use/cover class definitions of the Esri 2020 Land Cover

Land cover types	Code	Definition
Water	1	Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.

Trees	2	Any significant clustering of tall (~15-m or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).
Grass	3	Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures.
Flooded vegetation	4	Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.
Crops	5	Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.
Scrub/shrub	6	Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs, and tufts of grass, savannas with very sparse grasses, trees or other plants
Built Area	7	Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.
Bare ground	8	Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.
Snow/ice	9	Large homogenous areas of permanent snow or ice, typically only in mountain areas or highest latitudes; examples: glaciers, permanent snowpack, snow fields.
Clouds	10	No land cover information due to persistent cloud cover.

As detailed in Table 2 and Table 3, both the maps depict the GLC at 9-10 general land cover types which are mostly in line with the class definition of the WorldCover 2020 product. However, there are also discrepancies between the products in terms of the thematic definition of the land cover/ land use definitions. Overall, the FROM-GLC10 map has a more similar thematic representation to the WorldCover 2020 product as this map is based on the LCCS. The main discrepancies are the tundra class of the FROM-GLC10 map (Table 2) which is a mix of shrubs, grass, and lichen classes in the WorldCover 2020 product. Similarly, greenhouse farming is included in crop class while this type of area is included in the “built-up” class of WorldCover 2020 as per the land cover type definition.

The Esri 2020 Land Cover has discrepancies with the WorldCover 2020 product in terms of the thematic representations. Firstly, the flooded vegetation class includes rice paddies and irrigated /inundated agriculture. This type of cropland is included in the cropland class of the WorldCover 2020 product. Secondly, the scrub/shrub class includes clusters of plants that are dispersed over an area without any specification of cover percentage. The clusters of plants can be bushes, shrubs, and tufts of grass. The latter is included in the grassland class of the WorldCover 2020 product. Third, mangroves are included in both trees and flooded vegetation, which makes the land cover types not mutually exclusive.

Regardless of the discrepancies, both the products are at 10m resolution and temporally similar to the WorldCover 2020 product. Therefore, these two products were visually compared with the WorldCover 2020 product.

In addition, we visually compared the WorldCover 2020 product with the 100m resolution CGLS-LC 2019 product (Buchhorn et al. 2020). The CGLS-LC100 2019 product is a GLC map produced by the CGLS (Buchhorn et al. 2020). This product is at 100m resolution, depicting 10 land cover types at a generic level (Level 1), with further detailed classes related to tree cover at Level 2. The product is based on the Proba-V satellite data.

2.2.2. Visual comparison

We compared the WorldCover 2020 product visually with Google Earth VHR images and the two 10m resolution GLC products (e.g. FROM-GLC10 and Esri 2020 Land Cover). The FROM-GLC10 map was downloaded from http://data.ess.tsinghua.edu.cn. The Esri 2020 Land Cover product was accessed from the Living Atlas of ESRI.
Next, a visual comparison of the WorldCover 2020 product with the CGLS-LC100 2019 product was also done (https://lcviewer.vito.be/2019).

2.3. Spatial accuracy assessment

Spatially explicit accuracy estimates of land cover products are of considerable value for user communities in various fields, from biodiversity to agricultural monitoring. Well-known accuracy values such as kappa, or overall accuracy give a general idea of the thematic accuracy of the map, but don't provide information on the spatial differences in map quality. Spatial accuracy estimates, however, inform users regarding the degree of uncertainty in land cover mapping across space, thus building confidence in using different land cover products. From a user's perspective, these spatially explicit accuracy estimates help when comparing different land cover products in order to choose the best product for a region of interest.

2.3.1. Definition and input data sets

We define spatial accuracy as a probability that a map is correct in a certain area. The map is considered to be correct if it is in agreement with a reference data set, which is assumed to be the truth.

To calculate a spatial accuracy layer of the WorldCover 2020 map, we aggregated the map to a 100m resolution for two reasons, (1) adjust to spatial parameters of the reference data set; (2) minimise computational resources. The size and quality of the reference data set are very important. Therefore, we collected the reference data set from the most reliable sources, taking into account temporal and thematic consistency. The reference data set includes the validation data set, used for the statistical validation (section 2.1); the CGLOPS training data set at 100m (Buchhorn et al. 2020); CrowdVal reference data set for a few African countries (IIASA 2019), and additionally collected data for Greenland and the most famous desert areas. The reference data set has its limitations that should be considered while interpreting the spatial accuracy layer. The first limitation is that majority of the data has been collected for the year 2015 but the validated map is for the year 2020. The second limitation is that the CGLOPS training data set has been used in map production. However, in the map production, the CGLOPS data has been used at 10m resolution, it has been filtered and modified following a set of rules (described in the product user manual). So, it differs from the original data at 100m but, anyway, it adds some positive bias while interpreting the spatial accuracy layer. The agreement between the reference data set and the WorldCover 2020 product is 72% (independent validation accuracy is above 74%), which shows that the mentioned above bias is small. Also, during a visual inspection, we found that the CGLOPS data contributed a lot to mapping uncertainty hotspots (or low accuracy areas), due to its higher density compared with other sources of data.

The reference data set consisted of 203 073 sample sites at 100m resolution.

2.3.2. Geographically weighted logistic regression

To develop a spatial accuracy layer, we applied a geographically weighted logistic regression (GWR) since it is computationally less expensive than other approaches (e.g. kriging). Logistic regression is a commonly-used classification method and is a generalised linear model employed when the response variable is binary. GWR estimates model parameters at each geographical location by using a distance weighted kernel, so that the observations closer to the studied location have more influence on the parameter estimates than the observations further away (Fotheringham 2002). GWR was developed by Brunsdon et al. (1998) as a spatial statistical method that allows regression parameters to vary over space.

As input data, binary information if the map agrees with the reference data was used; as a search radius, an adaptive moving kernel was applied, searching for 100 nearest neighbours, which is the minimum number of observations required to calculate logistic regression. The calculations were done for a 1-degree grid. The resolution of the grid depends on reference data set density. In our case, the search radius of 100 nearest neighbour corresponds to a distance of a few degrees. This means that calculations at finer resolutions do not provide users with more information. All calculations have been done in R statistical environment, using such packages as spgwr, sp, and raster.

3. Results

3.1. Statistical Accuracy Assessment

Overall accuracy estimates of the WorldCover 2020 product can be found in Table 4. On a global scale, using 1.93 million SSUs at 21 624 PSU locations, the overall map accuracy was 74.4±0.1.

In terms of class-specific accuracies, tree cover and 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 lower accuracies.

In general, at the global scale, there was a slight underestimation of moss and lichen and grassland class while a slight overestimation of trees was observed when comparing against the validation dataset.

Table 4: Confusion matrix (%) for the WorldCover 2020 product at a global scale, corrected by sample inclusion probabilities.

