D3 Final Report

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List of Abbreviations

FDA	Forest Development Authority – Republic of Liberia
LISGIS	Liberia Institute of Statistics and Geo-Information Services
MMU	Minimum Mapping Unit (for area features)
MMW	Minimum Mapping Width (for linear features)
REDD/REDD+	Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries

Applicable Documents

AD01	Request for Proposals for Selection of Consultant to Update of Liberia Land Cover and Forest map (Plantations and Forest Definition consideration) under the Additional Readiness Preparation Activities of the Forestry Development Authority; RFP No.: FDA/FCPF-AF/CONS/03; January, 2017
AD02	Technical Proposal Update of Liberia Land Cover and Forest Map in response to RFP No.: FDA/FCPF-AF/CONS/03; August, 2017
AD03	Contract for Consultant's Services to Update Liberia Land Cover and Forest map (Plantations and Forest Definition consideration) , Contract No.: FDA/FCPF-AF/GM/ULULCFM/01/18 between FDA and GeoVille GmbH, Austria, and Metria AB, Sweden; April 2018
AD04	Final report of LIBERIA LAND COVER AND FOREST MAPPING project; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; July, 2016. Available online at: www.fda.gov.lr/download/146/land-and-forest-cover/2724/liberia-land-cover-and-forest-mapping_-final_report_v1_1.pdf (accessed May 18th, 2018).
AD05	Technical specifications; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; July, 2014
AD06	Inception Report; Contract No.: FDA/FCPF-AF/GM/ULULCFM/01/18; April 2018

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Executive summary

The objective of the project **Update of the Liberia Land Cover and Forest Map** was to update and improve the current Forest and Land Cover map of Liberia by adapting its content to the National Forest Definition **established in January 2016**. The activity thus reflecting a compliant baseline for assessment of Liberia's natural resources and specifically for land degradation activity monitoring as well as biomass and emission estimations for MRV in REDD. In this new definition, Liberia recognizes the contribution of industrial agricultural plantations to national economy, but chose to exclude them from its forest definition. The inception report (D1) on the update to the Liberian Land Cover and Forest Map 2015 presented the output of project task 1.1 on the preparation and consolidation of the exact technical specifications for the updated Forest and Land Cover map and was approved by the FDA on Jun 22nd 2018. Based on the methodologies described in the Inception Report, the work commenced and progress was reported in Progress Report 1 and 2, submitted on 18.06.2018 and 23.07.2018 respectively. This final report summarizes the project activities and all of the results on a task by task basis.

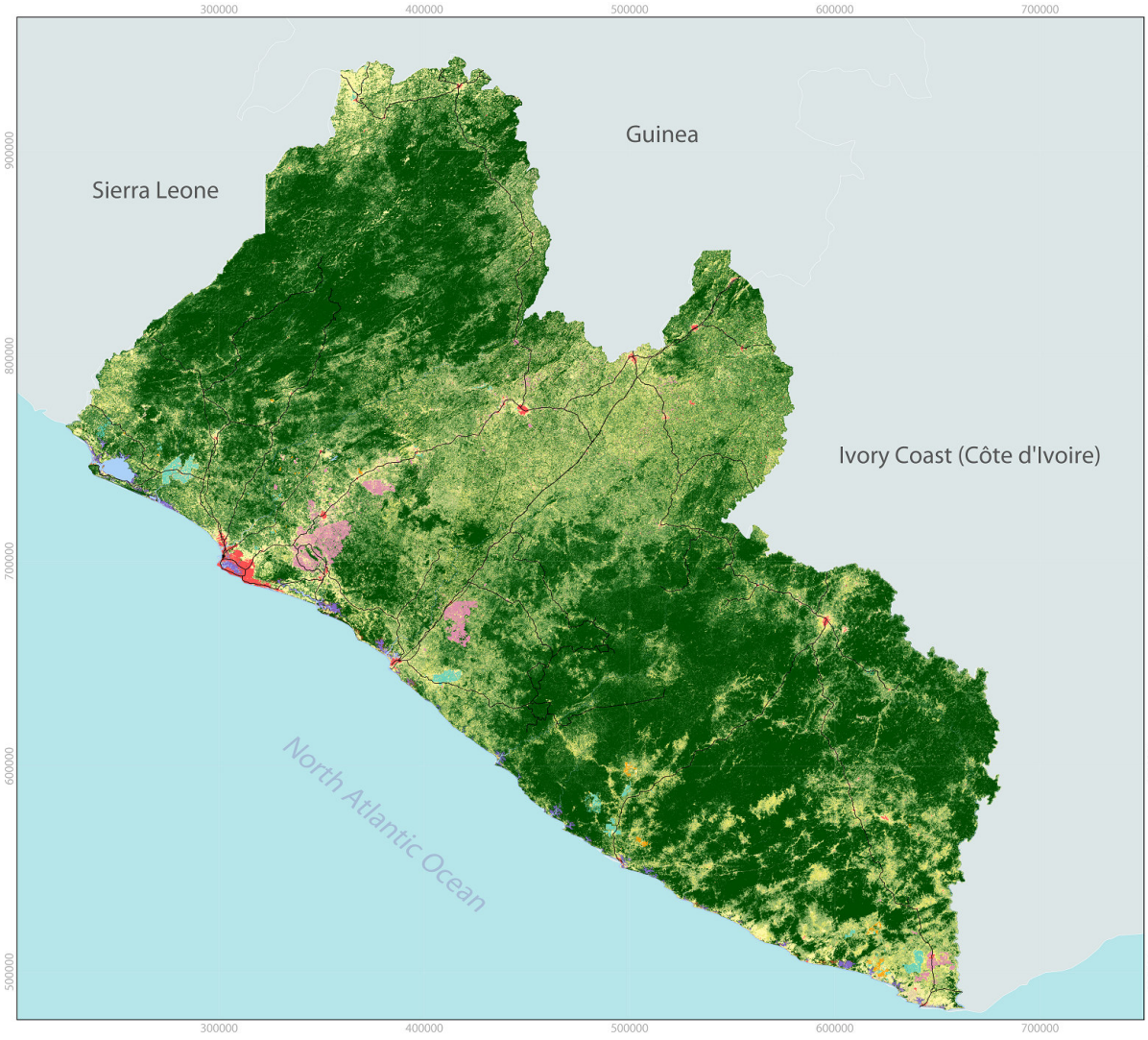

Figure 1: Updated Liberia Land Cover and Forest Map 2015 derived from high-resolution satellite imagery.

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1. Scope of document

This document covers all project activities under Task 1 (technical specifications and data acquisition), Tasks 2 (mapping) and 3 (validation). Task 1 activities were previously described in detail in the Inception Report but are included in the final report, too, in order to provide a complete summary of project activities. For each task, this document elaborates on the employed methodologies and presents the results of the task and its sub-tasks.

Chapter 2 introduces the reader to the project background to provide context to the activities discussed in the following chapters.
Chapter 3 reports on the results of Task 1, the technical implementation of mapping activities under Task 2 as well as the methodology and results for Task 3 (validation).
Chapter 4 summarizes the produced outputs along with their technical specifications.
Chapter 5 lists all deliverables submitted under this contract.
Chapter 6 provides an outlook on satellite based monitoring using the modern European Sentinel program to update the base map produced in this project in regular intervals.

