ISSN 1831-9424

European Commission

Mapping Global Forest Cover of the Year 2020 to Support the EU Regulation on Deforestation-free Supply Chains

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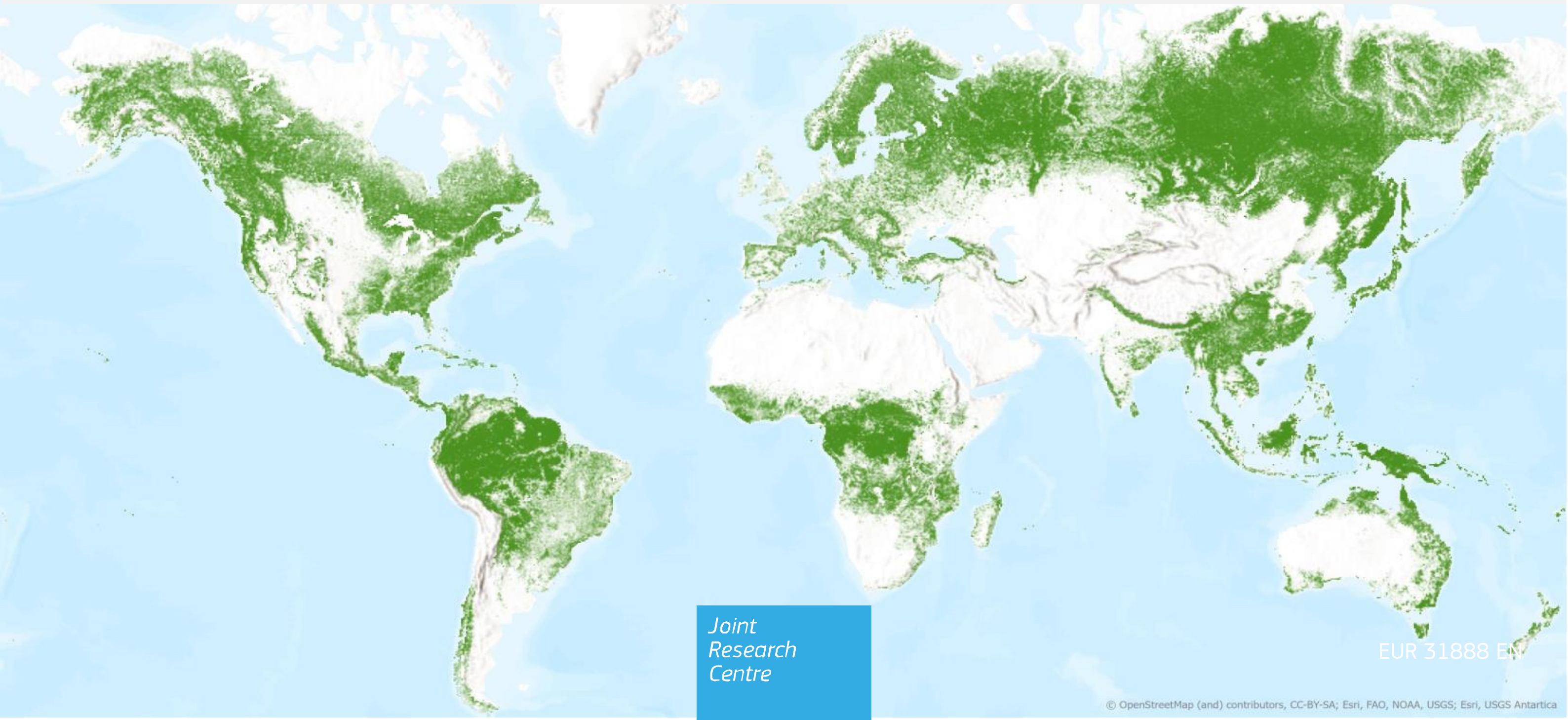

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EU Science Hub

JRC136960

EUR 31888 EN

PDF ISBN 978-92-68-13866-3 ISSN 1831-9424 doi:10.2760/262532 KJ-NA-31-888-EN-N

Luxembourg: Publications Office of the European Union, 2024

How to cite this report: European Commission, Joint Research Centre, Bourgoin, C., Ameztoy, I., Verhegghen, A., Desclée, B., Carboni, S., Bastin, J., Beuchle, R., Brink, A., Defourny, P., Delhez, B., Fritz, S., Gond, V., Herold, M., Lamarche, C., Mansuy, N., Mollicone, D., Oom, D., Peedell, S., San-Miguel, J., Colditz, R. and Achard, F., *Mapping Global Forest Cover of the Year 2020 to Support the EU Regulation on Deforestation-free Supply Chains*, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/262532, JRC136960.

Contents

Abstract

This document presents the input data, methodology and a preliminary assessment of the first version of the Global Forest Cover map for year 2020 at 10m spatial resolution (GFC 2020, version 1, dated 07 December 2023). GFC 2020 builds on several global data sets and provides a harmonized, globally consistent and spatially explicit representation of forest presence and absence for year 2020. The map aims to support the implementation of the EU Regulation on Deforestation-free supply chains. The primary access to GFC 2020 is via the EU Observatory on Deforestation and Forest Degradation.

Foreword

Forests are essential for humankind on Earth. Photosynthesis produces the oxygen we breathe. Trees remove CO_2 from the atmosphere and store huge amounts of carbon in their trunks, roots and soils – a function that is essential to achieve global climate ambitions. Forest ecosystems filter the air and water for pollutants and at the same time are home for a great deal of the flora and fauna. Besides these essential functions for our survival, forest have a significant water retention potential and serve the economy by providing raw materials and food. The social and cultural values of forests – providing the space to relax, regenerate and enjoy – are important for all and essential for some indigenous communities where forests are the place to be born, live and die.

Even though we speak about forests, it remains challenging to define which piece of land is a forest – and which is not. We know that 31% of the land on Earth is forest and deforestation was estimated to be 10 million ha per year during period 2015-2020 (FAO Global Forest Resources Assessment 2020), which is the equivalent to 25 football fields per minute. Despite the means of digitalization and the use of Earth Observation, the mapping of forests – that is the categorization of land where forests are present – is still very difficult and go far beyond mapping of trees. In addition to the national statistics about forest area with long timeseries, we provide maps localizing the presence/absence of forests for any given point of the map.

Under the European Green Deal there are several policies that require or will benefit from an accurate knowledge of forest presence and absence. At international level, the EU Regulation on deforestation-free supply chains (EUDR, Regulation (EU) 2023/1115) sets out rules to ensure that supply chains for key commodities are free of deforestation and forest degradation after 2020. The law requires the geographic location of sourcing areas and the assessment of deforestation and degradation risk from operators and traders, and competent authorities will need to verify a sample of declarations. This regulation can benefit from maps that are accurate and representative for the forest presence in 2020 although there is no obligation for stakeholders to use maps in the implementation of the EUDR. The global forest cover map for the year 2020 at 10m spatial resolution that the JRC has just produced with the support of a few non-JRC scientists is expected to potentially serve operators in the assessment of risk of deforestation when declaring plots of commodities and competent authorities for the sample selection of declarations to be checked with more detailed and robust data.

This global map on forest cover is provided free-of-charge by the Commission as one of many tools that operators can decide to use for the risk assessment. However, this map has a non-mandatory and non-exclusive role (other maps can be used) and is not legally binding (the presence of forest does not necessarily imply non-compliance, nor does the absence of forest imply compliance). This report documents the input data with a global scope and the methodology that were used to produce this new map and a first assessment of its quality. We hope that the map with scientific data helps all key actors to protect the world's forests, the lungs of our planet.

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Acknowledgements

We are grateful for technical support, feedback and comments received during numerous discussion from (in alphabetic order): Audric Bos (Université Catholique de Louvain), Giovanni Caudullo (Arcadia SIT s.r.l.), Thibauld Collet (Université Catholique de Louvain), Paula Veronica Figueiredo Vilar Pires Correia (JRC), Viola Heinrich (GFZ Potsdam), Klara Janouskova (ARHS), Andrea Lupi (Unisystems Luxembourg SARL), Andrea Marelli (Arcadia SIT S.r.l.), Daniela Requena Suarez (GFZ Potsdam), Dario Simonetti (Engineering Ingegneria Informatica S.p.A.), and Timothee Stassin (GFZ Potsdam). We thank Gregoire Dubois and an anonymous reviewer for their valuable comments to improve this report.

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Executive summary

Policy context

The "EU Observatory on Deforestation and Forest Degradation" (Observatory) provides access to global forest maps and spatial forest and forestry-related information and facilitates access to scientific information on supply chains. The Observatory also supports the implementation of the EU Regulation on Deforestation-free supply chains (EUDR) by linking deforestation, forest degradation and changes in the world's forest cover to the European Union's demand for bio-commodities and products. In this context, upon request by DG Environment, the JRC produced a Global Forest Cover map for year 2020 (GFC 2020) at 10m spatial resolution, corresponding to the cut-off date of the EUDR (31 December 2020).

Key conclusions

The GFC 2020 map, version 1 is a distinctive product derived from the combination of most recent, publicly available land cover and land use datasets or related products at fine spatial resolution with a global scope. The definition of forest in the map aligns with the forest definition by the Food and Agriculture Organization that is retained in the EUDR. In the context of the EUDR, the map aims to support operators to evaluate if a commodity under scrutiny (cattle, cocoa, coffee, oil palm, rubber, soya, wood) or a derived product, imported to or exported from the European Union market, was produced in areas that have been subject to deforestation after 2020. The map could also help competent authorities identify areas to carry out checks and tailor their enforcement efforts e.g., by acquiring and interpreting very high spatial resolution imagery.

The map is a harmonized and globally consistent representation of the presence or absence of forests in 2020 at 10m spatial resolution, retaining patches of at least 0.5 hectares. This is a service provided free of charge and publicly available by the European Commission via the Observatory to the global community concerned with gathering information about forest in 2020 or with implementing the EUDR. For due diligence, it is recommended to use GFC 2020 in combination with other forest or land use maps and complementary datasets, in particular at national scale, if existing and available. In the context of the EUDR, it should be noted that the GFC 2020 map has no authoritative status. The use of GFC 2020 is:

- Non-mandatory: There is no obligation for stakeholders, notably operators and competent authorities concerned with the implementation of the EUDR, to use GFC 2020 or any other map.
- Non-exclusive: The map on global forest cover, provided by the European Commission free-of-charge, complements the many cartographic products already available. Other maps may have advantages and the regulation does not prescribe modalities of and for map use.
- Not legally binding: The map is one of many tools that support the implementation of the regulation, notably the risk assessment. When overlaying polygons, the presence of forest in GFC 2020 does not necessarily imply non-compliance, nor does the absence of forest in the map imply compliance. It will be up to the operator to provide compelling evidence for the risk assessment and the competent authorities to carry out detailed and robust compliance checks.

Main findings

The approach aims to achieve a global spatial representation of forest cover for year 2020 by maximizing the value of existing global data layers via a synthesis approach. The methodology was developed and improved over several iterations, testing the usefulness of data sets and tuning parameters to improve the final map. The approach was carefully designed to be flexible and to include additional or revised data sets.

Experts who reviewed the work found the map to be an appropriate spatial representation of forest cover with no major large-scale mapping errors. Dense forests and forest edges in structured landscapes were found to be correctly mapped and delineated. More challenging areas such as dry forest lands, ecotones and complex landscapes with mosaics of degraded forest and agricultural plantations are prone to more frequent mapping errors. Technical artefacts such as stripes are of limited extent.