	Tree cover	**Shrubland**	**Grassland**	**Cropland**	**Built-up**	**Bare / sparse veg**	**Snow & ice**	**Permanent water bodies**	**Herbaceous wetland**	**Mangroves**	**Moss and Lichen**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**25.5**	2.1	3.0	0.4	0.1	0.1		0.1	0.1	0.0.	0.1	31.5	**80.8**	0.1
Shrubland	1.5	**3.3**	2.9	0.2	0.0	0.6	0.0	0.0	0.0	0.0	0.0	8.6	**38.6**	0.3
Grassland	1.0	1.6	**16.2**	1.3	0.0	1.8	0.0	0.1	0.4	0.0	0.9	23.4	**69.3**	0.2
Cropland	0.2	0.1	1.2	**7.5**	0.0.	0.1		0.0	0.1	0.0		9.2	**81.1**	0.2
Built-up	0.0	0.0	0.1	0.0	**0.5**	0.1		0.0	0.0			0.7	**67.7**	0.9
Bare / sparse vegetation	0.1	0.2	1.1	0.3	0.1	**15.1**	0.0	0.1	0.0	0.0	0.3	17.3	**87.5**	0.2
Snow & ice			0.0			0.1	**2.2**	0.0			0.0	2.4	**93.9**	0.2
Permanent water bodies	0.0	0.0	0.0	0.0	0.0	0.1	0.0	**2.3**	0.0	0.0	0.1	2.6	**88.5**	0.3
Herbaceous wetland	0.0	0.1	0.6	0.0	0.0	0.0		0.1	**0.5**	0.0	0.4	1.7	**27.8**	0.5
Mangroves	0.0	0.0	0.0			0.0		0.0	0.0	**0.1**		0.1	**68.6**	1.9
Moss and Lichen	0.0	0.1	0.7	0.0		0.4	0.0	0.0	0.0		**1.2**	2.5	**48.6**	0.5
Total	28.3	7.5	25.8	9.7	0.7	18.6	2.3	2.7	1.2	0.1	3.1	**100.0**		
Producer's accuracy	**89.9**	**44.1**	**63.0**	**76.7**	**67.9**	**81.4**	**97.9**	**85.0**	**40.6**	**51.5**	**40.0**		**74.4**	
Confidence interval ±	0.1	0.3	0.2	0.2	0.8	0.2	0.1	0.3	0.7	1.9	0.5			0.1

The accuracy of the WorldCover 2020 product at the continental level is listed in Table 5. Generally, most continents had accuracies around 70% or above, except Oceania. The overall accuracy was highest for Asia (80.7%) followed by South America, Europe, and Africa. The lower accuracy for Oceania could be due to high shrubland and grassland confusions in the open shrublands of Australia.

Table 5: Overall accuracy for the WorldCover 2020 product at the continental level and sample sites used (SSU- secondary sample units, PSU – primary sample units)

	Overall accuracy	Total SSU	Total PSU
Global	74.4 ± 0.1	1,935,650	21,624
Africa	73.6 ± 0.2	313,709	3,599
Europe	76.8 ± 0.2	282,703	3,118
Eurasia	70.2 ± 0.2	274,280	3,003
Asia	80.7 ± 0.1	284,481	3,064
Oceania	67.5 ± 0.2	248,205	2,961
North America	72.2 ± 0.2	258,486	2,880
South America	76.1 ± 0.2	273,786	2,999

The class-specific accuracies and the confusion matrices for each continent are listed in Tables 6-12. 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 had a higher omission error than commission error.

Cropland class was mapped with higher accuracies for all the continents except Africa where this class had higher omission error. In Africa, the cropland class was mostly confused with the grassland class. Mangroves class was mapped with moderate accuracies for continents in which this class has a presence. In South America and North America, this class tended to have higher omission errors than commission errors.

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 was tended to be omitted. 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 class. In contrast, in Europe where bare/sparse vegetation does not cover large areas, this class was mapped with lower accuracies.

3.2. Visual comparison with existing products.

<u>Comparison with 10m products.</u>

The WorldCover 2020 product has been visually compared with other 10m products namely: FROM-GLC10, Esri 2020 landcover, and VHR images of Google Earth. For easy visual comparison, the legends of the Esri 2020 landcover and FROM-GLC10 products were adapted to match the legend of the WorldCover 2020 product (Figure 5).

Figure 5 The legend of the WorldCover 2020 product

Built-up area

Figure 6 depicts the visual comparison of two urban areas, parts of New York and Singapore. In this comparison, it was clear that both the WorldCover 2020 and the FROM-GLC10 had a higher level of detail compared to the Esri 2020 landcover product. It was for instance possible to detect multiple green areas (tree and grass cover) within the cities and to identify linear features such as bridges when using these two products. However, when comparing the WorldCover 2020 and the FROM-GLC10 products it was noticeable that there have been some misclassifications within the FROM-GLC10 product. There has been a misclassification of water bodies within the city of New York which should have been built-up areas and around Singapore airport, there has been an overestimation of cropland. Better urban /built-up characterization of the WorldCover 2020 product compared with the FROM-GLC product might be related to the use of Sentinel-1 data in the WorldCover 2020 product generation.

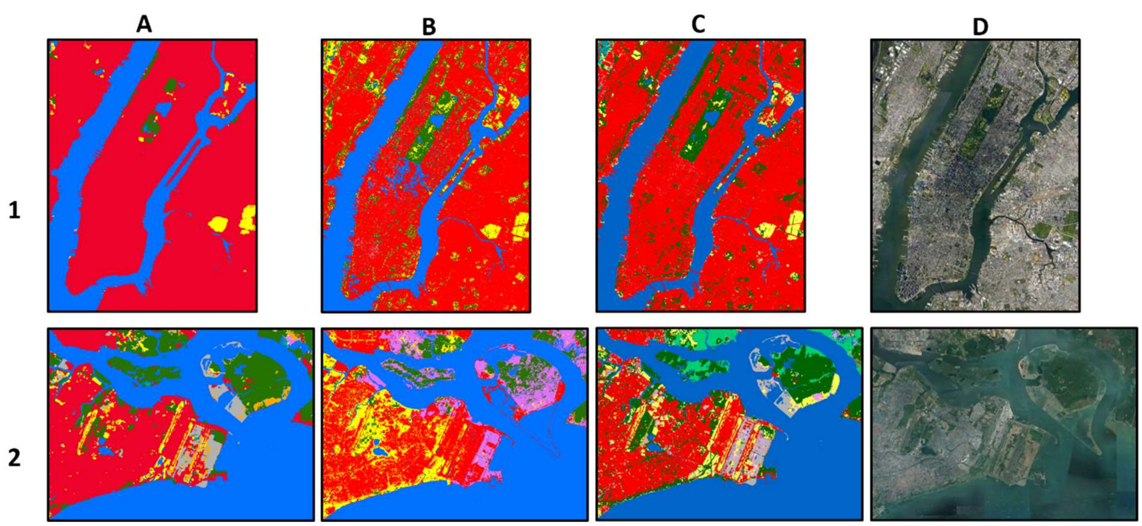

Figure 6 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C), and Google Earth (D) for urban areas. 1. New York City (Coordinates: 40°46'26.86"N 73°58'20.57"W), 2. Singapore (Coordinates: 1°22'18.0"N 103°57'22.2"E), see Figure 5 for legend

Wetlands

The visual comparison of wetlands in Figure 7 showed the difference between the products. It showed again a higher level of detail in the WorldCover 2020 and the FROM-GLC10 products compared to the other 10m resolution product; the Esri 2020 landcover. However, the FROM-GLC10 product did mostly classify wetland areas as grassland and very little with the wetlands class. Overall, the WorldCover 2020 product was able to detect more accurately the wetland areas within the depicted locations.

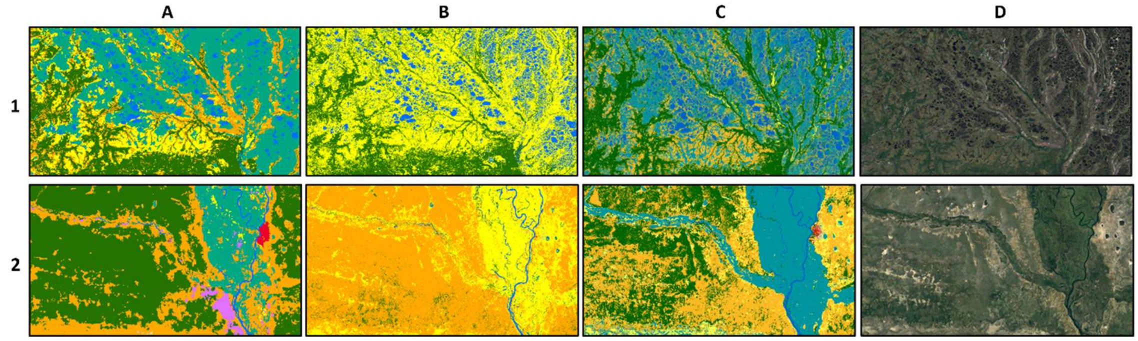

Figure 7 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C) and Google Earth (D) for wetland areas.1.Russia (Coordinates: 62°20'46.6"N 69°23'26.3"E) 2. Zambia (Coordinates: 16°09'24.2"S 23°14'12.5"E), see Figure 5 for legend

Mangrove/tree cover

The comparison made in Figure 8 focused on the classification of mangroves and tree cover. At the first location (the Rajang river delta, Malaysia) there were large differences visible between the products. This area is characterized by palm oil plantations as can be seen on the VHR image (Figure 8D). The Esri 2020 landcover product identified some plantations as cropland and others as trees. The FROM-GLC10 product characterized the majority of the area as cropland, whereas the WorldCover 2020 product classified it as tree cover. The differences in the products were mainly related to class definitions; Esri 2020 landcover classified oil palms as crops and others as trees.