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2. Background

The Government of Liberia through the Forestry Development Authority has received a grant from the Forest Carbon Partnership Facility (FCPF) for the Additional Readiness Preparation Activities. The fund is intended to undertake a comprehensive study and analysis of Reducing Emissions from Deforestation and Degradation (REDD) for developing the national REDD strategy for sustainable management of forests. The FCPF fund will also assist Liberia with the development of a Monitoring Reporting and Verification (MRV) system that will track the temporal and spatial changes in forest cover and associated drivers of deforestation and degradation. The spatial and statistical data will assist in driving the policies directed at enhancing sustainable development through sustainable forest management.

The assessment of Liberia's current forest monitoring capabilities and available data have emphasized the need for a dedicated capacity development effort that also encompasses the broader land resources sector, which was manifested in the *"Terms of Reference for Developing Capacities for a National Forest Monitoring and Measurement, Reporting and Verification System to support REDD+ participation of Liberia"* (Liberia Forest Development Authority and Wageningen University, January 12, 2015). In terms of identified required technical components for improvement of the national forest monitoring capacity, the report defined the following actions (page 35, Table 4):

1. Decide on a forest definition
2. Update and improve national forest map and/or land use map
3. Estimate changes in forest area at national level
4. Estimate activity data for forest degradation (i.e. comprehensive Forest Information System)
5. Estimate activity data for enhancement, sustainable management of forests and/or conservation

In March 2014 FDA procured the production of a satellite based national Land Cover and Forest Map of Liberia in support of Liberia's REDD+ readiness preparation activities, which was delivered end of 2015 through a Joint Venture of Metria (Sweden) and GeoVille (Austria). Specifications and thematic content of the map were defined in a joint workshop in Monrovia in April 2014. At the time of the project implementation and map production, Liberia did not yet have an official forest definition. A national definition of forest was agreed upon in the National Forest Definition Conference in Voinjama, Lofa County (Jan. 25-29th, 2016). According to the resulting resolution, "Liberia now adopts a National Forest Definition with

- a 30% minimum forest cover
- a 5 meter minimum height and
- a 1ha minimum areas.

Importantly, Liberia recognizes the contribution of industrial agricultural plantations to national economy but chooses to exclude them from its forest definition."

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While the 2015 produced Land Cover and Forest Map data of Liberia includes various forest cover density classes (<30%/30-80%/>80% forest cover), which were mapped at a 0.5 ha minimum mapping unit (MMU), it does not exclude separate industrial agricultural plantations (mainly rubber trees and oil palms) from its forest class, as this was not identified to be of importance at the time the map specifications were set and agreed by FDA in April 2014. The challenge was that the map reflected a total tree coverage, including plantations, and thus reflects a significantly biased natural forest tree cover area and is consequently unsuitable to serve as a baseline for REDD+ for MRV under the forest definition of Liberia.

The present project´s objective was to update the Land Cover and Forest Map to reflect the national forest definition, which will be a crucial component for taking stock of Liberia's forest according to the official forest definition. The updated forest extents along with ongoing REDD+ activities by the FAO will advance the REDD/REDD+ readiness implementation in Liberia. The updated and fully forest compliant map will constitute the baseline for setting-up a Monitoring Reporting and Verification (MRV) system, to monitoring future progress in reducing GHG emissions, to identify market possibilities of a financing mechanism for carbon stock through carbon sequestration and to assure sustainable forest management practices that can mitigate the vulnerabilities to climate change.

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3. Technical implementation and results

This section reports on the technical implementation and results based on the methodologies outlined in the Inception Report.

3.1. Elaboration of technical specifications (Task 1.1)

The objective of this task was to elaborate the exact technical specifications of the final updated map for approval by the FDA prior to project implementation. The technical specifications have been developed from the specifications of the previous mapping project with necessary amendments to reflect the updates required in the ToR. This was done to maintain consistency with the previous product in all areas not affected by the update. This task was completed during the inception phase and its results are presented in the Inception Report and are further reflected in the technical specifications of all deliverables listed in chapter 4.

3.2. Collection and pre-processing of all required satellite imagery and geospatial data (Task 1.2)

The objective of this task was to provide a complete overview of the required input data sets and perform necessary pre-processing to support the Task 2 mapping production (tasks 2.1 – 2.4) and validation (task 3). This task included the identification of all necessary input data, including all suitable EO data on the part of the JV and the ancillary data from FDA. The JV identified all suitable EO products available for processing with a special focus on the technical requirements for the mapping of land cover / land use classes listed in the technical specifications.

This section provides a comprehensive list of suitable input datasets that have been identified, acquired and pre-processed as required during the inception phase to form the basis of all mapping in Task 2 and Task 3 activities. The project reused all of the previously utilized Earth Observation data, namely the national coverage of Landsat 8 and the collection of RapidEye imagery. In addition to that, the project leveraged Sentinel 1 radar imagery (SAR), Sentinel 2 optical imagery, and, wherever needed, high resolution imagery from other sources. Google and Bing base maps have been utilized for subset activities such as validation wherever such imagery is available for the reference year 2015.

3.2.1. Base map for update from previous project

The JV had identified an intermediate map product from the previous project that contains all of the final thematic information at a resolution of 5m prior to the generalization to the target resolution of 10m and the application of the 0,5 ha MMU. This intermediate map product was pre-processed to form the basis of all updates. Part of this pro-processing was the alignment of the pixel grid with that of the Sentinel 2 sensors in anticipation of future change detection based on free and open Sentinel 1 and 2 data for monitoring.

3.2.2. Sentinel 1 & 2

The Sentinel satellite constellation is Europe´s next generation solution for modern land monitoring with a free and open data policy. Sentinel-2 satellites were launched starting in 2015 and gather optical data at greater spatial and temporal resolution than the Landsat satellites do, thus allowing for the detection of seasonal pattern every year given there are enough cloud free observations. An analysis of Sentinel-2 image availability was performed to assess pixel based availability of cloud free imagery to support time series analysis for Liberia. Furthermore, the analysis provides per-pixel information of how many months of cloud free observations are available. This is important to ensure that a time series analysis can draw

samples from the various stages during the growing season. Figure 2 illustrates the results for cloud free observations and number of months with cloud free observations in 2016, respectively. The analysis was repeated for 2017 and 2018.