GFC 2020 may show some discrepancies when compared to regional or national maps for specific commodities addressed under the EUDR, notably for cocoa and coffee and in specific areas for rubber. Meanwhile comparisons with regional maps for oil palm, soy and pasture (as surrogate for cattle) show satisfactory results. The preliminary overall accuracy of the map is estimated at 76% with higher omission than commission errors. However this estimate is indicative and needs to be revisited, as the validation sample set used for this preliminary assessment has a coarser resolution (sample plots of 100m x 100m) and an older date (year 2015).

Related and future JRC work

In 2024, the JRC will undertake a formal statistically and thematically robust accuracy assessment, in cooperation with an international network of scientists. The JRC will initiate work to assess the feasibility of mapping forest degradation with sub-classes of forest cover following the definition of the EUDR. The JRC foresees a second version of the GFC 2020 map available by the end of 2024 before the EUDR will become applicable.

Quick guide

This report describes the input data and methodology used to produce version 1 of the GFC 2020 map. It also includes a preliminary accuracy assessment of this new global map, a qualitative analysis carried out by external reviewers and a quantitative assessment against some existing regional maps for specific commodities.

1 Introduction

In 2019 the European Commission put forward a communication to protect and restore the world's forests (COM 2019). This communication includes, inter alia actions to:

A. "*Assess additional demand side regulatory and non-regulatory measures to ensure a level playing field and a common understanding of deforestation-free supply chains, in order to increase supply chain transparency and minimise the risk of deforestation and forest degradation associated with commodity imports in the EU*"

B. "*Build on the already existing monitoring tools, and establish an EU Observatory on deforestation, forest degradation, changes in the world's forest cover, and associated drivers. The objective of this is to facilitate access to information on supply chains for public entities, consumers and businesses*".

For action A, taking into consideration Council Conclusions from 16 December 2019 (Council 2019) and the Resolution of the European Parliament from 22 October 2020 including recommendations to the European Commission on an EU legal framework (EP 2020), on 17 November 2021 the European Commission proposed a Regulation "*on the making available on the Union market as well as export from the Union of certain commodities and products associated with deforestation and forest degradation*" (COM 2021). After successful negotiations with co-legislators Regulation (EU) 2023/1115 (EU 2023), in the following abbreviated "EUDR", was published on 9 June 2023 in the Official Journal, went into force 20 days later, and is going to become applicable on 30 December 2024. This Regulation lays down rules for seven commodities (cattle, cocoa, coffee, oil palm, rubber, soya, wood) and associated products. Operators need to ensure due diligence, including geographic coordinates about the sourcing location, and assess the risk of deforestation after the cut-off date.

For action B, the Council and the European Parliament welcomed the proposal for an EU Observatory, and inter alia called for no duplication of existing monitoring tools and the creation of an early warning system (Council 2019, EP 2020). On 7 December 2023, the "EU Observatory on Deforestation and Forest Degradation", in the following shortened to "Observatory", became public (COM 2023a). Besides providing access to global forest maps and spatial forest and forestry-related information, the Observatory facilitates access to scientific information on supply chains by linking deforestation, forest degradation and changes in the world's forest cover to the European Union's demand for commodities and products (COM 2023b).

As noted in Recital 31 of the EUDR, the Observatory plays a supporting role in the implementation of this Regulation. To this end, the Observatory includes the Global Forest Cover map for year 2020 (COM 2023c, COM 2023d), in the following abbreviated "GFC 2020", corresponding to the cut-off date as set out in the EUDR (31 December 2020). The map could serve operators in the assessment of risk of deforestation when declaring land parcels by geolocation for commodities and products imported to or exported from the European Union market.

Given the role as supporting - and not authoritative - tool in the context of the EUDR, information provided by the Observatory, including GFC 2020, is non-mandatory, non-exclusive and not legally binding. The latter means that a spatial match or non-match between a due diligence statement and forest in GFC 2020 does neither mean with full confidence that the parcel has been deforested or not been deforested, respectively, since 2020. GFC 2020 may also be used by competent authorities in identifying areas to carry out detailed and robust checks by acquiring and interpreting very high spatial resolution imagery. The objective of this report is to present (i) the data and methodology for GFC 2020 and (ii) a first qualitative evaluation by reviewers with a preliminary accuracy estimate.

2 Data and method

The GFC 2020 map is a harmonized, globally consistent representation for the presence or absence of forest in 2020, at 10m spatial resolution. The approach for identifying forest areas combines existing global wall-to-wall datasets or datasets with a global scope. The workflow does not incorporate local, regional, national, or continental data layers.

2.1 Definitions

The forest definition used in the GFC 2020 map aligns with definitions set out in the EUDR and by the Food and Agriculture Organization (FAO 2018) to the extent of what can be derived from satellite images. Notably, the GFC 2020 map displays predominantly forests with standing trees. Other limitations are linked to the availabilities of global datasets to map agricultural tree plantations or urban vegetation that should be distinguished consistently from forest cover.

Article 2(4) in the EUDR defines forest as:

"*'forest' means land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 %, or trees able to reach those thresholds in situ, excluding land that is predominantly under agricultural or urban land use*;"

Agricultural use and agricultural plantation are defined in Article 2 (5) and 2 (6), respectively, as follows:

- "*'Agricultural use' means the use of land for the purpose of agriculture, including for agricultural plantations and set- aside agricultural areas, and for rearing livestock.*"
- "*'Agricultural plantation' means land with tree stands in agricultural production systems, such as fruit tree plantations, oil palm plantations, olive orchards and agroforestry systems where crops are grown under tree cover; it includes all plantations of relevant commodities other than wood; agricultural plantations are excluded from the definition of 'forest'.*"

In other words, all plantations of relevant commodities other than wood, that is cattle, cocoa, coffee, oil palm, rubber, soya, are excluded from the definition of forest.

2.2 Input datasets

Several recent spatial data sets show the extent of global tree cover presence and change at a spatial resolution of 100m or finer (Brown et al., 2022; Hansen et al., 2013; Lesiv et al., 2022; Zanaga et al., 2022). While such datasets are useful as first layer of information, there is a particular challenge concerning the mapping and monitoring of forests given the fact that not every tree-covered pixel constitutes a forest. The transformation of tree cover status at pixel level, representing the state of the land as observed by Earth Observation systems, to "forest" cover status, as defined under a land use concept and with physical thresholds, requires additional data. There are tree-covered areas that do not meet the minimum crown cover or minimum area requirements or belong to other land uses such as agriculture tree plantations or urban. On the other hand, land used as forests may be temporarily unstocked, e.g. after a forest fire or clear-cut harvest.

Table 1. Descriptive information on the data used.

Dataset name	Dataset abbreviation	Description	Thematic information	Step in workflow	Resolution	Scope	Year	Reference
FAO Global Ecological Zones	FAO GEZ	Global Ecological Zones from FAO. We used the zones of Tropical rain forest, tropical moist deciduous forest, tropical dry forest and tropical mountain system as stratification	Stratification	Step 2	Vector	Global	2010	Global Ecological Zones (second edition)
UMD Drivers of global forest loss	UMD Drivers forest loss	Drivers of forest cover loss. We used the areas of commodity-driven deforestation and shifting agriculture.	Stratification	Step 2	10km	Global	2001-2021	Curtis et al., 2018
ESA World Cover	ESA WC	Tree cover (class 10), mangroves (class 95), and water (class 80) were used from ESA World Cover 2020 and 2021.	Tree cover	Step 1 and 2	10m	Global	2020 (v100), 2021 (v200)	Zanaga et al., 2022, 2021
WRI Tropical Tree Cover	WRI TTC	Tree cover inside and outside forests across the Tropics from WRI.	Tree cover	Step 1	10m	Tropics	2020	Brandt et al., 2023
UMD Global Forest Canopy Height	UMD GFCH	Gridded map of canopy heights from GEDI and Landsat. Used only over the Tropical rain forest ecological zone.	Tree height	Step 2	30m	Global	2019	Potapov et al., 2021
UMD Global land cover and land use	UMD GLC	Global land cover and land use from UMD. Classes of tree cover (classes 53-91 for terra firma and classes 171-211 for wetland) were used for step 1. Classes 252 (cropland), 0-37, 51-52, 120-157, 251 (other land cover) and 240-249 (built-up) were used for step 2.	Land cover	Step 1 and 2	30m	Global	2019	Hansen et al., 2022

Global Mangrove Watch	GMW	Mangrove extent from Global Mangrove Watch, version 3.0.	Land cover	Step 1 and 2	25m (0.8 arc seconds)	Global	2020	Bunting et al., 2022
JRC Tropical Moist Forest	JRC TMF	Transition map and annual change datasets of forest cover change in the humid tropics from JRC. Undisturbed, mangroves and degraded forest (classes 1-2 from Annual Change) along with old regrowth (>10 years old) of year 2020 have priority over masking layers of UMD GFCH (<5m), UMD GFC loss or other land cover from UMD GLC. Deforested land including conversion to agricultural plantations and deforested mangroves (classes 3-4 from Annual Change), and young forest regrowth (<10 years old, class 33 from Transition map) are used as masking layers over the Tropical rain forest ecological zone.	Land cover/use	Step 1 and 2	30m	Tropics	1990-2020	Vancutsem et al., 2021
UMD Global Forest Cover loss	UMD GFC loss	Global forest cover loss from UMD GLAD. All tree cover loss from 2001-2020 over commodity-driven deforestation and shifting agriculture areas (Drivers of forest cover loss) and not overlaying with forest cover loss from fire or with Forest cover from JRC-TMF were considered as masking layer.	Land cover	Step 2	30m	Global	2001-2020	Hansen et al., 2013
UMD Global Forest Cover loss from fire	UMD GFC - fire	Global forest cover loss from fire from UMD GLAD. We used the class forest loss due to other (non-fire) drivers as a stratification for GFC-loss dataset.	Land cover	Step 2	30m	Global	2001-2020	Tyukavina et al., 2022
JRC Global Human Settlement Layer	JRC GHSL	Global human settlement JRC, Built-Up Characteristics (BUILT-C). All values (1-25) were considered as masking layer.	Land cover	Step 2	10m	Global	2018	Pesaresi and Politis, 2023

JRC Global Surface Water	JRC GSW	Classes of permanent water, new permanent water and seasonal to permanent water (1,2 and 7) were used as masking layer only when not overlapping with mangrove area from JRC-TMF (classes 12, 61-64 from Transition map) or GMW. Mask of volcanic areas (lava flows) used to mask tree cover.	Land cover	Step 2 and 3	30m	Global	1990-2020	Pekel et al., 2016
UMD Global Cropland Extension	UMD Cropland	Overlapping extent of cropland mapped in 2003, 2007, 2011, 2015 and 2019 from UMD GLAD.	Land use	Step 2	30m	Global	2003-2019	Potapov et al., 2022
ESA World Cereal	ESA World Cereal	ESA World cereal for cereal crop mapping: temporary crops extent was used as masking layer.	Land use	Step 2	10m	Global	2021	Van Tricht et al., 2023
Oil palm plantation	Oil palm plantation	Industrial and smallholder map of closed-canopy oil palm plantations not overlapping with mangrove area from JRC-TMF or GMW.	Land use	Step 2	10m	Global	2019	Descals et al., 2021
Coconut plantation	Coconut plantation	Closed-canopy coconut palm. Plantation not overlapping with mangrove area from JRC-TMF or GMW.	Land use	Step 2	10m	Global	2020	Descals et al., 2023
WRI Spatial Database of Planted Trees	WRI SDPT	Spatial Database of Planted Trees (version 1.0) differentiating plantation forests from tree crops (stands of perennial tree crops, such as rubber, oil palm, coffee, coconut, cocoa, and orchards) compiled by WRI. Tree crops was used as a masking layer.	Land use	Step 2	Vector	Global	Varies	Harris et al., 2019
IIASA Global Forest Management	IIASA Forest Management	IIASA Forest management map. Only the agroforestry class was used as masking layer when intersecting with forest cover from JRC-TMF and GFC loss.	Land use	Step 2	100m	Global	2015	Lesiv et al., 2022

Source: JRC

We used various types of publicly available datasets on land cover and land use, tree cover and tree height (Table 1). Most datasets are derived from remote sensing with a spatial resolution varying from 10 to 30m. Vector data was also taken into account, if it is global in scope. Most of the data are close to the year 2020 but a few take longer periods into account. Stratification layers on ecological zones from FAO and drivers of global forest loss from the University of Maryland (UMD) were introduced in the workflow to further refine the combination of input datasets.