The second locations depict the mangrove area near Nieuw Nickerie in Suriname. The higher level of detail of the WorldCover 2020 and the FROM-GLC10 products was again clearly visible. However, both the WorldCover 2020 and Esri 2020 landcover showed more accurately the presence of mangroves. The separate mangrove class from the WorldCover 2020 provides the user with additional information regarding the type of vegetation compared to the flooded vegetation or trees classes used in the Esri 2020 landcover product.

The third location shows a forested area in Western Australia. The largest difference between the products was the depicted forested area. The FROM-GLC10 product showed a smaller forest area than the other two land cover products. When comparing this with the satellite image it showed that the FROM-GLC10 product underestimated the forested area.

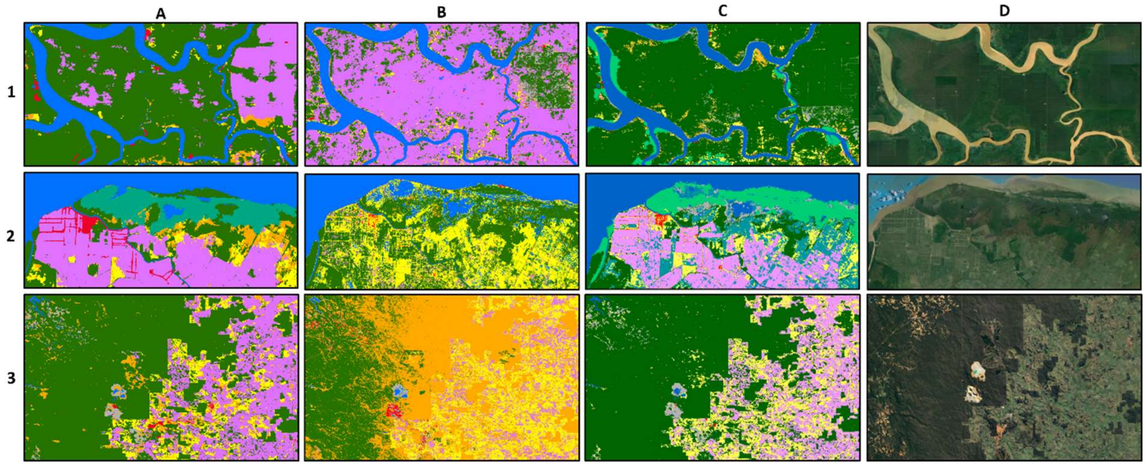

Figure 8 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C) and Google Earth (D) for areas with tree cover/ mangrove. 1. Malaysia (Coordinates: 2°24'36.8"N 111°31'00.1"E) 2. Suriname (Coordinates: 5°52'38.6"N 56°53'30.7"W) 3. Australia (Coordinates: 32°47'07.9"S 116°37'42.0"E), see Figure 5 for legend

Grassland and shrubs areas

Figure 9 shows a recurring pattern within the products when visualising shrubs, grassland and bare areas. The Esri 2020 landcover product identified much of the area as shrubs where the WorldCover 2020 and FROM-GLC10 classified these areas as a combination of bare/sparse vegetation and grassland. The WorldCover 2020 product overestimated the extent of grassland in these areas slightly. There was sparse vegetation visible in these areas during some of the months, however likely not to the extent which is currently visualized. In general, the Esri 2020 landcover product identified vast areas of grassland such as in Mongolian Steppe and Patagonia as shrubs or scrubs. Although this class includes some grass areas, it is still a large overestimation of this class.

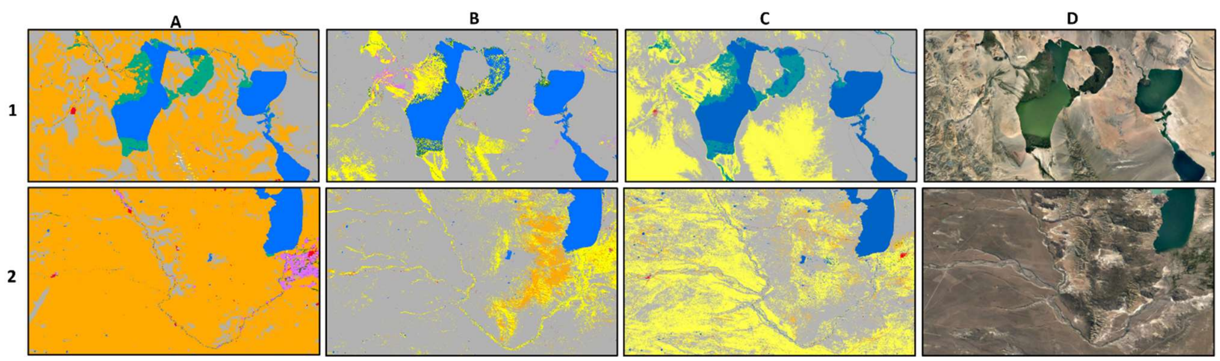

Figure 9 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C) and Google Earth (D) for dryland areas. 1. Mongolia (Coordinates: 48°02'26.6"N 92°35'13.0"E) 2. Argentinia (Coordinates: 45°47'27.8"S 69°30'28.6"W), see Figure 5 for legend

Cropland

Figure 10 shows two agricultural areas, one in the USA and the other one in Uganda. The Esri 2020 landcover product categorized most of the area as cropland, with additional in both examples an overestimation of built-up area. Both the WorldCover 2020 and the FROM-GLC10 products provided a level of detail that enabled the recognition of individual agricultural plots. For the example of the USA, it was possible to identify center pivot irrigation activities. The WorldCover 2020 product identified more tree cover, which represents orchards in this case, than the other 10m resolution

products. The FROM-GLC10 product did identify a few plots with orchards as tree cover but classified most as cropland.
For the location in Uganda, there has been an overestimation of tree cover in the region and an underestimation of cropland for the WorldCover 2020 product.