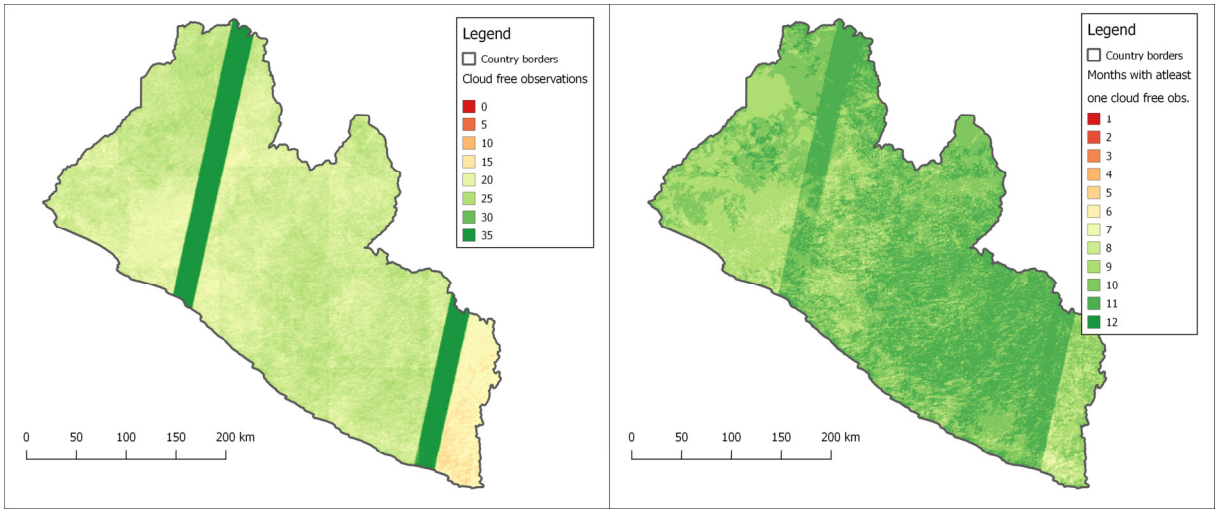

Figure 2: Left: Number of cloud free Sentinel 2 observations (per pixel) during 2016; **Right**: Number of months with cloud free observations (per pixel) during 2016.

It is evident that sufficient cloud free observations are available for a national time series to support the assessment of phenological change in woody vegetation. This was important because the identification of rubber tree plantations strongly depended on the detection of phenological differences between rubber trees and other forest types throughout the year.

Sentinel 1 satellites provide high resolution SAR (radar) imagery at various polarizations. SAR data is not affected by clouds or illumination by the sun. The active sensor provides cloud free images day and night and thus supports the identification of potential oil palm plantations via their regular surface structure as shown in Figure 3.

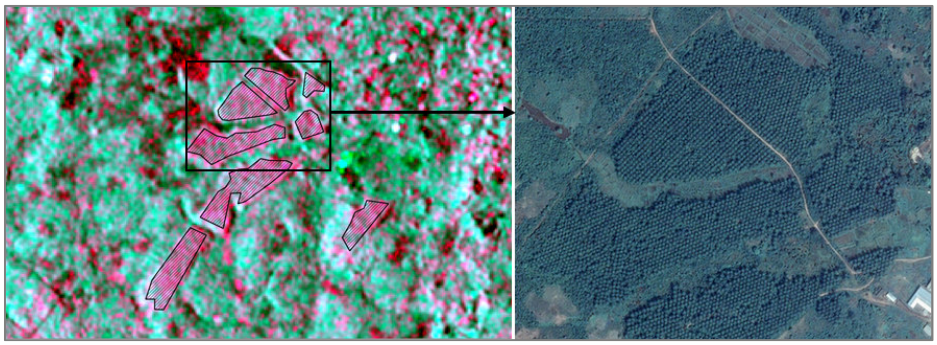

Figure 3: Striped black polygons indicating oil palm plantations on Sentinel-1 false colour composite of different polarizations (R: VV, G = VH, B=VV-VH).

The complete archive of Sentinel 2a and 2b imagery is available for processing at the supercomputer cluster EODC, to which the JV has access. Sentinel 2 imagery was utilized to support the classification of rubber tree plantations in 2015 via their spectral phenology throughout the following years 2016, 2017 and 2018.

Sentinel 2 imagery of 2015/16 was further used to support the detection and extraction of new road networks.

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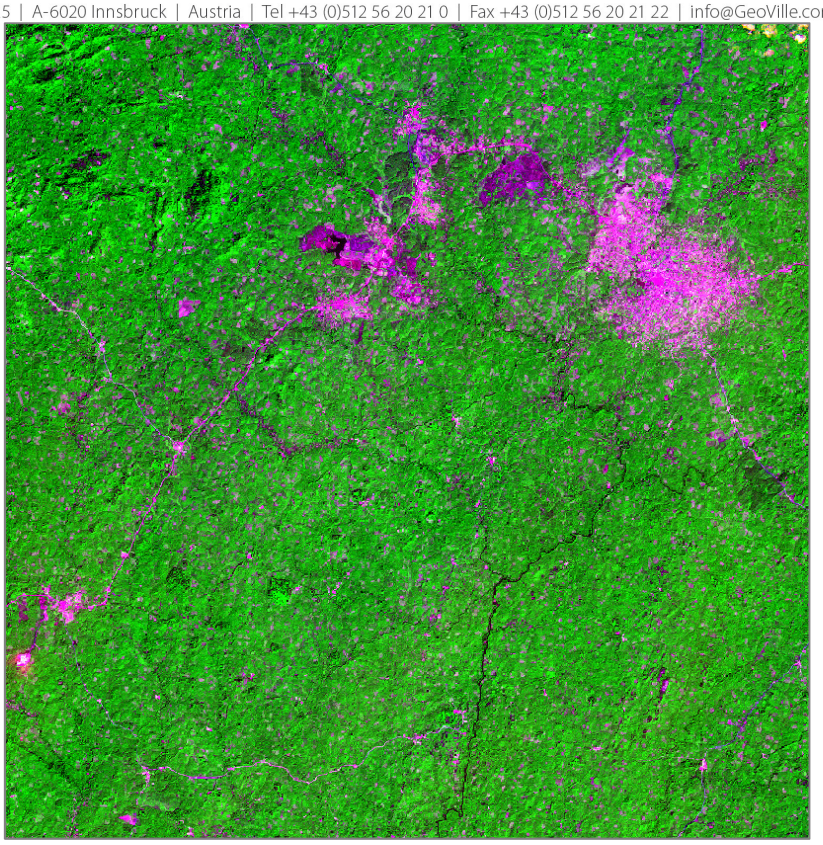

Figure 4: Example of cloud free false colour Sentinel 2 image (Gbamga).

3.2.3. Landsat 8 mosaic & Landsat 8 historic archive

All of the previously utilized Landsat imagery has been reused for the classification of plantations during 2015. In addition, the complete cloud free archive of Landsat 8 images for Liberia between 2014 and 2016 have been downloaded and used in the disaggregation of the 30% - 80% forest density class.