2.3 Methods

The first step in the workflow consists of mapping the global maximum extent of tree cover circa the year 2020. This step is crucial because areas not identified in the maximum tree cover extent cannot be labelled as forest cover in the following steps (with exception for small areas when applying a minimum mapping unit, see below). In a second step, a series of overlays and Boolean decision rules are applied to reduce this maximum extent of tree cover and align the remaining extent with the forest definition using datasets with a global scope covering tree height, agricultural land use, other land use, water and urban (Figure 1). These two first steps were consolidated through an iterative process involving literature screening of relevant datasets and both internal and external qualitative assessment (see section 2.4.1). In a third step, some corrections reduce confusion errors that are visible in specific areas. Finally, a minimum mapping unit of 0.5 ha is applied to filter isolated pixels. The workflow was fully performed with Google Earth Engine (GEE; Gorelick et al., 2017).

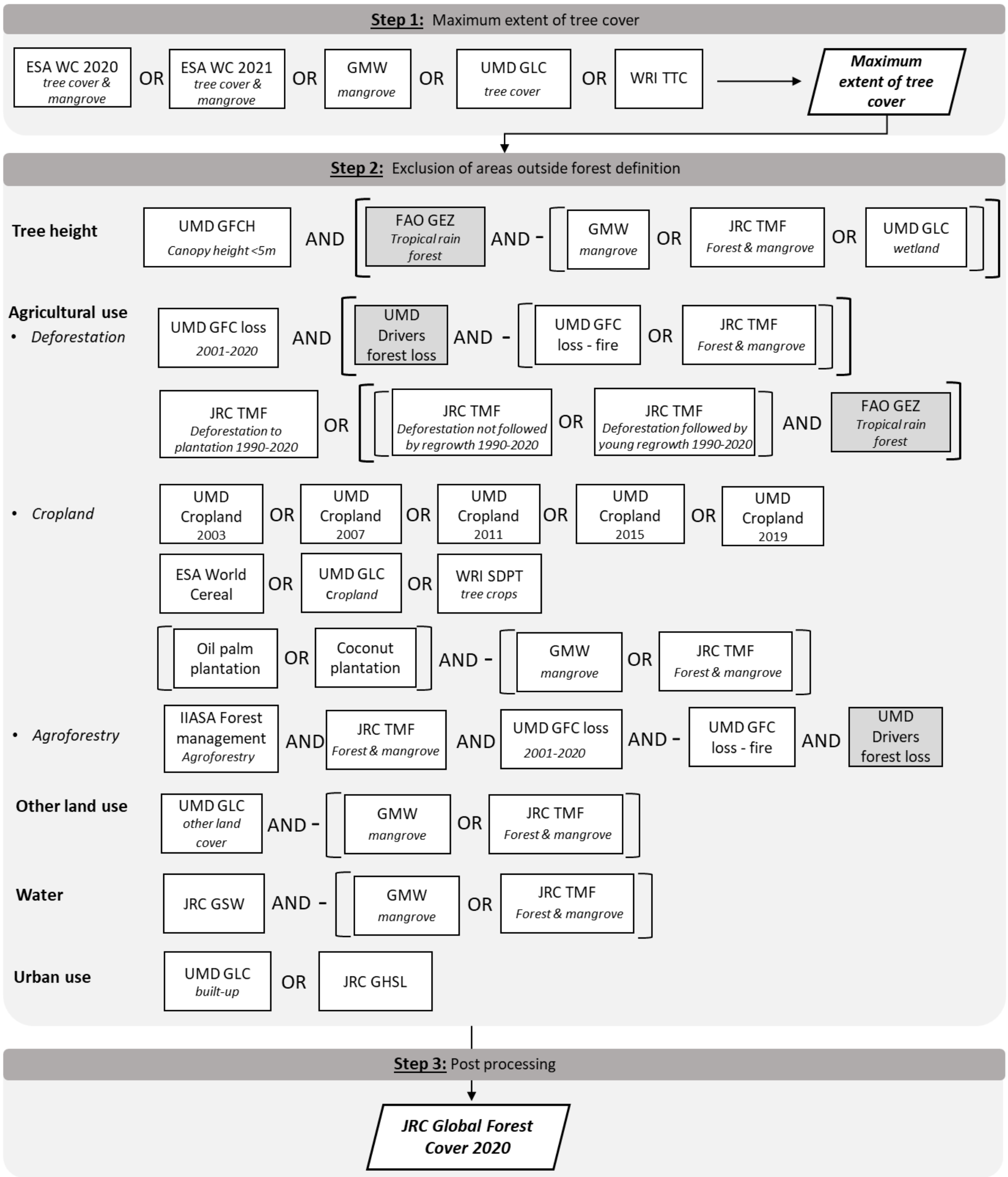
2.3.1 Step 1: Global maximum extent of tree cover

To create the global maximum extent of tree cover, we combined ESA World Cover 2020 and 2021 tree cover and mangroves, WRI Tropical Tree Cover 2020 (80% tree cover), UMD Global land cover and land use 2019, and Global Mangrove Watch (GMW) 2020 giving them equal weights. Transitions from trees/mangrove to water between ESA WC 2020 and WC 2021 over areas mapped as mangrove in GMW were excluded from step 1.

2.3.2 Step 2: Exclusion of areas outside forest definition

Five different masks were created (tree height, agriculture, other land use, water, and urban) to reduce the maximum extent of tree cover (output of step 1) and to match the forest definition. The GEDI gridded product of top canopy heights of less than 5m in the tropical rain forest ecological zone was used to create the mask of “tree height” (see categories for step 2 in Figure 1). This mask does not overlap with mangrove areas defined by GMW or over forest (undisturbed, degraded and forest regrowth of more than 10 years old), mangroves defined by JRC TMF, or over wetlands defined by UMD GLC 2019.

Figure 1. Three-step process used to create the GFC 2020 map (implemented in Google Earth Engine) using Boolean combination rules. Note that grey boxes represent stratification input layers.



Source: JRC

The mask of "agricultural use" was built through the combination of multiple datasets on land use, land cover and commodity maps. We addressed deforestation, Croplands and agroforestry as follows:

- We used tree cover loss from 2001 to 2020 from Hansen et al., 2013 in areas dominated by commodity-driven deforestation and shifting agriculture (Curtis et al., 2018). We excluded from the mask areas overlapping with forest cover loss due to fire from Tyukavina et al., 2022 and JRC TMF forest (undisturbed, degraded and regrowth) and mangrove (Vancutsem et al., 2021) corresponding to areas that have potential for recovery/regeneration and where tree cover loss does not imply a change in land use.

- Tropical moist forest conversion to agricultural plantation (mainly rubber and oil palm) was used for the whole tropical belt from the JRC TMF dataset. We added into this mask the areas of deforestation followed or not by regrowth (only regrowth of less than 10 years old were considered) from the JRC TMF only in Tropical rain forest ecological zone in order to reduce potential commission errors of deforestation detection in tropical dry and mountainous zones. Areas of deforestation followed by forest regrowth of more than 10 years were not included in the mask as we assume that the dominated land use is forest that regenerated over abandoned agricultural land. Young regrowth areas were included in the mask as they may not meet the forest definition in terms of land use (e.g. in shifting agriculture systems), tree cover or height.

- We produced a maximum extent mask of global cropland from UMD for the period 2003-2019 (Potapov et al., 2022). Additionally, we used the extent of ESA World Cereal temporary crops, UMD GLC cropland and tree crops polygons from the WRI SDPT database. Planted forest from SDPT was not included.

- We used the extent of global oil palm and coconut plantation from Descals et al., (2023) and Descals et al. (2021) except in areas mapped as mangroves in GMW or in JRC TMF to reduce the overestimation of palms detection and give priority to mangrove datasets.

- We intersected the agroforestry class from the IIASA Forest Management map with forest classes from JRC TMF and UMD GFC loss by specifically excluding UMD GFC fire in areas dominated by commodity deforestation and shifting agriculture. The rationale behind this is to mask out tree crops (e.g. full sun or shaded cocoa plantations) that may be classified as undisturbed, degraded or forest regrowth in the JRC TMF dataset.

For “other land use”, we used UMD other land cover including areas of true desert, semi-arid, dense short vegetation, open trees of less or equal than 4m, salt pan, sparse vegetation in wetlands and ice except when overlapping with mangroves from GMW or forest area from the JRC TMF.

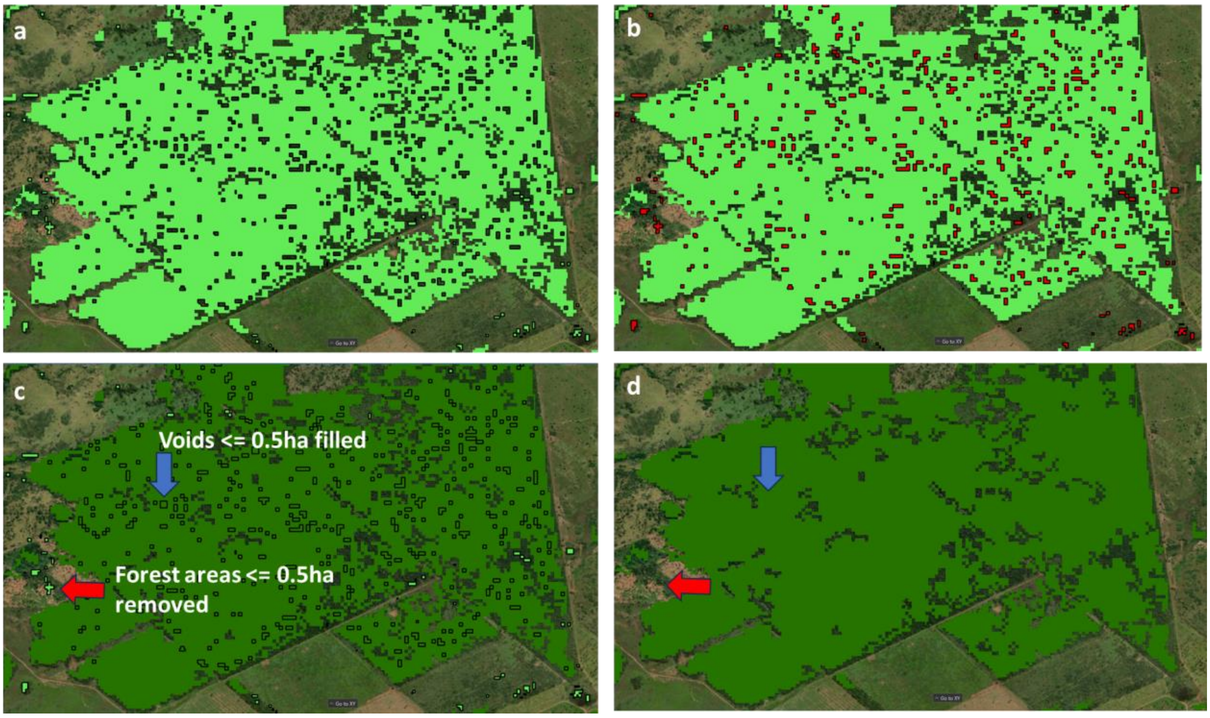
Permanent water, new permanent water and seasonal to permanent water transitions from the JRC Global Water Surface database was used as a mask for “water” except when overlapping with mangroves from GMW or forest area from the JRC TMF.