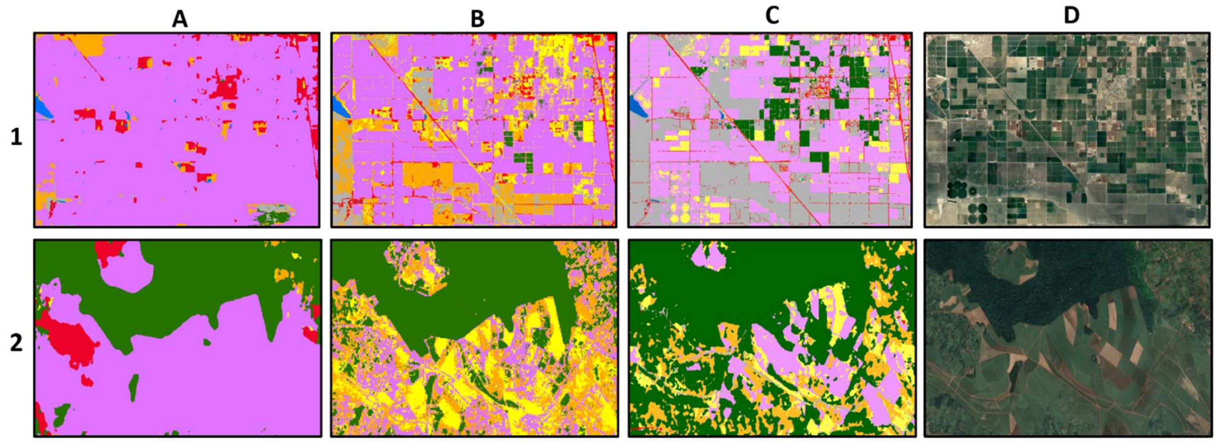

Figure 10 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C) and Google Earth (D) for cropland areas. 1. USA (Coordinates: 35°11'41.5"N 119°06'20.8"W) 2.Uganda (Coordinates: 0°22'20.9"N 33°00'19.4"E), see Figure 5 for legend

Snow/Ice

There was a main agreement among the 10m resolution products on the snow/ice cover in the region of Jostedalsbreen National Park displayed in Figure 11. The WorldCover 2020 and FROM-GLC10 products provided more details regarding the edges of the snow and ice area, with the tundra class.

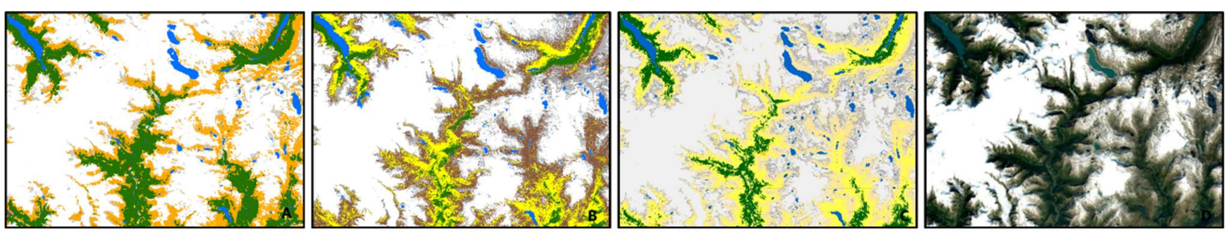

Figure 11 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C), and Google Earth (D) for a snow/ice area in Jostedalsbreen National Park, Norway. (Coordinates: 61°43'59.9"N 7°18'19.3"E), see Figure 5 for legend

Waterbody/salt lake

Figure 12 shows an example of a salt lake. The 10m resolution products all gave a different interpretation of the presence of water, where the FROM-GLC10 indicated the largest water area. The Esri 2020 landcover and WorldCover 2020 gave a more accurate representation of the actual situation.

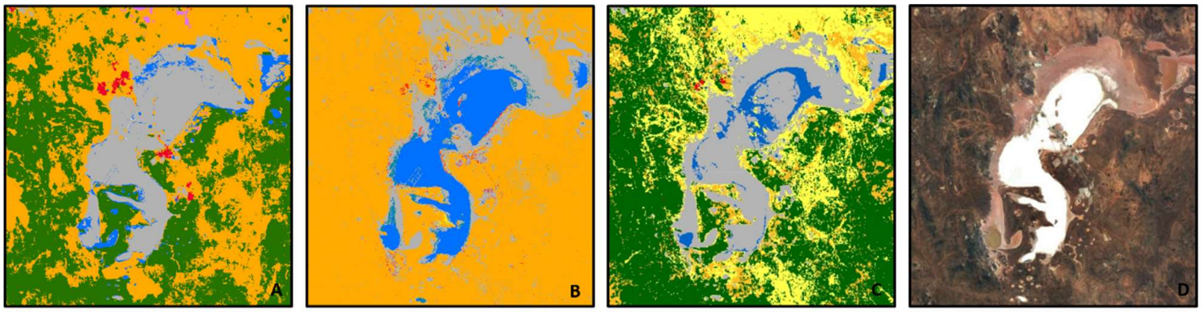

Figure 12 Comparison of Esri 2020 landcover (A), FROM-GLC10 (B), WorldCover 2020 (C), and Google Earth (D) for Lake Lefroy, Australia. (Coordinates: 31°18'46.5"S 121°43'30.1"E), see Figure 5 for legend

To summarize, the visual comparison between three 10m resolution GLC maps revealed a depiction of a high level of details with land cover characterization in the WorldCover 2020 and the FROM-GLC10 products as compared with the ESRI 2020 LandCover product. The WorldCover 2020 and FROM-GLC product were in agreement with characterizing main land cover types, however, the WorldCover 2020 product performed better in areas such as Australia and Oceania. Regarding the ESRI 2020 LandCover product, although this product depicts land cover at 10m resolution, the level of details was less compared to the other two products.
Note that this visual comparison is not a spatially explicit comparison of the WorldCover 2020 product with other products, as the comparison was done for a limited number of examples. As such the examples used for visual comparison may not capture all the strengths and weaknesses of the WorldCover 2020 product, compared with the other two 10m resolution maps.

<u>Comparison with a 100m resolution product</u>
The WorldCover 2020 product was visually compared with the CGLS-LC100m 2019 map. Figure 13 shows four visual examples for comparison. The legend colours of the two maps are the same. As can be seen in Figure 13, with the 10m resolution of the WorldCover 2020 product, the landscapes were mapped in great detail. Areas with fragmented forest stands, cities, and areas with linear objects such as roads and rivers were mapped in greater detail in the WorldCover 2020 product. Figure 13 A exemplifies the level of details with the WorldCover 2020 depicted as opposed to the CGLS-LC100 2019 map at 100m resolution.

Next, compared with the CGLS-LC100 2019 map, the WorldCover 2020 product better-depicted wetland areas (Figure 13B and C). The CGLS-LC100 2019 map had less area as wetlands near the Camargue National Park and Montpellier, while the WorldCover 2020 product mapped more areas as wetlands. In Figure 13B, the CGLS-LC100 2019 map depicted shrubland areas in surrounding Montpelier city in France. When compared visually, the WorldCover 2020 product corresponded better with the VHR images of Google as there are more grassland and cropland areas rather than shrubs.

Mangrove areas near Port Harcourt of Nigeria were mapped as herbaceous wetland in the CGLS-LC100 2019, while this area was correctly mapped in the WorldCover 2020 as mangroves (legend colour-aquamarine)(Figure 13C). In areas east of Port Harcourt city, cropland areas were mapped correctly in the CGLS-LC100 2019 product. This area was mapped as mostly grassland in the WorldCover 2020 product. As was observed in the statistical validation of the WorldCover 2020 product (Table 6), the WorldCover 2020 product tended to underestimate cropland with higher confusion with grassland class.
Similarly, in Figure 13D, in areas west of Maracaibo of Venezuela, cropland areas were correctly mapped in the CGLS-LC100, in contrast, the WorldCover 2020 product mapped this area as mostly

grassland. However, the WorldCover 2020 product provided a better characterization of other land cover types such as urban and more detailed forest area depictions.