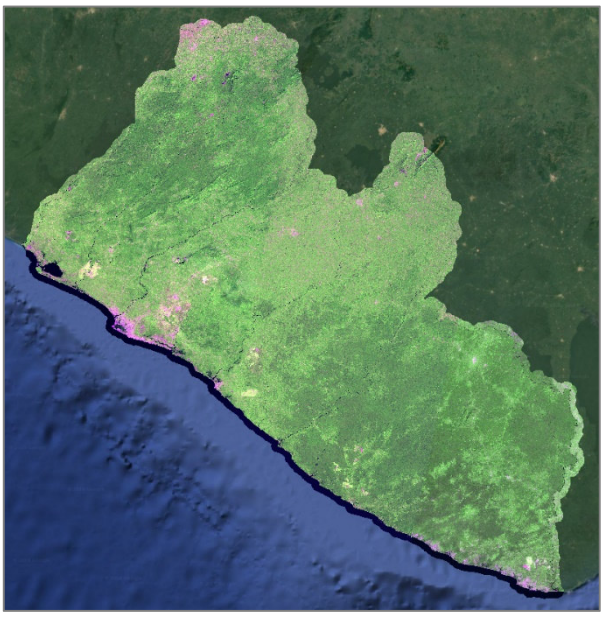

Figure 5: Coverage of Landsat satellite data used in previous project.

3.2.4. Rapid Eye

The available RapidEye dataset has been reused to support the classification and validation work. An almost full coverage is available with RapidEye satellite data (Figure 6) with a spatial resolution of about 6 meters. The EO data was acquired by the satellite sensors during 2011-2013.

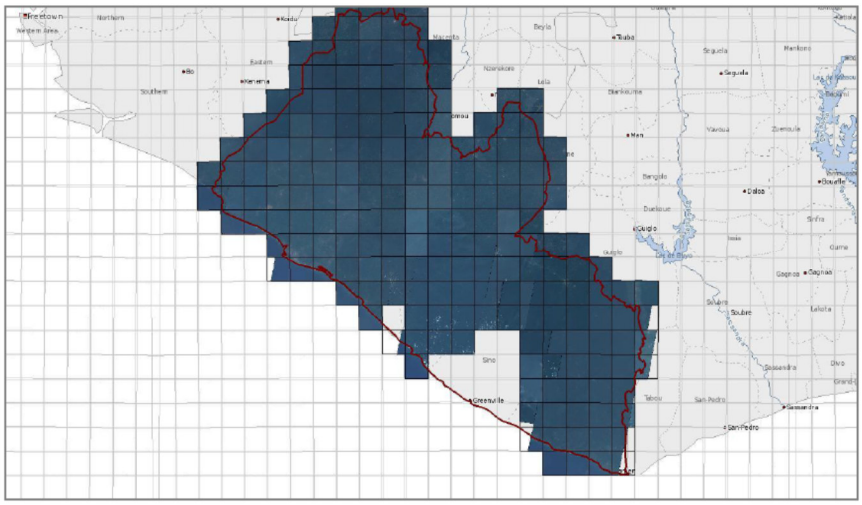

Figure 6: Coverage of RapidEye satellite data.

3.2.5. Ancillary data

Apart from the earth observation (EO) data from satellites, several additional geospatial datasets are available to support the mapping activities under Task 2, most notably Task 2.4 that depends on ancillary data to intersect concession layers with the updated map, but also the mapping and delineation of plantations and the disaggregation of mangroves and swamps from their combined class. These datasets are listed in Table 1.

In order to complete Task 2.4, FDA and the JV GeoVille/Metria need to agree on a selection of layers to be processed in that task as well as a ruleset for intersection.

Table 1: List of ancillary datasets.

Name	Description	Format	Source	Comments
Concession boundaries	Borders of concessions	Vector	Old versions provided by Ministry of Agriculture Liberia & World Bank	Up-to-date delineations needed from FDA/LISGIS (if available) for Task 2.4
Plantations	Borders of industrial / smallholder plantations	Vector	Transparent World	Up-to-date delineations to be provided by FDA/LISGIS (if available)
Mangroves	Mangrove survey data	Vector	Conservation International	Available
Global Mangroves	Mangrove data for 2010	Vector	Global Mangrove Watch	Available
Primary and secondary roads	Lines of streets and roads	Vector	LISGIS, OpenStreetMap OSM	Latest road network; Available

Administrative Borders	Country borders of Liberia and surrounding countries	Vector	Global Administrative Boundaries GADM	Available

3.3. Mapping of rubber tree and oil palm plantations and mangroves (Task 2.1)

Oil palm and rubber tree plantations have been mapped on the national scale to exclude these areas from the forest domain in adherence to the official national forest definition. Conversely, mangrove forests meeting the forest definition must be included in the forest domain and therefore be separated from swamps. Finally, the previous tree cover density classes needed to be reclassified or recoded and an additional 60% threshold introduced.

3.3.1. Mapping of oil palm plantations

The differentiation of oil palm plantations from natural forest is difficult and cannot reliably be done solely using multispectral analysis due the spectral similarity of oil palms and other tree types. The most characteristic features that differentiates oil palms from trees is their orderly surface structure. Oil palms are arranged in regular patterns and oil palms themselves have a common and recognizable crown pattern. Following an in-depth literature analysis, the following methodology was employed in the production of the oil palm plantation dataset (both smallholder and industrial).

Sentinel 1 C-Band SAR imagery of different polarizations was used to identify oil palm plantations and differentiate them from natural forest thus producing a map of potential sites for plantations in 2015. These potential plantation sites needed to be assessed using very high resolution imagery as a purely SAR based detection would result in coarse results and insufficiently accurate delineation, especially for smallholder plantations. Consequently, potential oil palm sites were mapped and subjected to visual interpretation using very high resolution imagery in focus areas (within a 1 km distance buffer of the updated road network) to turn the potential sites into a final layer of oil palm plantations. The differentiation of smallholder and industrial plantations is based exclusively on their detected sizes. Although all other classes in the Rural & Agriculture domain have a MMU of 0.5 ha, plantations effectively have a MMU of 1 ha due to their definition (Smallholder: 1 ha – 5 ha, and industrial: >5 ha). This resulted in the exclusion of any detected plantation of a size of less than 1 ha. Apart from the calculated area of each plantation, their proximity to industrial plantation features was also considered in the disaggregation of the plantations into smallholder and industrial, as industrial plantations often times include smaller patches separated from larger areas by roads or fields, These patches were attributed to the industrial plantation in the immediate surrounding.