For urban use we took the maximum extent of UMD GLC built-up (0-100% built-up classes) and JRC GHSL to create a mask for “urban”.

2.3.3 Step 3: Post-processing

We used the mask of lava flows from the Global Surface Water database to exclude forest pixels in volcanic areas. Artefacts remaining in input datasets that propagated to the final map such as the visible stripe patterns due to the Landsat-7 scan line corrector failure were manually masked out or filled using class tree cover from ESA World Cover 2021. To align with the forest definition, we applied a minimum mapping unit of 0.5ha (Figure 2). Patches of forest that did not reach the area of 0.5ha were labelled non-forest, and non-forest patches smaller than 0.5ha were labelled forest. This post-processing operation was based on the computation of each pixel area in square meters (latitude-dependent). We used the eight-neighbour rule to map patches.

Figure 2: Post-processing step including identification of forest gaps and small/isolated patch sizes from the pre-processed GFC map (Figure 2a and 2b where concerned pixels are shown in red). Figure 2c shows explicitly the two actions performed where forest gaps of size less than 0.5ha are filled, and mapped forest area of less than 0.5ha are removed. Figure 2d shows the resulting post-processed GFC map.



Source: JRC, Background data: Google, © 2024 Maxar Technologies.

2.4 Validation methods

2.4.1 Expert qualitative assessment

A preliminary version of the forest map was reviewed by a group of experts from European institutions. Table 2 shows the allocation of nine world regions (Figure 3) to reviewers. The goal of this qualitative review was to report obvious errors and spatial misalignments between forest in the map and on satellite image (mainly base images from Google) at regional–to-landscape scale (avoiding assessment of individual forest pixels which is not indicative of the overall forest distribution). We asked reviewers to screen the forest map at high zoom level (scale bar at approximately 2km), report on the general forest pattern and provide coordinates of potential issues which can be of various types:

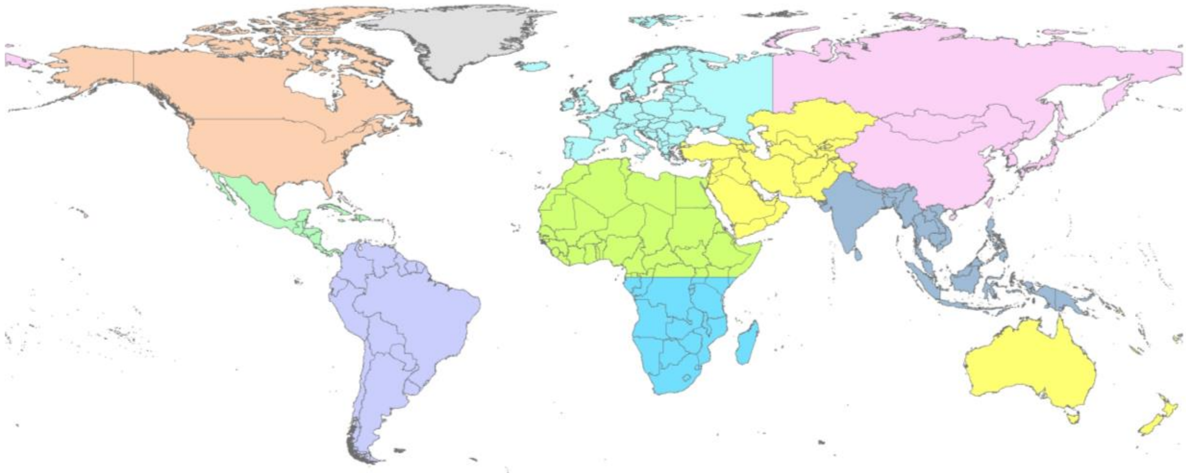
- Processing: A failure of the algorithm to process a part of the map or correct processing over a specific region. This type of issue is rare, normally occurs in form of tiles, and generally can be noted at moderate zoom levels.
- Data: Patterns in input data used as layers in the generation of this map. This error is less common. A typical example is striping patterns that are likely related to sensor issues.
- Mapping: The mapping approach leads to over or underestimation of forest (commission and omission errors) or major misalignments, including patterns that do not correspond at all with the underlying satellite image. This is by far the most common issue.

Table 2. Allocation of nine world regions to reviewers

Reviewer	**Institution**	**Region**
Steffen Fritz	IIASA	North America
Stephen Peedell	JRC	Central America and the Caribbean
Duarte Oom	JRC	South America
Martin Herold	GFZ Potsdam	Europe and Western Russia
Valery Gond	CIRAD	Northern and western Africa
Pierre Defourny	Université Catholique de Louvain	Southern Africa
Danilo Mollicone	FAO	Northern and Eastern Asia
Jean-Francois Bastin	Université de Liège	Southern and South-eastern Asia
Andreas Brink	JRC	Central Asia, Middle East, Australia and Oceania

Source: JRC

Figure 3. Spatial distribution of nine world regions.



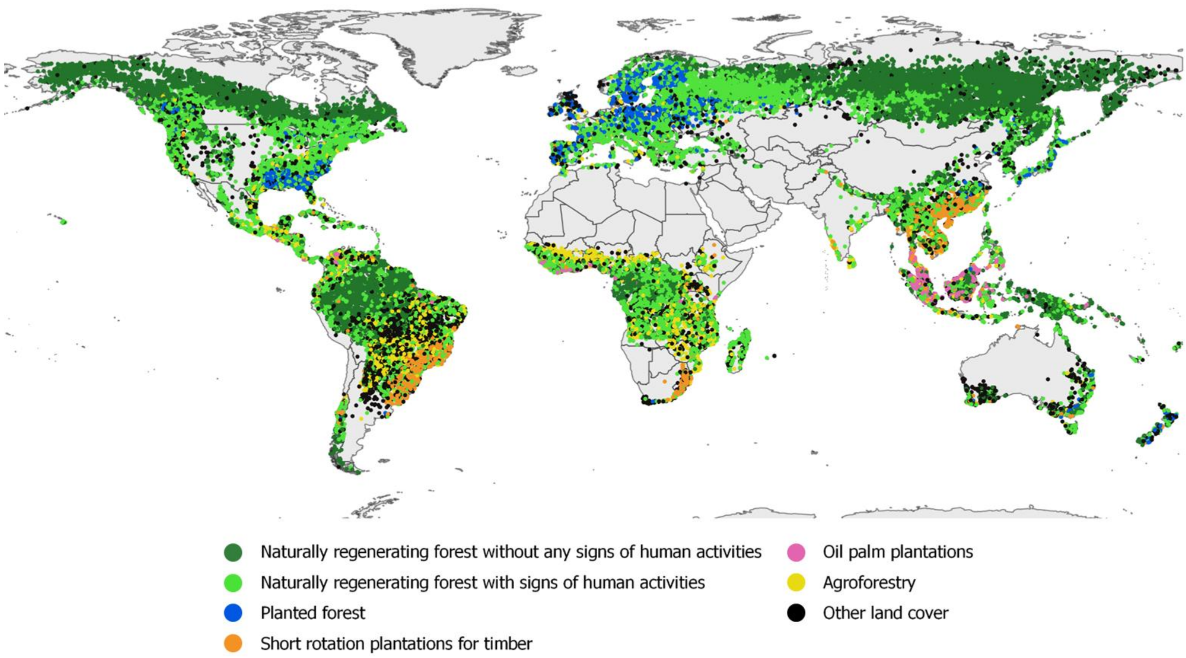
Source: JRC

2.4.2 Preliminary accuracy assessment

For a first assessment of the map quality, we undertook a preliminary accuracy assessment using existing interpreted points. We selected the IIASA reference dataset created for the 2015 Global Forest Management map (Lesiv et al., 2022) because of the global coverage and the forest definition close to the GFC 2020 map. The randomly stratified sample set (n=49,942) was collected by IIASA through crowdsourcing (flag 1) and represents various types of global forest management for year 2015 at 100m spatial resolution (Figure 4). Even though some inconsistencies exist (differences in reference years, scale and classes), this reference dataset was found useful for a preliminary accuracy estimate of the GFC 2020 map.

The IIASA reference dataset is a global representation of forest land use depicting naturally regenerating forest without any signs of human activities (e.g., primary forests), naturally regenerating forest with signs of human activities (e.g., logging, clear cuts etc.), planted forest, short rotation plantations for timber, oil palm plantations and agroforestry. The different classes were grouped to match the forest definition of GFC 2020. For this accuracy assessment, naturally regenerating forest with/without signs of human activities, planted forest and short rotation plantations for timber were grouped together into the forest strata. Omission and commission errors were derived from an area-weighted 2x2 matrix of forest/non-forest.

Figure 4: Reference dataset on the type of forest management.



Source: JRC adapted from Lesiv et al. (2022) obtained through crowdsourcing (Flag 1).

3 Map results

3.1 Data access

GFC 2020 is open source and freely accessible for visualisation and download at:

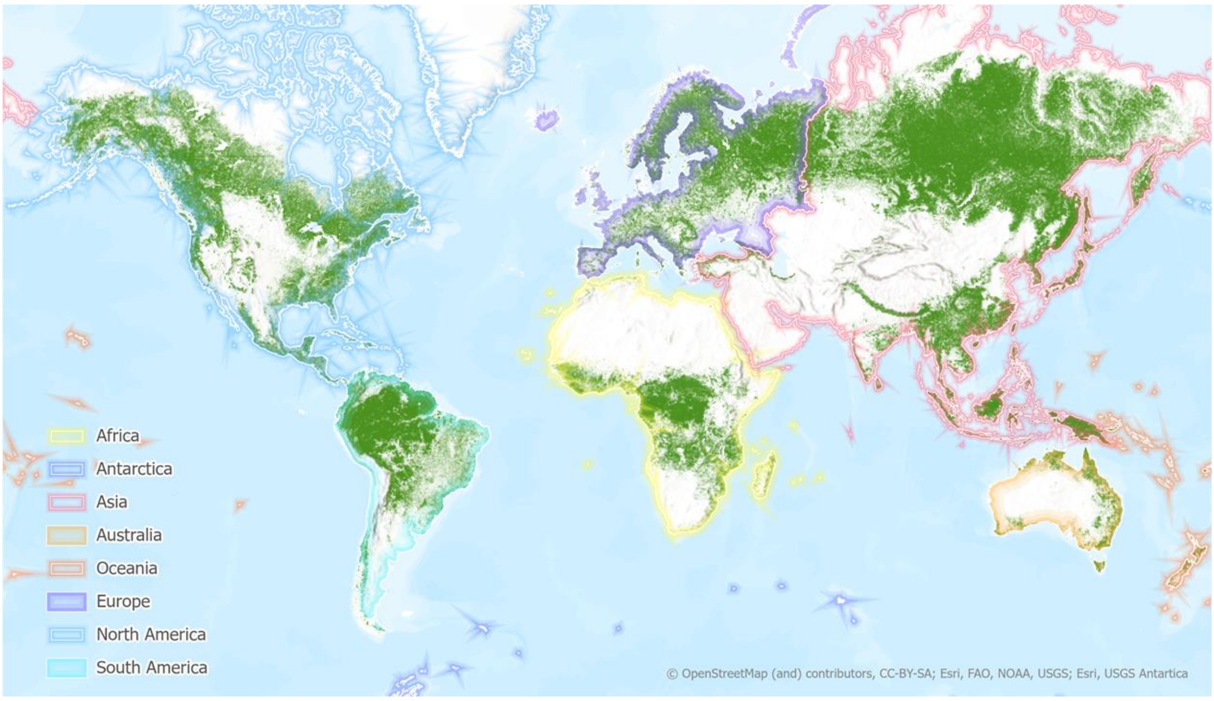
- EU Forest Observatory website (visualisation): https://forest-observatory.ec.europa.eu/forest/gfc2020
- JRC Data catalogue (metadata): https://data.jrc.ec.europa.eu/dataset/10d1b337-b7d1-4938-a048-686c8185b290
- Forobs website (download in tiles) - https://forobs.jrc.ec.europa.eu/GFC
- WMS (visualisation) - https://ies-ows.jrc.ec.europa.eu/iforce/gfc2020/wms.py?
- GEE asset (visualisation and processing) - https://developers.google.com/earth-engine/datasets/catalog/JRC_GFC2020_V1