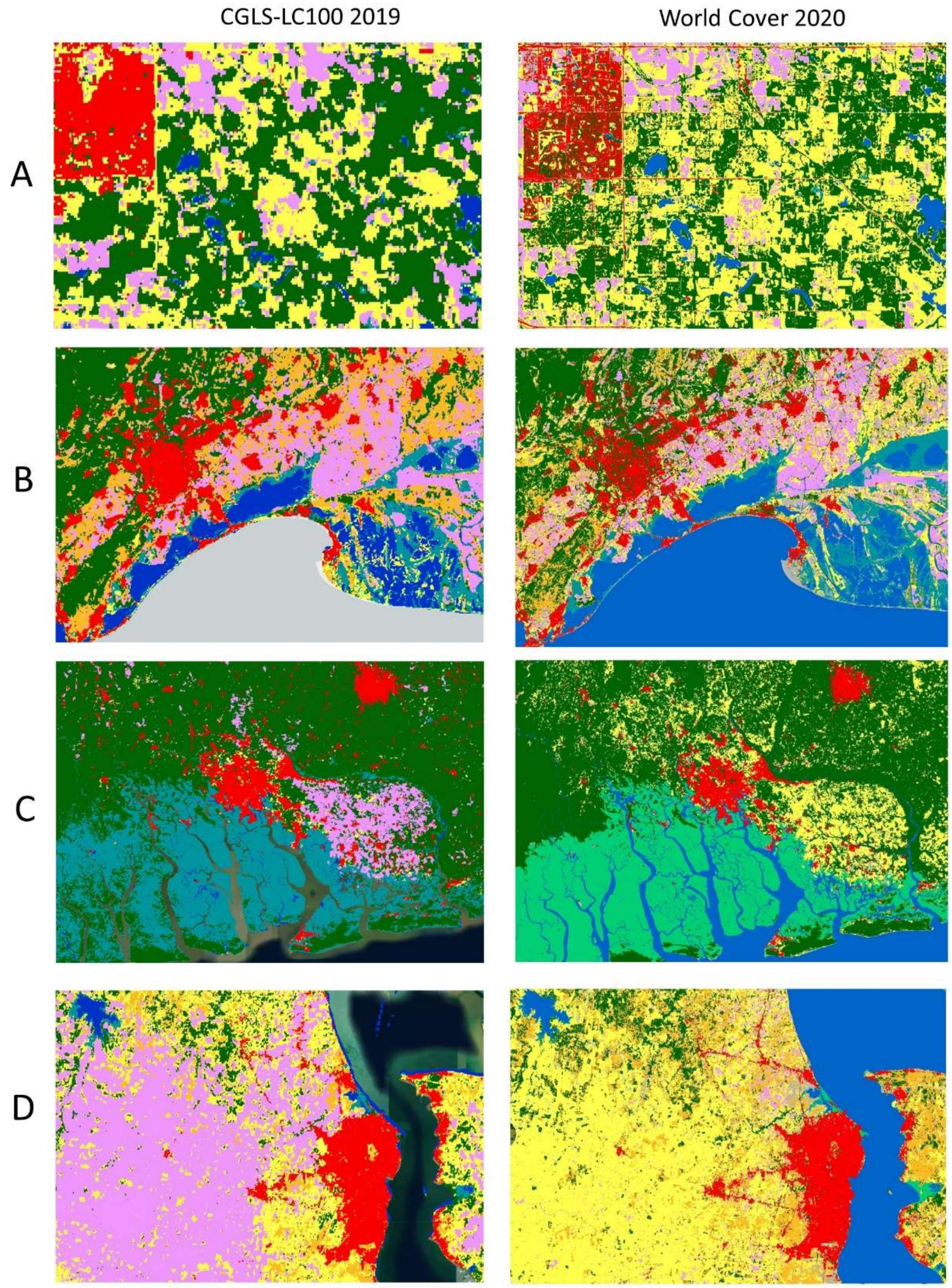

Figure 13. Comparison of the CGLS-LC100 2019 and WorldCover 2020 products (A: Area east of Edmonton, Canada, B: Montpellier and surroundings in France, C: Port Harcourt, Nigeria, D. Area west of Maracaibo, Venezuela), see Figure 5 for legend

3.3. Spatial accuracy assessment

Figure 14 gives more detailed information on the quality of the WorldCover 2020 product compared to the confusion matrices at the continental level (Table 6-12). It illustrates the spatial accuracy layer calculated for the WorldCover 2020 product, aggregated to 100m resolution. The layer provides information on the overall agreement between the map and the reference data set and highlights the most uncertain areas. This agreement has been calculated as a probability that the map agrees with the reference data set, with values ranging from 0 to 99.

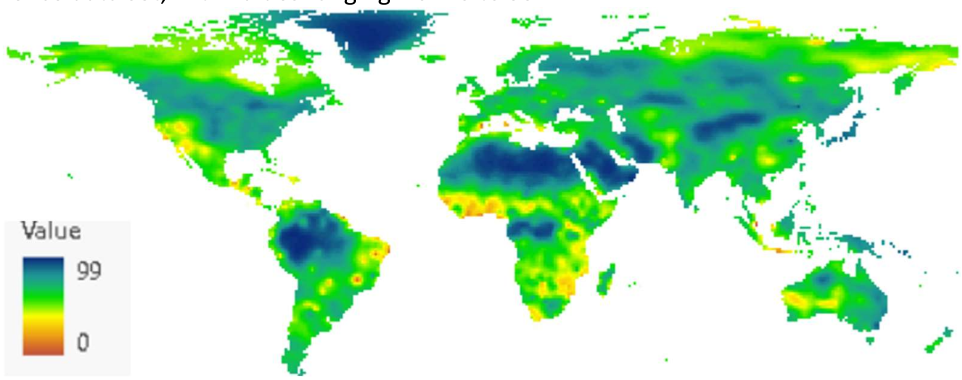

Figure 14 Spatial accuracy layer. Note: results are highly driven by the input reference data set and may not capture all the mistakes

By analysing the spatial accuracy layer, users would see that the map has issues in the following areas:

- In Russia, there is high confusion between lichens and bare, and lichens and grassland.
- In Canada, wetlands are considerably underestimated and there is one artefact (Figure 15).
- In the USA, there is confusion between tree cover and shrubs, as well as, bare land and shrubs.
- In Central America, wetlands are underestimated.
- In Brazil, croplands are underestimated
- In Argentina, confusion between tree cover and shrubs
- The problematic areas in Africa are well known. Those are very fragmented areas, with mixed croplands, tree cover, and shrubs.
- In Europe, issues with shrubs and tree cover delineation (Table 7).
- In Indonesia, issues related to the delineation of tree cover and shrubs.
- In Australia, confusion between grassland and shrubs, and also bare land and shrubs.

Users should note that the results displayed in Figure 14 are highly driven by the input reference data set and may not capture all the mistakes. To improve it, there is a need to increase the reference data set in size.

4. Limitations

Our statistical validation and visual comparison with other products revealed that the WorldCover 2020 product characterizes the land cover at a global scale with higher quality and good spatial details making use of 10m resolution Sentinel-1 and Sentinel-2 data. However, our assessment also revealed that this product has some limitations which can be tackled in future mapping efforts.

As can be seen in Figure 15, it can also occur that there are some anomalies in the WorldCover 2020 product. Figure 15A, there is a sharp divide between cropland and grassland while similar anomalies can be found in Western Mongolia related to the moss/lichen and grassland classes. Figure 15 C shows sharp boundaries between wetland and grassland classes. These artifacts can be tackled in future mapping efforts.