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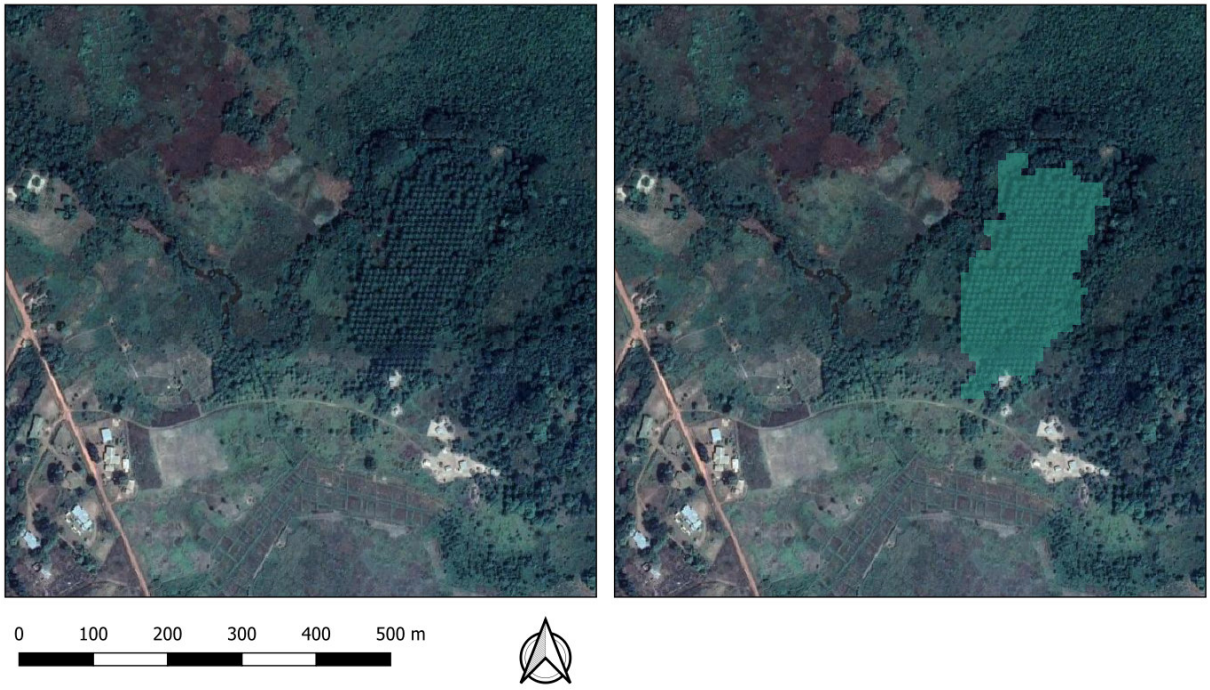

Figure 7: Detection of smallholder oil palm plantations. These plantations were often detected within close proximity to villages.

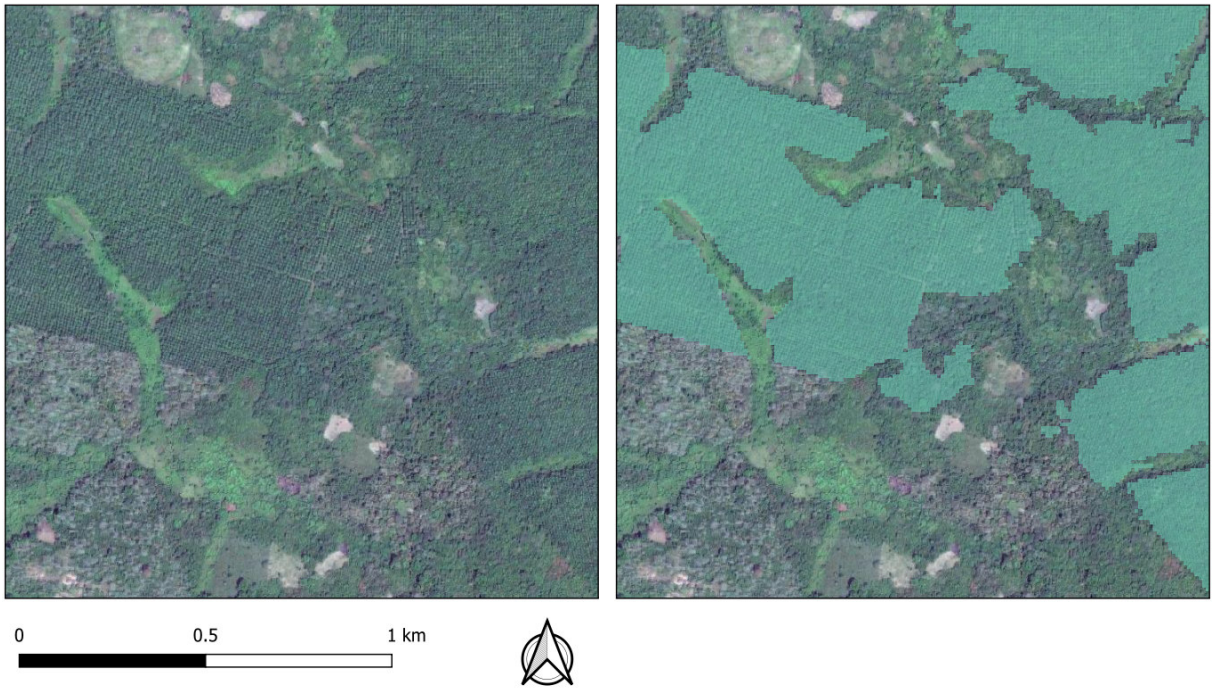

Figure 8: Large industrial plantations were reliably detected and accurately delineated.

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Mapping of rubber tree plantations

Unlike oil palm plantations, rubber trees do have a distinct spectral signature throughout the calendar year. Their defoliation during the dry season results in a particular seasonal patterns on optical spectral indices. Therefore, the mapping was done using spectral analysis of an optical time series. While the plantations are mapped for the base year of 2015, in the case for slowly growing rubber trees, it was decided to utilize the modern capabilities of the Sentinel-2 data archive (2015-2018) to detect rubber trees across Liberia. Since rubber trees take a few years to grow to the point where they are clearly identifiable as such on satellite images, any rubber tree plantations detected in 2016, 2017 and 2018 must have been present in 2015 also. Importantly, newer plantations that did not exist in 2015 have not been mapped.

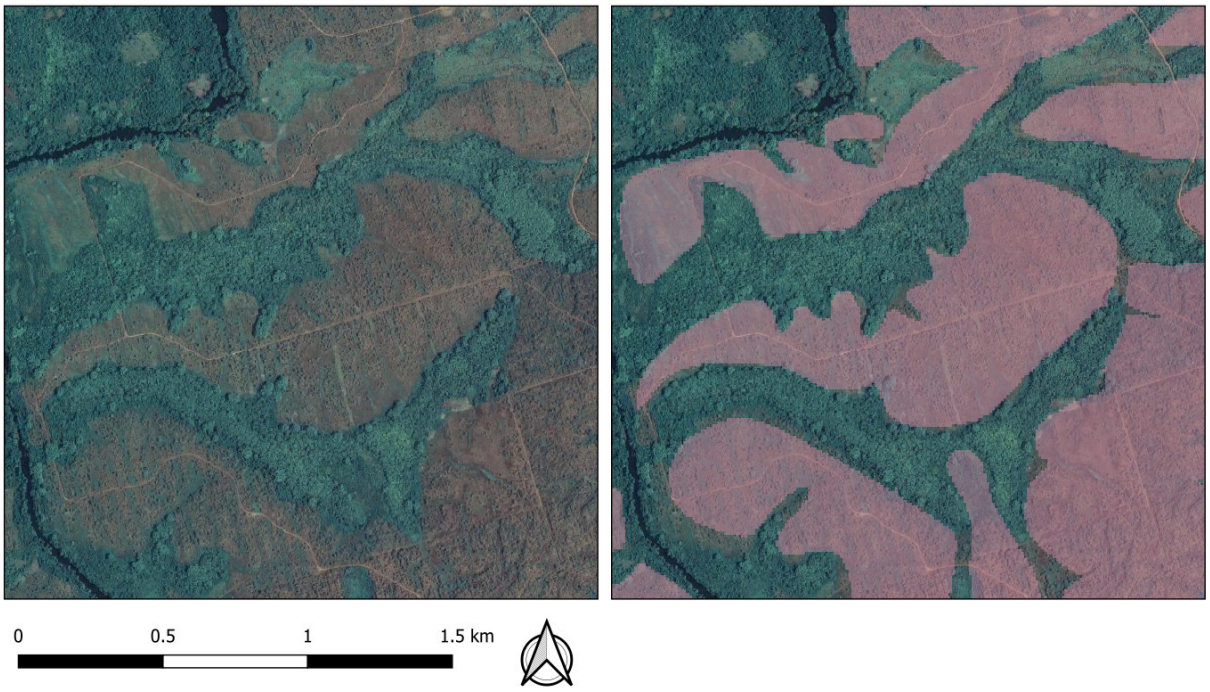

Figure 9: Large industrial plantations were detected and delineated taking advantage of their characteristic seasonal spectral signature, as also evident in the VHR scene in this example.