We invite all users to consult the frequently asked questions of the Observatory for further information on the map: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fforest-observatory.ec.europa.eu%2FFrequently_Asked_Questions_EUFO.docx&wdOrigin=BROWSELINK

3.2 The global forest cover map for year 2020

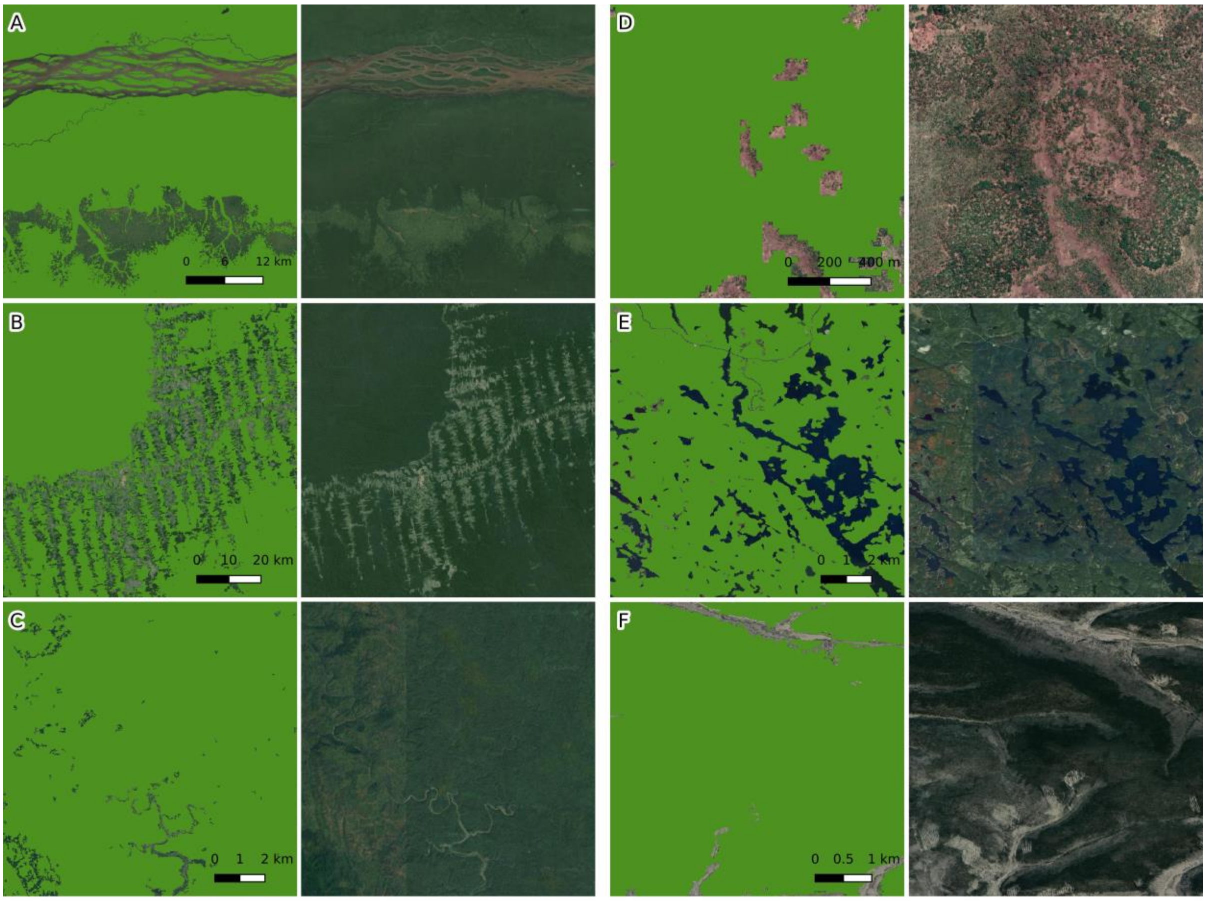
The GFC 2020 map captures forest cover extent globally for year 2020 (Figure 5). Figure 6 depicts close-ups of the GFC 2020 map over different biomes. Figure 7 shows forest area estimates at continental level.

Figure 5: Global forest cover map for year 2020.



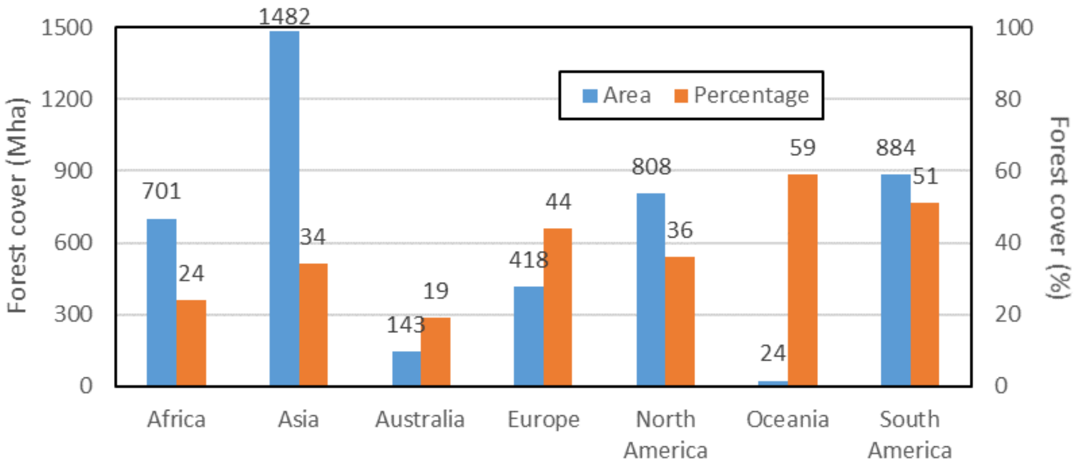
Source: JRC, Background data: ©OpenStreetMap (and) contributors, CC-BY-SA; Esri, FAO, NOAA, USGS; Esri, USGS.

Figure 6: Global forest cover map for year 2020 over different biomes compared to Very High Resolution Images. (A) Tropical closed evergreen broad leaf forest in Central Africa (20.5°E, 1.9°N), (B) Tropical closed evergreen broad leaf forest in the Amazon (54.8°W, 4.1°S), (C) Tropical closed deciduous broad leaf forest in South East Asia (96.1°E, 17.9°N), (D) Open forest deciduous broad leaf forest in Africa (22.2°E, 8.6°N), (E) Closed evergreen needle leaf forest in North America (82.1°W, 46.9°N), (F) Closed deciduous needle leaf forest in Siberia (105.3E, 53.5°N).



Source: JRC, Background data: Google, © 2024 Maxar Technologies.

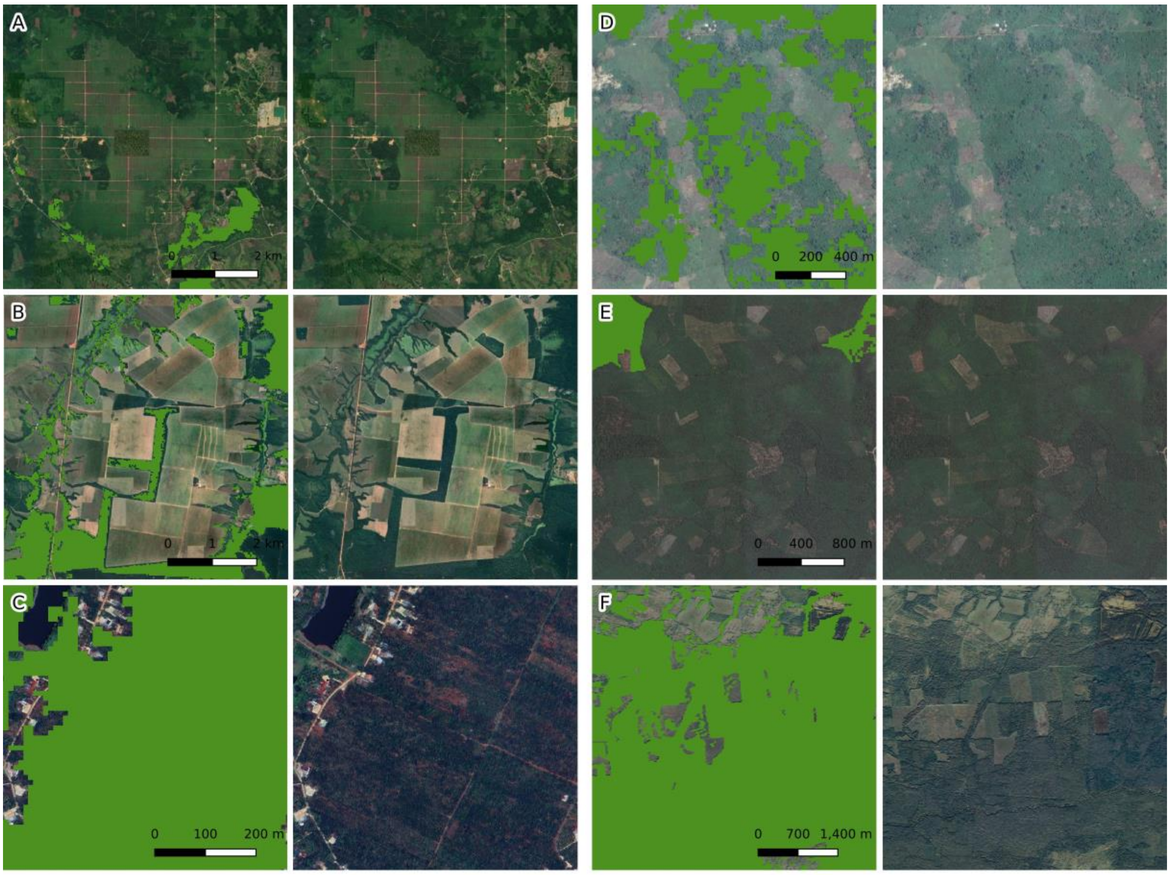
Figure 7: Area estimates of the global forest cover map for year 2020 in Million hectares and percentage of forest cover relative to the total land area at continental level (for regions see Figure 5).



Source: JRC., Continental delineation: ESRI basemaps.

To the extent possible GFC 2020 excludes areas that do not meet the definition of forest. As illustrated in Figure 8, GFC 2020 discriminates well industrial oil palm plantation (A) and soy fields (B) from forests. On the contrary, coffee (C) and cacao (D) are not well discriminated. The mapping of both commodities is particularly challenging because the crops grow in the shade below an existing tree canopy, and often cultivation is carried out by smallholders, which complicates the detection with optical satellite images at 10m spatial resolution or coarser. Large scale rubber plantations (E) are identified well but the detection of production sites by smallholders decreases. Logged forests (F) represent a specific challenge because mapping by satellite images labels unstocked forest as non-forest due to temporary no standing trees.