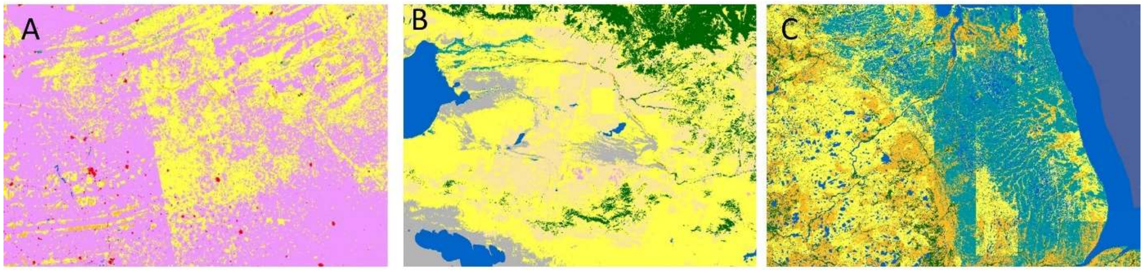

Figure 15 Examples of artefacts in the WorldCover 2020 product with sharp boundaries between land cover types (A) Nigeria -Coordinates: 12°58'05.2"N 8°24'32.6"E; (B) Western Mongolia- Coordinates 50°39'05"N 93°31'32"E; (C) Canada - Coordinates 57°45'40"N 94°10'51"W; see Figure 5 for legend

As identified in the spatial accuracy assessment and continental accuracy estimates, the separation between tree cover and shrubs areas could be improved, particularly the accuracy of the shrubs class is lower for all the continents. Due to the similarity between natural vegetation classes, it is challenging to accurately separate shrublands. Furthermore, underestimation of cropland areas has been noted in South America and Africa due to the challenges in the separation between grasslands and croplands.

Although the comparison with other products revealed improvements in characterizing aquatic land cover types such as mangrove and wetlands, the wetland class was mapped with lower accuracy and this class has been underestimated in Canada and Central America. Since the wetland class is a challenging class due high water dynamics and water influence, further attention can be paid to improve this class, also for improving this class in the training and validation datasets.

The validation of the WorldCover 2020 product was done at 10m resolution. At this high resolution, the geolocation errors of VHR images used for validation data collection and the geolocation errors of the Sentinel-1 and Sentinel-2 data used for map generation can influence the accuracy estimation (Figure 4). We used SSUs that have similar land cover types with at least 2 of their direct neighbours for validating the 10m resolution WorldCover 2020 product. However, further assessments could be done to assess the accuracy of high-resolution products taking into consideration of the possible geolocation errors. For example, accuracy assessments at coarser level e.g., 3x3 SSUs or at the PSU level (100x100m area) could be investigated, next to the 10m resolution assessment.

5. Conclusions

This document reports the validation process of the WorldCover 2020 product. The 10m resolution WorldCover 2020 product depicting the GLC for the year 2020 was validated. 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 2020 product, this validation dataset was updated to the year 2020 by revisiting a random subset of the dataset and the sample sites which have higher possibility of land cover change identified using a time series algorithm, BFAST. This allowed to provide an independent and statistically-robust global and continental accuracy assessment at the time of the release of the WorldCover 2020 map in October 2021.

Our 10m resolution validation showed that the overall accuracy of the WorldCover 2020 product is 74.4 ±0.1%. In terms of land cover types, tree cover and snow/ice, and cropland classes had high accuracies, while shrubs, herbaceous wetland, and moss/lichen classes were mapped with low accuracies. Overall accuracy at the continental level is mostly above 70%, with the highest accuracy of 80.7% for Asia and the lowest accuracy of 67.5% for Oceania. The lower accuracy for Oceania could be due to high shrubland and grassland confusions in the open shrublands of Australia.

Our visual comparison revealed that the WorldCover 2020 and the FROM-GLC products captured landscapes at a higher level of detail than the ESRI 2020 Landcover product. Further, the WorldCover 2020 product had better characterization of land cover in areas such as Australia and Oceania. Compared to the CGLS-LC100 2019 product, the WorldCover 2020 product underestimates cropland in areas such as South America and Africa, which could be focused on future efforts of improving the map characterization.

Spatial accuracy assessment was conducted for the WorldCover 2020 product using more than 200 000 reference data locations to highlights areas that are mapped with good quality and areas that require attention for future efforts.

Overall, the WorldCover 2020 product shows promising results in characterizing the World’s land cover at 10m resolution making use of Sentinel 1 and Sentinel 2 data for the 2020. Users of the map encouraged to make use of the statistical accuracy analysis at global and continental level, and the spatial accuracy assessment to best apply the WorldCover 2020 product for their purposes.

6. References

Brunsdon, C., Fotheringham, S., & Charlton, M. (1998). Geographically Weighted Regression-Modelling Spatial Non-Stationarity. *Journal of the Royal Statistical Society. Series D (The Statistician), 47*, 431-443

Buchhorn, M., Bertels, L., Smets, B., De Roo, B., Lesiv, M., Tsendbazar, N.-E., & Li, L. (2020). *Copernicus Global Land Service: Land Cover 100m: version 3 Globe 2015-2019: Algorithm Theoretical Basis Document*. https://doi.org/10.5281/zenodo.3938968

Bunting, P., Rosenqvist, A., Lucas, R.M., Rebelo, L.-M., Hilarides, L., Thomas, N., Hardy, A., Itoh, T., Shimada, M., & Finlayson, C.M. (2018). The Global Mangrove Watch—A New 2010 Global Baseline of Mangrove Extent. *Remote Sensing, 10*, 1669

Clerc, S. (2021). *Sentinel 2 data product quality reports*.

https://sentinels.copernicus.eu/web/sentinel/data-product-quality-reports

Di Gregorio, A. (2005). *Land cover classification system: classification concepts and user manual: LCCS*. Rome, Italy: Food and Agriculture Organization of the United Nations

ESRI. (2021). *Esri 10-Meter Land Cover*.2021,July 5, https://livingatlas.arcgis.com/landcover/

Fotheringham, A.S.B., C.; Charlton, M. (2002). *Geographically Weighted Regression: The Analysis of Spatially Varying Relationships;* . John Wiley & Sons: Chichester, UK,

Fritz, S., McCallum, I., Schill, C., Perger, C., See, L., Schepaschenko, D., van der Velde, M., Kraxner, F., & Obersteiner, M. (2011). Geo-Wiki: An online platform for improving global land cover. *Environmental Modelling & Software, 31*, 13

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J., & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography, 20*, 154-159

Gong, P., Liu, H., Zhang, M., Li, C., Wang, J., Huang, H., Clinton, N., Ji, L., Li, W., Bai, Y., Chen, B., Xu, B., Zhu, Z., Yuan, C., Ping Suen, H., Guo, J., Xu, N., Li, W., Zhao, Y., Yang, J., Yu, C., Wang, X., Fu, H., Yu, L., Dronova, I., Hui, F., Cheng, X., Shi, X., Xiao, F., Liu, Q., & Song, L. (2019). Stable classification with limited sample: transferring a 30-m resolution sample set collected in 2015 to mapping 10-m resolution global land cover in 2017. *Science Bulletin, 64*, 370-373

Gong, P., Wang, J., Yu, L., Zhao, Y., Zhao, Y., Liang, L., Niu, Z., Huang, X., Fu, H., Liu, S., Li, C., Li, X., Fu, W., Liu, C., Xu, Y., Wang, X., Cheng, Q., Hu, L., Yao, W., Zhang, H., Zhu, P., Zhao, Z., Zhang, H., Zheng, Y., Ji, L., Zhang, Y., Chen, H., Yan, A., Guo, J., Yu, L., Wang, L., Liu, X., Shi, T., Zhu, M., Chen, Y., Yang, G., Tang, P., Xu, B., Giri, C., Clinton, N., Zhu, Z., Chen, J., & Chen, J. (2013). Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. *International Journal of Remote Sensing, 34*, 2607-2654

Hamilton, S. (2015). CGMFC-21, MFW, Global Mangrove Levels by Pixel (~30m), 2000 - 2012. In S. Hamilton (Ed.): Harvard Dataverse

IIASA. (2019). *CrowdVal project*.2021,October 15, https://iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/CrowdVal.html

Olofsson, P., Stehman, S.V., Woodcock, C.E., Sulla-Menashe, D., Sibley, A.M., Newell, J.D., Friedl, M.A., & Herold, M. (2012). A global land-cover validation data set, part I: fundamental design principles. *International Journal of Remote Sensing, 33*, 5768-5788