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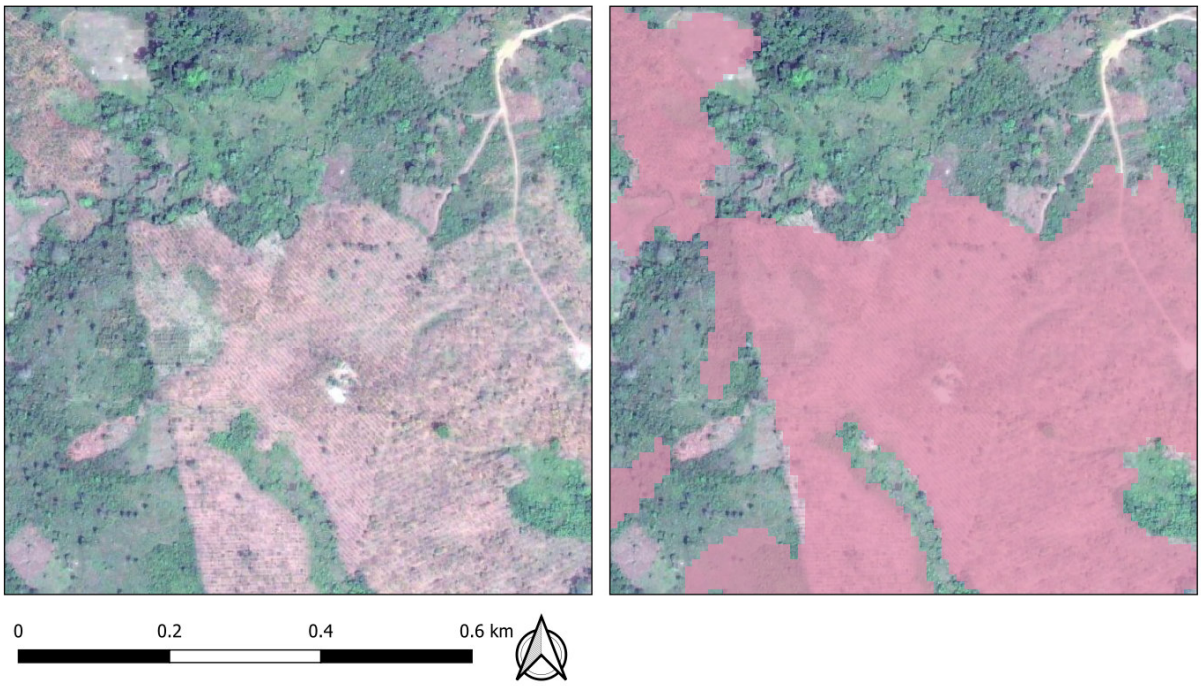

Figure 10: Another example of an industrial sized rubber tree plantation. The typical linear alignment is also evident in the VHR imagery.

3.3.2. Disaggregation of mangrove forest and swamps

The disaggregation of Mangrove Forest from the combined Mangrove & Swamp class was necessary in order to include the Mangrove Forest in the Forest domain and retain the remaining swamps in the Rural & Agriculture domain. Mangrove forest was kept as a separate class within the forest domain and not merged into the existing forest density classes.
Mangrove Forest has been separated out based on spectral separation in the 2015 Landsat imagery supported through information contained in these two existing datasets on Mangroves in Liberia:

- the national mangrove dataset from Conservation International, mapped based on Landsat 8 data from December 2014 – January 2015 and
- the Global Mangrove dataset from Global Mangrove Watch, originally compiled 2010

Both datasets were analysed and compared to each other (Figure 11). The separation of mangroves and swamps was confined to the outlines of the previously combined mangrove & swamp class.

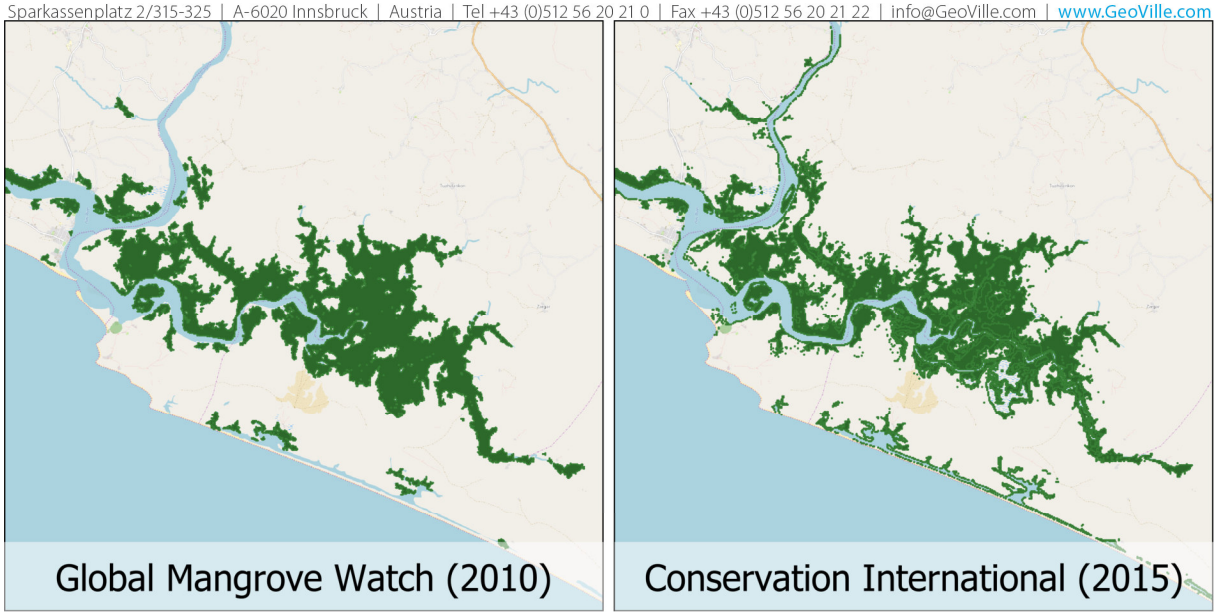

Figure 11: Comparison of ancillary data on mangroves in Liberia.