Figure 8: Close-ups of the global forest cover map for year 2020 for different commodities. (A) Industrial oil palm plantations (111.3°E, 0.1°S), (B) Agricultural landscape dominated by pastureland and soybean plantations (47.3°W, 3.1°S), (C) Coffee plantations (108.2°E, 12.6°N), (D) Cocoa plantations (6.8°W, 5.9°N), (E) Rubber plantations (105.5°E, 3.4°S) and (F) recently logged (clear-cut) forest, regrowing forest, unstocked forest (33.5°E, 56.1°N).



Source: JRC, Background data: Google, © 2024 Maxar Technologies.

3.3 Qualitative expert's feedback

This section reports observations by external experts on a pre-final version of the map, summarized in general observations and specific feedback by region. Based on the reviewer's feedback, the map was again improved (see section 3.3.3). Changes between the map version for review and the final map are overall small. The observations and reports made in the external review process provide valuable feedback for understanding the strengths and weaknesses of the final GFC 2020 map.

3.3.1 General observations

All reviewers reported that the map aligns well with the expected forest pattern in the region they reviewed. There were no large-scale errors in mapping or data processing that had to be corrected at a broad scale.

Overall, reviewers reported more omission errors than commission errors. However, they noted that viewing a map with response data in the background favours the detection of omissions, because omitted forest is not "hidden" by the superimposed forest layer. Several experts stated that more commission than omission errors can be assumed in an unbiased assessment for their region. Another limitation of the assessment tool was the limited availability of response data, notably without date of image acquisition, and no time series. Comparisons with Google Earth Pro (using the history scroll bar function) showed that in many cases response data were post 2020 but a few dated back to 2014.

Almost all reviewers noted minor terrain effects in the forest map (in a few cases also severe) with south facing slopes showing omissions (situation on the northern hemisphere). While forest presence/absence can indeed change with exposition, reviewers deemed the tree height and density on south-facing slopes as sufficient under the definition of forest. Thus, the issue likely resulted from darker surfaces, shade effects and possibly moisture retention on north facing slopes with generally denser forest.

While dense forest stands were hardly missed and their edges generally well delineated, dry forests and ecotones are clearly the most challenging regions. There is an intrinsic problem when assigning discrete classes – in this case binary: forest or non-forest – to a landscape that shows a continuous transition from one class to the other. These are also areas where expert judgement will differ, which was acknowledged by all reviewers. In most cases, reviewers could relate to the mapping of dry forests with the tendency towards omission, which in this case was perceived to reflect the reality.

Water boundaries, linear features such as rivers, riverine vegetation and gallery forests, and mangrove were noted as challenges. The issues may be partially related to response data of different date with changing river courses, especially in deltaic systems. Another challenge is the correct representation of the minimum tree height for low forests in wetlands and mangroves.

Data and processing issues were reported for selected areas. Stripes from satellite scan lines were the most prominent issues. Occasionally reviewers reported effects from the 30m products that were used in the map production, creating small blocks in a 10m map. Isolated forest or non-forest pixels were also observed, which should have been cleaned by the minimum mapping unit approach.

3.3.2 Specific observations

Table 3. Overview of main mapping issues by regions, for allocation and spatial coverage see Table 2 and Figure 3.

Region	**Tendency towards omission or commission errors?**	**Issues over large areas?**	**Data or processing issues?**	**Very obvious errors that disturb "map reading"?**	**Significant issues in dry forests or other ecotones?**
North America	No tendency	None	10m vs 30m data, isolated forest pixels or non-forest pixels	None	Minor omission towards tundra ecozone and peatlands
Central America and the Caribbean	Omission	None	Limited geometric shifting	Topographic issues, Missing uncertainty	None
South America	Omission	None	Some geometric issues, severe striping in Southeast Bolivia	Homogeneous forest stands that are mapped as fragmented forests	Misclassifications of forest with plantations
Europe and Western Russia	Omission	None	None	None	Tendency towards commission
Northern and western Africa	No tendency	None	None	None	None
Southern Africa	No tendency	Misclassification of grasslands	None	Overemphasized patterns of homogeneous forests in protected areas vs. surrounding	Higher omission and commission with no tendency
Northern and Eastern Asia	Omission	Specific areas in Russian taiga with omissions	None	Fire disturbances	Tendency towards omission
Southern and South-eastern Asia	Omission in India	Mapping inconsistencies in East-India	Severe striping in East India	Omission in India, topographic issues	None
Central Asia, Middle East, Australia and Oceania	Commission	Plantations in Northern Turkey, misclassification with shrub in Pakistan and Australia	Isolated pixels of non-forest in contiguous forest stands	None	Commission with shrubland

Source: JRC.

North America: GFC 2020 presents forests with good to very good accuracy, especially for denser forest stands, with a balance between commission and omission errors. Mountainous regions tend towards higher omission. On the contrary, commission errors were noted for low tress or shrubby vegetation in wetlands, in particular in the south-eastern USA. The reviewers found omission of forest in the boreal-tundra ecotone, where sparse forests stands are still present. In Canada, forests occasionally overlap with wetlands and water bodies. Patterns of intensive forest management, e.g. in the Pacific Northwest or the south-eastern USA were difficult to assess, because of the missing acquisition date of the response data. In few cases reviewers noted a difference between 30 vs 10m input data and found isolated forest or non-forest pixels.

Central America and the Caribbean: While the map delineates well forests in Central America, especially in flat terrain, forest mapping for the Caribbean Islands is perceived less accurate. In mountainous regions there is a notable omission of forest on south-facing slopes. The map shows issues with the correct delineation of linear features, tidal zones and mangrove areas that meet the minimum height of the forest definition. In a few cases some clear cuts were not detected. Occasionally the reviewer observed geometric shifts of 10 to 20m between features in the map and the response data.

South America: In general, the forest map demonstrates a high level of accuracy, correctly delineating the major forested areas and at broad scale distinguishes well between agricultural plantations and forest. The Brazilian Cerrado, a mixed landscape of Brazilian tropical/sub-tropical grassland, savanna and shrubland that interfaces with agricultural areas, exposes omission errors, often as speckle or small patches of undetected forest or a spatial misalignment with the fishbone deforestation pattern in the response data. Other omissions were noted in the Bolivian Dry-Chaco for tropical/subtropical moist broadleaf forests. The reviewer noted commission errors or forest edge infringement with oil palm plantations, often for recent land cover changes, notably in Colombia. Terrain effects were generally minor. In few cases burned areas in the response data set were mapped as forests, albeit it is unclear if the imagery for this review was acquired in 2020. The reviewer noted data processing artefacts, likely an effect of combining maps with different projections and resolutions in south-western Bolivia, striping in south-eastern Bolivia and geometric shifts and issues with coastline alignment in southern Chile.

Europe and Western Russia: The map represents well forest stands in Europe; the accuracy is assumed to be well above 80%. In few cases the edge of forest stands could be mapped better. Some contiguous forests in the response data were mapped as fragmented forests. Misclassification were more prevalent in areas with low tree cover or trees with shrubs in the Mediterranean. Forest tends to be overestimated in the boreal-tundra transition zone. In eastern Russia, omission errors were present in clear-cut areas that had significantly regrown. The forest edge around urban areas could be improved, and in some cases treed parks in cities remain in the map. The map distinguishes orchards from forest. In some cases, isolated forest pixels were found.

Northern and Western Africa: The map detects well plantations of cacao and rubber in Cote d'Ivoire and Liberia (mapped as non-forest), also if the plantation was established more recently, against the surrounding older and denser forests. Misclassifications occurred in more challenging contexts such as cacao plantations in degraded forest environments and palm oil plantation mixed with cacao. Other confusions concerned frequent omissions of Eucalyptus and, albeit less common, commission errors with orchards and banana fields. The reviewer reported, according to his opinion, a generally good delineation of dry forests also in complex areas but noted that any interpretation may depend on the reviewer, the context and the aim. In Liberia and Sierra Leone some fallow agricultural areas with trees were classified as forest. Sparse forest stands in the Maghreb may have misclassification issues. Urban forest patches are generally well identified.

Southern Africa: At general level the map resembles well the expected forest patterns. Especially forest in flat terrain is mapped accurately, separating plantations from genuine forest stands. Terrain and illumination effects cause minor misclassifications in mountainous areas. Commission errors are more prevalent in agricultural landscapes surrounding urban areas where croplands were underestimated, for aquatic and riparian vegetation where flooded grasslands were classified as forest, and in residential or urban areas with residual woodlands classified as forests. Complex landscapes show higher misclassifications for mixed land-use areas in the tropical zone, the mixed tree/shrub cover in the dry zone, and, less often, forest plantations. Reviewers noted spatial inconsistency in protected areas (national parks and wildlife sanctuaries) with forest presence versus adjacent areas with similar vegetation. Reviewers reported a notable salt and pepper effect with patches below the 0.5ha minimum mapping unit. Mapping of fragmented forest areas was less accurate, which is attributed to layers with coarser spatial resolution (~30m), and for some regions sensor-related issues such as striping patterns were reported.

Northern and Eastern Asia: The map has overall a good quality. The reviewer found three larger areas that needed improvement. There are logging schemes in central eastern Russia east of the Ural Mountains that should be reported as forests. A large forest area at the Russian-Mongolian border was omitted. Finally, in the central taiga burned larch stands should be classified as forest (see section 4 on the limitation regarding burned forests). Minor improvements were suggested for the taiga-tundra ecotone which showed overestimation of forest cover. Transitions from taiga forest to grasslands and the semi-desert Asian interior plateaus were found to be generally correct. No significant issues were reported for China.

Southern and South-eastern Asia: Dense forests in flat areas and in mountainous terrain are generally well mapped. Terrain issues with illumination and topographic shade effects are particularly prevalent on the Indian sub-continent. Forests on south facing slopes are frequently omitted or spatially underestimated even though close-up checks reveal sufficient tree height and density. Overall, there is a good distinction between forest and palm oil plantations, especially when the pattern is rectangular and thus fitting better to the pixel grid. Misclassification or an incorrect delineation are common in challenging situations such as with very small or mixed plantations. Gallery forests, forest corridors, riverine forested land, mangroves and treed wetlands were found to be very challenging (and thus prone to error) throughout this region. In Eastern India there were significant scan line patterns due to sensor failures.

Central Asia, Middle East, Australia and Oceania: Dense forests were mapped well across diverse areas, with a clear tendency towards overestimating the forest extent. Commission errors were noted for continental shrublands and dry forests, dark slopes in mountainous terrain and dark barren rock or volcanic surfaces, and in a few cases with permanent snow in high mountain areas of the Caucasus and Central Asia. Forest on Pacific Islands was overestimated. Even though not very prevalent, agricultural tree plantations were misclassified as forests. Occasionally, contiguous forest areas exposed speckle of non-forest, without clear reason.

3.3.3 Improvements

The final map was improved based on the external review. The following main issues were corrected by adjustments or additional data layers to mask areas or improve the classification:

- Urban areas: improved in step 2 by adding the JRC GHSL.

- Water surfaces: improved in step 2 by adding the permanent (and transitions from seasonal to permanent water) water bodies from the JRC Global Surface Water product. A global data set for mangroves was added to step 1 and 2 of the mapping approach.
- Terrain issues with omissions of forest cover: In step 2 a modification regarding sparse forests (including sparser classes in step 1) in product UMD-GLC solved to a large extent the observed differences between north and south facing slopes and overall, the errors of omissions of forest cover reported by the reviewers.
- Scan lines: Manual correction in step 3 for identified regions with severe effects.
- Misclassifications in Siberia: Correction of three regions with misclassifications over large areas. Improvements used additional input data in step 1 and a modification for classes used from UMD-GLC in step 2.
- Dry forest: The mapping improved with additional data from WRI TTC.
- Minimum mapping unit: The initial minimum mapping unit algorithm was faulty. It was replaced with a correction for latitude to correctly represent the 0.5ha minimum area requirement for forest and non-forest patches.