Pengra, B., Long, J., Dahal, D., Stehman, S.V., & Loveland, T.R. (2015). A global reference database from very high resolution commercial satellite data and methodology for application to Landsat derived 30m continuous field tree cover data. *Remote Sensing of Environment, 165*, 234-248

Stehman, S.V., Wickham, J., Smith, J., & Yang, L. (2003). Thematic accuracy of the 1992 National Land-Cover Data for the eastern United States: Statistical methodology and regional results. *Remote Sensing of Environment, 86*, 500-516

Tsendbazar, N., Herold, M., Li, L., Tarko, A., de Bruin, S., Masiliunas, D., Lesiv, M., Fritz, S., Buchhorn, M., Smets, B., Van De Kerchove, R., & Duerauer, M. (2021). Towards operational validation of annual global land cover maps. *Remote Sensing of Environment, 266*, 112686

Tsendbazar, N.E., Herold, M., de Bruin, S., Lesiv, M., Fritz, S., Van De Kerchove, R., Buchhorn, M., Duerauer, M., Szantoi, Z., & Pekel, J.F. (2018). Developing and applying a multi-purpose land cover validation dataset for Africa. *Remote Sensing of Environment, 219*, 298-309

Verbesselt, J., Hyndman, R., Newnham, G., & Culvenor, D. (2010). Detecting trend and seasonal changes in satellite image time series. *Remote Sensing of Environment, 114*, 106-115

Wickham, J., Stehman, S., Fry, J., Smith, J., & Homer, C. (2010). Thematic accuracy of the NLCD 2001 land cover for the conterminous United States. *Remote Sensing of Environment, 114*, 1286-1296

Annex

Table 6. Confusion matrix (%) for the WorldCover 2020 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	**15.1**	1	1.71	0.39	0.01	0.01	0.03	0.02	0.03	15.1	18.3	**82.6**	0.3
Shrubland	3.9	**7.6**	6.65	0.89		0.75	0.01	0.04	0.01	7.55	19.8	**38.1**	0.6
Grassland	0.71	1.4	**14.7**	2.24	0.01	1.83	0.01	0.48		14.7	21.4	**68.8**	0.5
Cropland	0.14	0.2	1.1	**4.06**	0.01	0.15		0.05		4.06	5.69	**71.4**	0.7
Built-up	0.02		0.18	0.01	**0.27**	0.12				0.27	0.6	**45.5**	2.5
Bare / sparse veg	0.04	0.2	1.06	0.35	0.08	**30.1**	0.05			30.1	31.9	**94.4**	0.3
Permanent water bodies	0.02					0.07	**1.16**	0.03		1.16	1.28	**90.6**	0.9
Herbaceous wetland	0.01		0.22	0.06		0.01	0.03	**0.5**		0.5	0.82	**60.5**	1.9
Mangroves			0.02				0.03	0.02	**0.13**	0.13	0.19	**66.3**	3.5
Correct	15.1	7.6	14.7	4.06	0.27	30.1	1.16	0.5	0.13				
Total	20	10	25.7	7.99	0.38	33.1	1.31	1.14	0.18				
Producer's accuracy	**75.8**	**73.2**	**57.4**	**50.8**	**71.1**	**91.1**	**88.7**	**43.4**	**71.6**			**73.63**	
Confidence interval ±	0.4	0.7	0.5	0.7	3.2	0.3	0.9	1.6	3.4				0.2

Table 7. Confusion matrix (%) for the WorldCover 2020 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	**31.53**	1.86	4.69	0.69	0.5	0.16		0.09	0.05	0.02	31.53	39.58	**79.7**	0.3
Shrubland	0.26	**0.5**	0.71	0.02		0.04					0.5	1.54	**32.7**	1.5
Grassland	1.39	1.12	**16.5**	3.95	0.24	0.63		0.09	0.27	0.53	16.5	24.74	**66.7**	0.4
Cropland	0.22	0.26	1.76	**22.08**	0.03	0.04			0.02		22.08	24.42	**90.4**	0.2
Built-up	0.03		0.13	0.03	**1.72**	0.1					1.72	2	**85.8**	0.9
Bare / sparse veg	0.07	0.09	0.44	0.33	0.17	**0.69**	0.03	0.05		0.07	0.69	1.94	**35.4**	1
Snow and ice						0.11	**0.61**			0.01	0.61	0.74	**83.2**	1.2
Permanent water bodies	0.02		0.03			0.04		**2.37**			2.37	2.47	**96.1**	0.4
Herbaceous wetland	0.01		0.34	0.04		0.01		0.02	**0.26**		0.26	0.71	**37.1**	1.7
Moss and Lichen	0	0.02	0.58			0.6	0.06	0.01	0.02	**0.56**	0.56	1.87	**30.2**	1.3

Correct	31.53	0.5	16.5	22.08	1.72	0.69	0.61	2.37	0.26	0.56				
Total	33.52	3.88	25.17	27.13	2.67	2.42	0.71	2.64	0.64	1.21				
Producer's accuracy	**94.1**	**13.0**	**65.6**	**81.4**	**64.4**	**28.3**	**86.1**	**89.7**	**41.4**	**46.8**			**76.8**	
Confidence interval ±	0.2	0.7	0.4	0.3	1.1	0.9	1.2	0.7	1.9	1.7				0.2

Table 8. Confusion matrix (%) for the WorldCover 2020 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	**32.25**	4.33	5.77	0.05	0.02	0.04		0.15	0.11	0.33	32.25	43.06	**74.9**	0.3
Shrubland	0.13	**0.66**	0.39			0.27			0.03	0.02	0.66	1.5	**44.1**	1.5
Grassland	0.87	1.33	**21.29**	0.69	0.01	1.96		0.08	0.5	2.1	21.29	28.84	**73.8**	0.3
Cropland	0.02	0.01	1.02	**4.94**		0.02			0.04		4.94	6.05	**81.6**	0.6
Built-up	0.01		0.04	0	**0.11**	0.04					0.11	0.2	**55.8**	3.6
Bare / sparse veg	0.01	0.02	0.47	0.02	0.02	**3.82**	0.01	0.06	0.01	0.16	3.82	4.59	**83.2**	0.6
Snow and ice						0.01	**0.2**				0.2	0.21	**95.7**	1.3
Permanent water bodies	0.02		0.04			0.06		**3.39**	0.06	0.08	3.39	3.66	**92.6**	0.5
Herbaceous wetland	0.12	0.26	2.23	0.01		0.04		0.24	**1.24**	1.68	1.24	5.81	**21.3**	0.6
Moss and Lichen	0.08	0.28	2.44			0.87		0.02	0.06	**2.33**	2.33	6.07	**38.4**	0.8
Correct	32.25	0.66	21.29	4.94	0.11	3.82	0.2	3.39	1.24	2.33				
Total	33.49	6.9	33.69	5.72	0.17	7.12	0.21	3.94	2.05	6.71				
Producer's accuracy	**96.3**	**9.6**	**63.2**	**86.3**	**66.2**	**53.6**	**95.1**	**86.0**	**60.4**	**34.8**			**70.23**	
Confidence interval ±	0.1	0.4	0.3	0.6	4	0.6	0.6	0.7	1.4	0.7				0.2

Table 9. Confusion matrix (%) for the WorldCover 2020 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**	**Moss and Lichen**	**Correct**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**24.25**	1.34	2.19	0.93	0.11	0.13		0.09	0.03	0.05		24.25	29.1	**83.3**	0.2
Shrubland	0.2	**0.3**	0.62	0.18	0.01	0.28		0.01	0.01	0.01		0.3	1.61	**18.5**	1.2
Grassland	0.82	0.9	**9.78**	0.9	0.02	1.58		0.04	0.13		0.01	9.78	14.2	**68.9**	0.5
Cropland	0.66	0.13	1.45	**12.77**	0.06	0.37		0.19	0.24	0.01		12.77	15.9	**80.5**	0.4