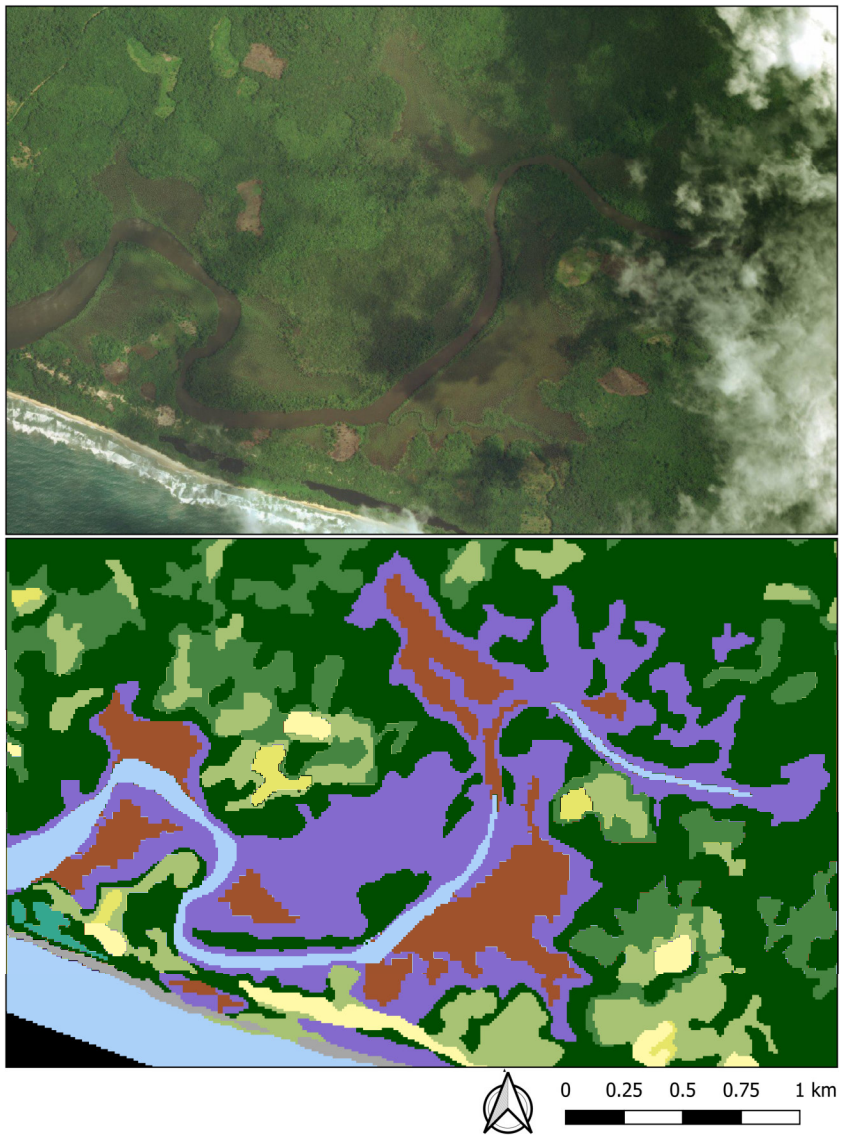

Figure 12: Separation of Mangrove Forest (purple) from remaining Mangroves and Swamps (brown) confined to the area previously occupied by the combined Mangroves & Swamps class.

3.3.3. Forest density disaggregation (new 60% threshold)

The forest density classes were amended to reflect the official forest definition with a minimum threshold of 30% tree crown coverage and the final density classes of 30%-60%, 60%-80% and 80%-100% had been defined. The previous class of <30% density has been recoded into the rural & agriculture domain and will thus no longer be part of the forest domain. The class of >80% tree cover density remains unchanged. The new threshold of 60% was introduced to divide the previous class of 30-80% tree cover density into two classes ranging from 30-60% and 60-80%, respectively. This separation is based on a time series analysis of Landsat 8 imagery captured between 2014 and 2016.

The following table illustrates the three changes to the forest classes as compared to the previous base map, as well as their mode of change:

Table 2: Updates of forest density classes.

Previous tree cover class	Updated class	Conversion mode
<30%	<30% tree cover	Recoding
30% - 80%	30% - 60% forest	Reclassification
	60% - 80% forest	Reclassification
>80%	>80% forest	-

The delineation of the two sub-density classes is based on the occurrence of bare areas within the forest derived from the calculation of bare soil index (BI) and the use of the Hansen Tree Cover Density map as an additional data set. The basic idea of using the bare soil index is based on the contradictory condition between bare soil and vegetation.

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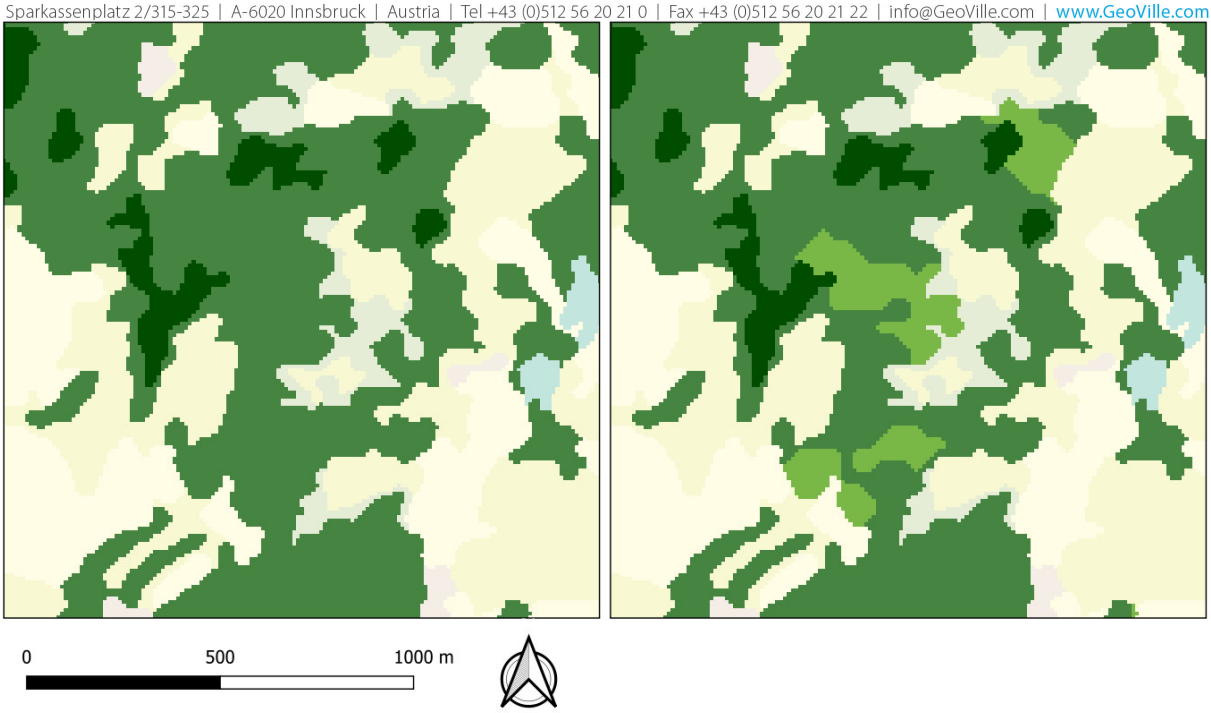

Figure 13: Disaggregation of the 30% - 80% density class (left) into two separate density classes with a 60% threshold to separate them (right). The majority of the area has a density of 60% - 80% tree crown cover and only smaller patches fall into the lower density class (30% - 60%).