3.4 Comparison with sample-based reference forest/non-forest dataset

The preliminary quantitative assessment of the final GFC 2020 map against the IIASA forest management samples results in an overall accuracy of 76.6%. The commission and omission errors (complements of User and Producer accuracy, respectively) of the forest class were estimated at 4.8% and 39.7%, respectively (Table 4). After reviewing some sample locations, we noted two main reasons that can explain these error rates: (1) an edge effect with samples falling close to the forest boundary in our 10m map compared to 100m sample locations by IIASA, and (2) a change in forest cover between 2015 for IIASA samples and 2020 as data for the forest cover map. We regard the statistics provided here as preliminary and recognize the need for further statistical analysis with sample interpretation that meets the forest definition and the land use corresponding to year 2020.

Table 4. Confusion accuracy matrix in area (Mha) showing agreement between IIASA reference dataset and the GFC map (U.A. User Accuracy, P.A. Producer Accuracy).

	IIASA GFM			
GFC 2020	**Non forest**	**Forest**	**Total**	**U.A. (%)**
Non forest	5,610.88	2,795.52	8,406.40	66.7%
Forest	212.65	4,247.19	4,459.83	95.2%
Total	5,823.53	7,042.70	12,866.23	
P.U. (%)	96.3%	60.3%		76.6%

Source: JRC, Lesiv et al. (2022) obtained through crowdsourcing (Flag 1).

3.5 Comparison with existing commodity maps

A comparison between the GFC 2020 map and available recent regional and national datasets, not used for the production of the map, gives a first quantitative assessment to which degree the GFC 2020 map distinguishes forest from land for commodities (except wood) of interest for the EUDR. This list of datasets is non-exhaustive.

Table 5. Area and percent of commodity area that coincides with forest from the global forest cover map for year 2020.

Country	Source, mapping year and reported user accuracy (UA) and producer accuracy (PA) for the given commodity, if available	Commodity area [ha]	Commodity area labelled forest in GFC 2020 [ha]	Percentage of commodity area labelled forest in GFC 2020 [%]
Cocoa				
Ivory Coast (1)	Kalischek et al., 2023 for 2021 (UA: 92.6%, PA: 90.9%)	4,364,349	2,126,476	49
Ghana (1)	Kalischek et al., 2023 for 2021	2,704,431	1,662,633	61
Coffee				
Brazil	MapBiomas Brazil 2020, Souza et al., 2020 for 2020	1,227,453	824,756	67
Vietnam (2)	Bourgoin et al., 2020 for 2018 (UA: 74%, PA: 76%)	44,767	25,596	57
Oil Palm				
Indonesia	MapBiomas Indonesia 2020a for 2020	15,363,082	1,722,812	11
Indonesia	MapBiomas Indonesia 2020b for 2020	16,989,663	489,479	3
Soy bean				
Brazil	Song et al., 2021 for 2020 (UA: 92%, PA: 83%)	17,756,138	11,259	0.06
Brazil	MapBiomas Brazil 2020, Souza et al., 2020 for 2020	41,117,019	480,064	1.17
Bolivia	Song et al., 2021 for 2020	210,905	61	0.03
Argentina	Song et al., 2021 for 2020	2,169,861	88	0.004
Paraguay	Song et al., 2021 for 2020	1,635,419	1,248	0.08
Uruguay	Song et al., 2021 for 2020	334,561	63	0.02
Pasture land				
Brazil	MapBiomas Brazil 2020, Souza et al., 2020 for 2020	151,536,777	10,443,660	7
Argentina Chaco	MapBiomas Chaco 2020 for 2020	4,541,362	155,403	3
Bolivia Chaco	MapBiomas Chaco 2020 for 2020	2,147,350	93,645	4
Paraguay Chaco	MapBiomas Chaco 2020 for 2020	7,169,439	483,644	7
Rubber				
Indonesia	Wang et al., 2023 for 2021 (UA: 99%, PA: 94%)(3)	4,716,271	1,723,162	37
Thailand	Wang et al., 2023 for 2021	3,719,392	2,644,150	71
Malaysia	Wang et al., 2023 for 2021	981,968	203,402	21
Vietnam	Wang et al., 2023 for 2021	1,596,985	1,083,054	68
Cambodia	Wang et al., 2023 for 2021	621,113	272,639	44
China	Wang et al., 2023 for 2021	1,095,799	1,054,208	96
Laos	Wang et al., 2023 for 2021	577,051	405,354	70
Myanmar	Wang et al., 2023 for 2021	775,385	559,203	72

(1) We used threshold 0.65 to define cocoa from Kalischek et al. 2023.

(2) Only Di Linh district, Lam Dong province.

(3) Accuracy assessment across insular Southeast Asia for rubber: UA:95%, PA: 53%. Accuracy assessment across mainland Southeast Asia for rubber: UA:99%, PA: 99%.

Source: JRC, further sources noted in column "Source, mapping year and reported user accuracy (UA) and producer accuracy (PA) for the given commodity, if available".

Table 5 shows for different commodities the area and percentage of forest in GFC 2020 that overlaps with the area identified for that commodity from an external map. Pasture land is a surrogate for rangeland used for cattle production. The percentage indicates the commodity-specific commission error of forest in GFC 2020. Statistics indicate that the GFC 2020 map distinguishes well forest from land used for oil palm and soybean production and pasture land. This result was to be expected for soy bean and pasture land with no woody life forms. For oil palms the process made use of external global data layers to separate agricultural trees from forests. Albeit trees, in particular more recent oil palms can be distinguished from forests by semi-automatic procedures because of the use of contextual information for plantations in step 2 (Descals et al., 2023; Descals et al. 2021). On the contrary, GFC 2020 shows high errors for cocoa and coffee. Both commodities grow in the shade of a higher tree canopy that is harder to distinguish from forest with optical images. Also, there is a general lack of global data layers to discern coffee and cocoa fields from forest land. Rubber is a commodity with mixed results depending on the country.

4 Limitations and lessons learnt

The GFC 2020 map includes a number of limitations (i.e. omission or commission errors) linked to datasets and technical mapping issues (see annex 1 and 2 for non-exhaustive lists of specific and general known issues). The tables of these two annexes will be regularly updated and made available on the webpage https://forobs.jrc.ec.europa.eu/GFC

Issues linked to input datasets are mostly due to (i) omission of tree cover around the 180-degree longitude and (ii) presence of stripping patterns that have propagated from Landsat (Landsat 7 ETM+). When possible, stripping artefacts showing forest cover (commission errors) have been manually removed (see section 2.3.3).

Mapping issues are due to several reasons:

- **Insufficient data on agricultural tree plantations at global scale:** GFC 2020 may incorrectly indicate tree plantations for agricultural use as forest if there is no or incomplete data for masking. In particular, tree crops are not mapped comprehensively for all crop types and regions. Industrial oil palm plantations and other large palm plantations can be detected from earth observation data but old plantations (older than the monitoring period of Earth Observation methods) or smallholder plantations remain challenging. Among the commodities targeted by the EUDR, coffee and cocoa datasets show by far the lowest accuracy. There are three interrelated reasons for high errors: (i) the age of the plantations, in particular when older than the monitoring period of the JRC TMF or UMD GFC datasets, (ii) the absence of global data layers and (iii) the fact that those crops can grow in the shade of a higher tree canopy (agroforestry systems), which can be confused with degraded forest when observed with optical satellite images. The removal of single trees observed over the last two to three decades (e.g. identified as forest degradation in JRC TMF) in combination with data on forest management type from Lesiv et al. (2022) may partially tackle this issue. However, Lesiv et al. (2022) is known to underestimate the extent of agroforestry systems.

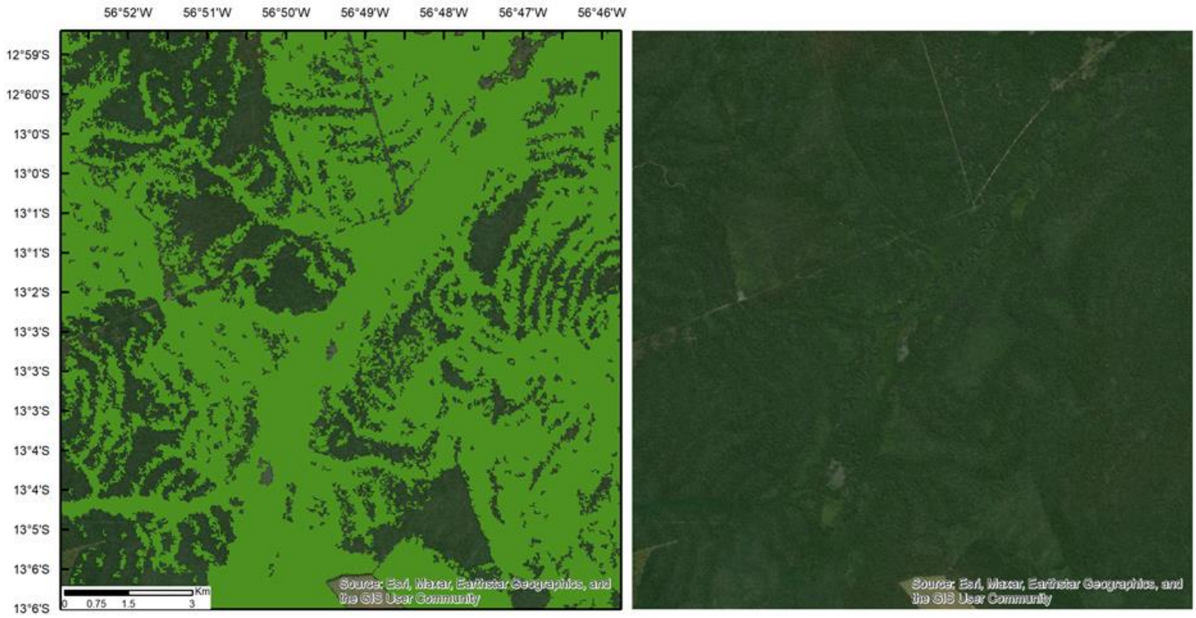
- **Shifting cultivation and forest regrowth:** The forest class of GFC 2020 map may include areas under shifting cultivation or land that is temporarily not used for agricultural production (set aside agricultural land with young tree growth). In the tropical belt, the JRC TMF data identify younger shifting cultivation as non-forest in the GFC 2020 map. Forest in GFC 2020 excludes areas of tropical moist forest regrowth that is less than 10 years old to minimise potential confusion with shifting cultivation systems. The GFC 2020 map does not apply any time threshold for fallow land outside the humid tropics due to the absence of global datasets regarding forest regrowth.

- **Unstocked forest**: In contrast to the forest definition of the EUDR, the forest class in GFC 2020 may not include all temporarily unstocked forests due to the absence of standing trees during year 2020 (Figure 9). An absence of trees from land that was, is and will be used as forest may be due to recent fires, other natural disturbances (storms, diseases) or clear-cut harvesting. This issue is partially addressed by not using tree cover loss up to year 2020 from Hansen et al (2013) in step 2 if this loss overlays with a fire from Tyukavina et al. map (2022) or with the “forestry driver” class from Curtis et al. (2018).

- **Propagation of omission** and **commission errors:** Some errors from input datasets may be retained in the final GFC 2020 map.