Built-up	0.07		0.1	0.06	**0.98**	0.19						0.98	1.4	**69.6**	1.4
Bare / sparse veg	0.22	0.38	2.17	0.61	0.23	**30.09**	0.03	0.12	0.06		0.1	30.09	34	**88.5**	0.2
Snow and ice						0.03	**0.37**					0.37	0.4	**91.5**	0.9
Permanent water bodies	0.01		0.01	0.06		0.21		**1.89**	0.02			1.89	2.21	**85.5**	0.8
Herbaceous wetland			0.07	0.05		0.01		0.06	**0.1**			0.1	0.29	**33.5**	2.9
Mangroves	0.03					0.01				**0.13**		0.13	0.18	**72.9**	3.2
Moss and Lichen	0.02	0.02	0.52			0.13	0.01				**0.01**	0.01	0.71	**1.6**	0.5
Correct	24.25	0.3	9.78	12.77	0.98	30.09	0.37	1.89	0.1	0.13	0.01				
Total	26.29	3.07	16.9	15.55	1.41	33.02	0.41	2.41	0.6	0.2	0.1				
Producer's accuracy	**92.3**	**9.7**	**57.9**	**82.1**	**69.1**	**91.1**	**89.9**	**78.7**	**16.1**	**66.4**	**8.1**			**80.7**	
Confidence interval ±	0.2	0.6	0.5	0.4	1.4	0.2	1	0.8	1.5	3.8	2.7				0.1

Table 10. Confusion matrix (%) for the WorldCover 2020 product for Oceania, corrected by sample inclusion probabilities.

	Tree cover	**Shrubland**	**Grassland**	**Cropland**	**Built-up**	**Bare / sparse veg**	**Permanent water bodies**	**Herbaceous wetland**	**Mangroves**	**Moss and Lichen**	**Correct**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**12.1**	1.34	5.98	0.03	0.02	0.22	0.02	0.01	0		12.1	19.72	**61.4**	0.5
Shrubland	1.27	**4.63**	8.23			1.88			0		4.63	16.01	**28.9**	0.8
Grassland	1.14	2.25	**44.14**	0.57	0.03	6.29	0.03	0.13	0	0.06	44.14	54.64	**80. 8**	0.3
Cropland	0.01	0.01	0.61	**3.26**		0.03					3.26	3.92	**83.2**	0.7
Built-up			0.01		**0.1**	0					0.1	0.12	**85.2**	3.3
Bare / sparse veg	0.02	0.06	1.82	0.05	0.01	**2.97**	0.03			0.02	2.97	4.99	**59.6**	1.2
Permanent water bodies	0.01		0.01			0.02	**0.26**	0.01			0.26	0.31	**84.0**	1.9
Herbaceous wetland	0.02	0.01	0.06			0.07		**0.01**			0.01	0.17	**3.5**	0.4
Mangroves			0.01			0.01			**0.05**		0.05	0.07	**69.8**	4
Moss and Lichen										**0.01**	0.01	0.01	**100**	0
Correct	12.1	4.63	44.14	3.26	0.1	2.97	0.26	0.01	0.05	0.01				
Total	14.57	8.3	60.87	3.91	0.16	11.53	0.35	0.16	0.05	0.1				
Producer's accuracy	**83.04**	**55.79**	**72.51**	**83.46**	**61.38**	**25.79**	**75.47**	**3.78**	**88.19**	**5.3**			**67.5**	

Confidence interval ±	0.5	1.1	0.3	0.7	3.8	0.7	2.7	0.4	4.1	2.6				0.2

Table 11. Confusion matrix (%) for the WorldCover 2020 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	**24.07**	2.02	2.65	0.1	0.1	0.11		0.12	0.11		0.18	24.07	29.45	**81.7**	0.3
Shrubland	1.39	**3.11**	1.87	0.02	0.01	0.58		0	0.05	0.01	0.11	3.11	7.15	**43.6**	0.7
Grassland	1.13	2.4	**12.12**	0.94	0.06	0.56		0.15	0.3		3.19	12.12	20.85	**58.1**	0.4
Cropland	0.04	0.01	0.7	**6.75**	0	0.03		0.01	0.02			6.75	7.56	**89.2**	0.4
Built-up	0.03	0	0.08	0.01	**0.44**	0.05						0.44	0.61	**72.7**	2
Bare / sparse veg	0.06	0.32	0.68	0.11	0.07	**4.14**	0.09	0.08	0		1.37	4.14	6.93	**59.8**	0.7
Snow and ice						0.66	**11.76**				0.05	11.76	12.47	**94.3**	0.2
Permanent water bodies	0.02	0	0.06			0.2	0.03	**4.59**	0.06		0.32	4.59	5.28	**87.0**	0.6
Herbaceous wetland	0.03	0.05	0.39	0.06	0	0.04		0.14	**0.44**		0.89	0.44	2.03	**21.5**	0.9
Mangroves								0		**0.02**		0.02	0.02	**77.4**	4.5
Moss and Lichen	0.1	0.16	0.98	0.01		1.44	0.01	0.14	0.04		**4.76**	4.76	7.65	**62.3**	0.7
Correct	24.07	3.11	12.12	6.75	0.44	4.14	11.76	4.59	0.44	0.02	4.76				
Total	26.87	8.09	19.54	7.99	0.68	7.81	11.89	5.23	1.01	0.03	10.87				
Producer's accuracy	**89.6**	**38.5**	**62.1**	**84.5**	**65.3**	**53.1**	**98.9**	**87.7**	**43.2**	**55.6**	**43.8**			**72.21**	
Confidence interval ±	0.2	0.7	0.4	0.5	1.9	0.7	0.1	0.6	1.6	6.1	0.6				0.2

Table 12. Confusion matrix (%) for the WorldCover 2020 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**	**Moss and Lichen**	**Correct**	**Total**	**User's accuracy**	**Confidence interval ±**
Tree cover	**42.1**	3.24	2.1	0.38	0.03	0.14		0.18	0.17	0.14	0.02	42.1	48.52	**86.8**	0.2
Shrubland	1.7	**4.67**	2.47	0.08		0.99			0.05			4.67	9.96	**46.8**	0.7
Grassland	1.24	2.35	**15.38**	1.11	0.03	1.82		0.08	1.04	0.07	0.14	15.38	23.26	**66.1**	0.4
Cropland	0.12	0.06	1.71	**6**	0.01	0.11			0.04			6	8.04	**74.6**	0.6
Built-up	0.01		0.03		**0.26**	0.03						0.26	0.34	**78.0**	2.1
Bare / sparse veg	0.08	0.2	0.72	0.06	0.03	**5.74**	0.07	0.03	0.02			5.74	6.96	**82.4**	0.6
Snow and ice						0.01	**0.15**					0.15	0.16	**92.3**	0.5

Permanent water bodies	0.02	0.01	0.01	0.01		0.14		**1.23**	0.03	0.01		1.23	1.46	**83.9**	1
Herbaceous wetland	0.06	0.04	0.41					0.04	**0.43**	0.08		0.43	1.06	**40.3**	1.8
Mangroves								0.02	0.03	**0.09**		0.09	0.14	**63.6**	3.3
Moss and Lichen		0.02	0.03			0.02					**0.01**	0.01	0.09	**16.0**	5.6
Correct	42.1	4.67	15.38	6	0.26	5.74	0.15	1.23	0.43	0.09	0.01				
Total	45.32	10.6	22.87	7.64	0.37	9.01	0.22	1.58	1.82	0.39	0.19				
Producer's accuracy	**92.9**	**44.0**	**67.3**	**78.5**	**72.2**	**63.7**	**67.2**	**77.7**	**23.5**	**23.4**	**7.1**			**76.1**	
Confidence interval ±	0.1	0.6	0.4	0.5	2.3	0.6	2.4	1.1	1.1	2	2.6				0.2