- **Difference of spatial resolution:** the spatial resolution of input datasets varies mainly between 10m and 30m resolution with a few coarser datasets. This difference may lead to sharp boundaries between forest and non-forest area and may underestimate forest edge detection.

Figure 9: Unstocked forest mapped partially as non-forest in the global forest cover map for year 2020 (left panel) due to absence of tree cover after recent fires as seen from recent high-resolution imagery (right panel).



Source: JRC, Background data: ESRI, © 2024 Maxar Technologies.

The development of the GFC 2020 map followed an iterative approach, using "the try and error principle". In the following we elaborate on some of the lessons learnt.

Improvements of specific areas by ecological region need to be carefully tested and generally require additional data layers. For example, we tried to reduce a large area of forest commission error in central northern Siberia by using the FAO ecoregion layer. While we were able to improve the map in the targeted region, the ecoregion layer created artificial demarcation lines of forest cover in other parts of the boreal zone, namely in northern Canada. As our approach is aimed at ensuring a globally consistent mapping, a local improvement for a limited area of an ecoregion cannot be performed.

The exclusion of tree cover lower than 5m height using the UMD Global Canopy Height dataset was leading to large omissions in open and dry forests. After visual inspections and comparison with regional datasets (e.g. in Tanzania from Verhegghen et al., 2022), it was decided to restrict its use over closed canopy tropical rain forests.

We initially tested the global Copernicus land cover map for year 2019 at 100m spatial resolution (Buchhorn et al., 2020) as one data layer for step 1. However, we noted significant spatial patterns propagating the coarser 100 m resolution into the 10m resolution map. Secondly, and likely related to this coarser resolution, there were several misclassifications of forests near urban areas. Therefore, a decision was taken to substitute the global Copernicus land cover map of year 2019 at 100m with the ESA WorldCover datasets of year 2020 and 2021 at 10m and the UMD GLC at 30m.

Regarding the application of a minimum mapping unit of 0.5 ha we initially used a simple pixel count approach for the entire globe. Given that the geographic projection of the GFC 2020 map uses the WGS84 geodetic datum the area of each pixel varies by latitude, with pixels at higher latitude representing a smaller area than 0.01 ha. Using a pixel number threshold of 50, this resulted in retaining patches smaller than 0.5 ha at higher latitudes. Therefore, we corrected this issue by calculating the undistorted area in square meters per pixel and then by applying the threshold of 0.5 ha.

We assembled all data sources to a common geodetic datum and binned to a common 10m reference geographic grid. In general, the GEE environment performed well with re-projections on the fly. During intermediate processing steps we observed occasionally slivers of pixels or pixels in parallelogram shape, especially for areas that are distant from zero-degree latitude and longitude. We could not find such effects in the final map and assume that the improved minimum mapping unit algorithm tackled this issue.

The lessons learnt during the iterative process allowed to refine the selection of input data, the mapping methodology, and the rules and thresholds after each iteration. This resulted in a carefully optimised process that can be improved with the potential addition of new or revised global-scope input datasets, notwithstanding the need for repeated visual and quantitative analysis of any future revised version of the GFC 2020 map. It is important to note that high quality spatial datasets on commodities are deemed a major asset for improving the conversion from tree cover extent to forest extent (Radeloff et al., 2024). Our harmonized, globally consistent approach to map the world's forests requires the availability of such high-quality spatial datasets for commodities at global level.

5 Conclusions

This new Global Forest Cover map for year 2020 (GFC 2020) is expected to be widely used by the international community of stakeholders interested in forest monitoring issues at global level. The GFC 2020 map is a harmonized globally consistent representation of the presence or absence of forests in 2020 at 10m spatial resolution, retaining forest or non-forest patches of at least 0.5 hectares. The production of this GFC 2020 map is a unique and efficient exercise that was conducted through the assembly of the most recent, publicly available, wall-to-wall spatial products with a global scope regarding the presence of tree cover or other land uses that do not meet the forest definition.

A first comparison of GFC 2020 with regional or national maps of cocoa, coffee and rubber plantations indicate notable discrepancies for cocoa and coffee. Comparisons with regional maps of other commodities such as oil palm, soy and pasture land show satisfactory results (i.e. low commission errors). In the context of the EU Regulation on deforestation-free supply chains (EUDR), the GFC 2020 map can be used in the risk assessment phase of the due diligence exercise. It is recommended to use other spatial datasets on forest cover at national or regional level in combination with GFC 2020 or as alternative dataset if considered more appropriate, notably more accurate. The GFC 2020 map has no authoritative status, and its use is:

- Non-mandatory: There is no obligation for stakeholders, notably operators and competent authorities concerned with the implementation of the EUDR, to use GFC 2020 or any other map.
- Non-exclusive: The map on global forest cover, provided by the European Commission free-of-charge, complements the many cartographic products already available. Other maps may have advantages and the regulation does not prescribe modalities of and for map use.
- Not legally binding: The map is one of many tools that support the implementation of the regulation, notably the risk assessment. When overlaying polygons, the presence of forest in GFC 2020 does not necessarily imply non-compliance, nor does the absence of forest in the map imply compliance. It will be up to the operator to provide compelling evidence for the risk assessment and the competent authorities to carry out detailed and robust compliance checks.

The GFC 2020 map is expected to serve operators in the assessment of risk of deforestation when declaring plots of land from which commodities or products within the scope of the EUDR are imported to or exported from the European Union market. In this perspective the European Commission foresees the interoperability between the information system in which due diligence declarations will be registered (Art 33 of EUDR) and GFC 2020. The map could also help competent authorities in identifying areas to carry out detailed and robust checks and tailor their enforcement efforts by acquiring and interpreting very high spatial resolution imagery.

A second version of the Global Forest Cover map of year 2020 is planned to be released by end of 2024. The inclusion of new or improved datasets with a global scope and refinements of the workflow are expected to alleviate some of the known issues. For instance, the potential additional use of coffee and cocoa climate suitability maps (Grüter et al., 2022; Ovalle-Rivera et al., 2015) as a stratification layer may allow to refine the masking of tree cover in combination with land cover and land use datasets that were discarded in GFC 2020 version 1 workflow due to their coarse resolution or low global accuracy (e.g. Global Copernicus land cover 2019 or USGS Global Cropland Extent Product from Thenkabail et al., 2021). Subsequent releases could also benefit from the forthcoming land cover and forest map produced under the global component of the Copernicus Land Monitoring Service.

Finally, two main streams will be followed to provide important additional information. First, a statistically robust validation exercise will be performed during 2024 to provide an accuracy estimate of the GFC 2020 map. Secondly, four sub-classes of forest cover will be considered for potential addition in the GFC map legend: primary forest, naturally regenerated forest, planted forest and plantation forests following the definition of the EUDR. As for the forest / non forest delineation in the GFC 2020 map, the quality of the delineation of these four sub-classes will depend on the availability and accuracy of related spatial datasets or proxies.

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List of abbreviations and definitions

Abbreviations	Definitions
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
EU	European Union
EUDR	Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010
FAO	Food and Agriculture Organization of the United Nations
GEDI	Global Ecosystem Dynamics Investigation
GEE	Google Earth Engine
GEZ	Global Ecological Zones
GFC	Global Forest Cover
GFCH	Global Forest Canopy Height
GHSL	Global Human Settlement Layer
GLAD	Global Land Analysis and Discovery
GLC	Global Land Cover
GMW	Global Mangrove Watch
GSW	Global Surface Water
IIASA	International Institute for Applied Systems Analysis
JRC	Joint Research Centre
NOAA	National Oceanic and Atmospheric Administration

Abbreviations	**Definitions**
Observatory	EU Observatory on deforestation and forest degradation
SDPT	Spatial Database of Planted Trees
TMF	Tropical Moist Forest
TTC	Tropical Tree Cover
UMD	University of Maryland
USGS	United States Geological Survey
WC	World Cover
WRI	World Resources Institute

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Annexes

Annex 1. Non-exhaustive list of known issues by coordinates (7 December 2023)

Longitude	Latitude	Description of the issue	Date	Source
-60.39555	-18.33929	Stripes	12/6/2023	Producer
13.84255	8.77345	Stripes	12/6/2023	Producer
23.6801	9.8767	Stripes	12/6/2023	Producer
24.80143	9.6225	Stripes	12/6/2023	Producer
26.04346	9.29019	Stripes	12/6/2023	Producer
30.17033	6.45132	Stripes	12/6/2023	Producer
31.24432	4.85705	Stripes	12/6/2023	Producer
33.02064	4.41722	Stripes	12/6/2023	Producer
32.32384	-12.5015	Stripes	12/6/2023	Producer
20.0363	-10.4397	Stripes	12/6/2023	Producer
19.7457	-9.0165	Stripes	12/6/2023	Producer
20.4062	-8.8466	Stripes	12/6/2023	Producer
19.6471	-8.0315	Stripes	12/6/2023	Producer
19.91755	-7.11935	Stripes	12/6/2023	Producer
17.76592	-6.60281	Stripes	12/6/2023	Producer
-2.1058	8.8034	Stripes	12/6/2023	Producer
14.794	7.7276	Stripes	12/6/2023	Producer
19.7644	9.446	Stripes	12/6/2023	Producer
21.7979	9.4115	Stripes	12/6/2023	Producer
21.7333	10.4042	Stripes	12/6/2023	Producer
-61.5989	-19.399	Stripes	12/6/2023	Producer
64.1821	67.9923	commission error in polar areas	12/6/2023	Producer
-0.04501	51.53422	urban park misclassified as forest	12/6/2023	Producer
41.689082	-0.816276	omission of dry forest (large area in Somalia)	12/6/2023	Producer
13.07921	52.37414	Geometric shift due to crossing of different input layers at various spatial resolution	12/6/2023	Producer
-73.53428	45.515974	urban park misclassified as forest	12/6/2023	Producer
179.9415	-16.184	Missing forest area	12/6/2023	Producer

Annex 2. Non-exhaustive list of known issues by regions (7 December 2023)

Region	Issue
Urban areas	Heterogeneous categorization of urban forests and residual woodlands. Some urban parks may be included as forests in the final map (commission errors)
Global	Artefacts (striping patterns) linked to data and technical issues from Landsat 7 ETM+ satellite sensor (commission errors).
Global	Salt and pepper effect although it has been mitigated by the post-processing steps
Global	Geometric shifts due to crossing of different input layers that result in commission or omission errors along forest edges
Global	heterogeneous classification of forest in seasonally inundated areas (areas along riparian forests and rivers)
Mountainous areas	Underestimation of forests in areas with high slopes (omission errors)
Tropical dry forest	Separation between tropical dry open forests and shrublands are often difficult to capture, leading to mapping with heterogeneous accuracy in tropical dry domain (mix of omission and commission errors)
Indonesia, Malaysia, West Africa	Overestimation of forest cover in areas with small-holder oil palm plantations or mixed oil palm plantations (oil palm mixed with other crops) or oil palm plantations with low canopy coverage resulting in commission errors
Ivory Coast, Ghana, Cameroon	Overestimation of forest cover in cocoa production area, including both full-sun and shaded cocoa agroforestry systems (commission errors)
Vietnam, Brazil	Overestimation of forest cover in coffee production area (commission errors)
Global	Potential confusion between forest cover and tree plantation for agricultural use (e.g. orchards) or rubber plantations
Global	Recently burned and clear cut logged forests may be classified as non-forest cover due to the absence of standing trees (omission errors)
Tropics	Forest edges in heterogeneous landscapes may not be accurately mapped due to the complex mosaics between forests and other land cover (omission errors)
Polar	Commission error, in some areas dense short vegetation is classified as forest
Easternmost Siberia	Block of forested land mapped in no tree or very sparse tree area
180-degree longitude	Missing forest area

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