In a first step, the bare soil index was calculated based on the Landsat 8 time series from 2014 to 2016 in 30m spatial resolution and Sentinel-2 data from 2015-2016 at a spatial resolution of 10m. This was reclassified into three different bare soil intensity classes as high, medium and low indicator for bare soil occurrence based on meaningful threshold values. Since the BI only indicates the degree of open soil, the Hansen tree cover density map was used as additional indicator to confirm and improve the outcome of the BI. The combination of both datasets was therefore applied on the basis of threshold and logical combination approaches. To meet the requirements of the already available Liberia land cover map, the updated tree cover map is resampled from 30m to 10m spatial resolution and a minimum mapping unit of 0,5 ha for forest sub-categories is applied. In the last step the new tree cover masks, 30-60% and 60-80% were integrated into the existing land cover map of Liberia in the areas previously occupied by the tree cover class with 30-80% density.

3.4. Task 2.2 - Geometric aggregation of forest areas to 1ha MMU

A minimum mapping unit of 1ha has been defined in the official forest definition. This needed to be reflected in the updated Land cover and Forest Map 2015. All classes that fall in the forest domain have been collectively aggregated to a MMU of 1ha, while the individual sub-classes retain a MMU of 0.5 ha within the forest domain.
The sequence of processing steps built upon the ungeneralised, updated forest and land cover map from task 2.1 and is described below.

1. Combining of all single classes into forest / non-forest, and no-data masks, thereby providing separate layers to quickly provide forest cover (forest excluding plantations), non-forest areas (including plantations and tree cover <30%) and no data for areas outside of Liberia´s national boundaries.
    a. Temporarily recoding of the forest domain classes (“Forest 30-60%”, “Forest 60%-80%”, “Forest >80%”, and “Mangrove”) into a single class “Forest”.
    b. Temporarily recoding of all other classes (excluding the no-data to “Non-Forest”.

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   c. No-data (areas outside Liberian territory) are coded "No-data" and will not be affected by filtering.
2. A filter of 1 ha MMU was appllied to the forest/non-forest masks (outputs from 1a and 1b)
3. Reclassifying all resulting forest areas (output 2a) into the separate, ungeneralised forest classes of the intermediate full legend map.
4. Reclassifying all resulting non-forest areas (output from 2) into the separate, ungeneralised non-forest classes of the intermediate full legend map.
5. Merge of reclassified forest and non-forest areas (outputs 3 & 4) with no-data areas and combination into one complete dataset again.
6. Recoding, reformatting and colour coding of the aggregated output from step 5 according to the specifications defined in the Inception Report.

The reason for these complex filtering procedure is to ensure that forest or non-forest patches will have a MMU strictly adhering to the forest definition. Internal composition of forest and non-forest areas have been generalised to 0,5ha and forest patches may thus contain sub-category features smaller than 1ha (i.e. areas 0,5ha – 1ha in size).

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3.5. Task 2.3 - Updating of road network

The existing dataset on road network was updated to the reference year 2015. Roads exceeding a width of approx.. 10m were updated using automated change detection based on Sentinel-2 optical imagery, followed by manual enhancement of the automatically generated results. All manual enhancement was performed at a scale of 1:25.000 to produce the dataset for a target scale of 1:50.000. The definition for the four feature classes remains unchanged. The updated road network is submitted as a separate vector layer in ESRI shapefile and kml/kmz formats. Figure 14 illustrates an example of the changes made to updated the road network.

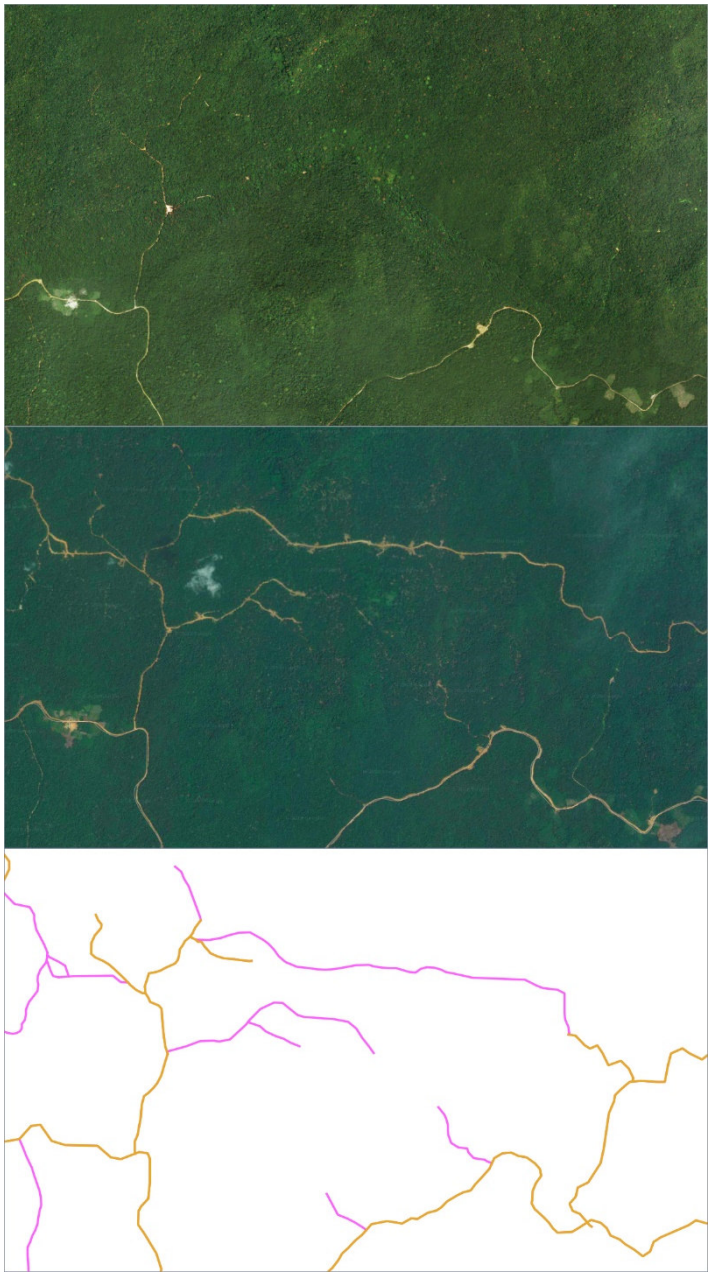

Figure 14: Example of updated road network (bottom, updated roads in purple) and a comparison of 2015 imagery (middle) with pre-2015 imagery of the same area (top).

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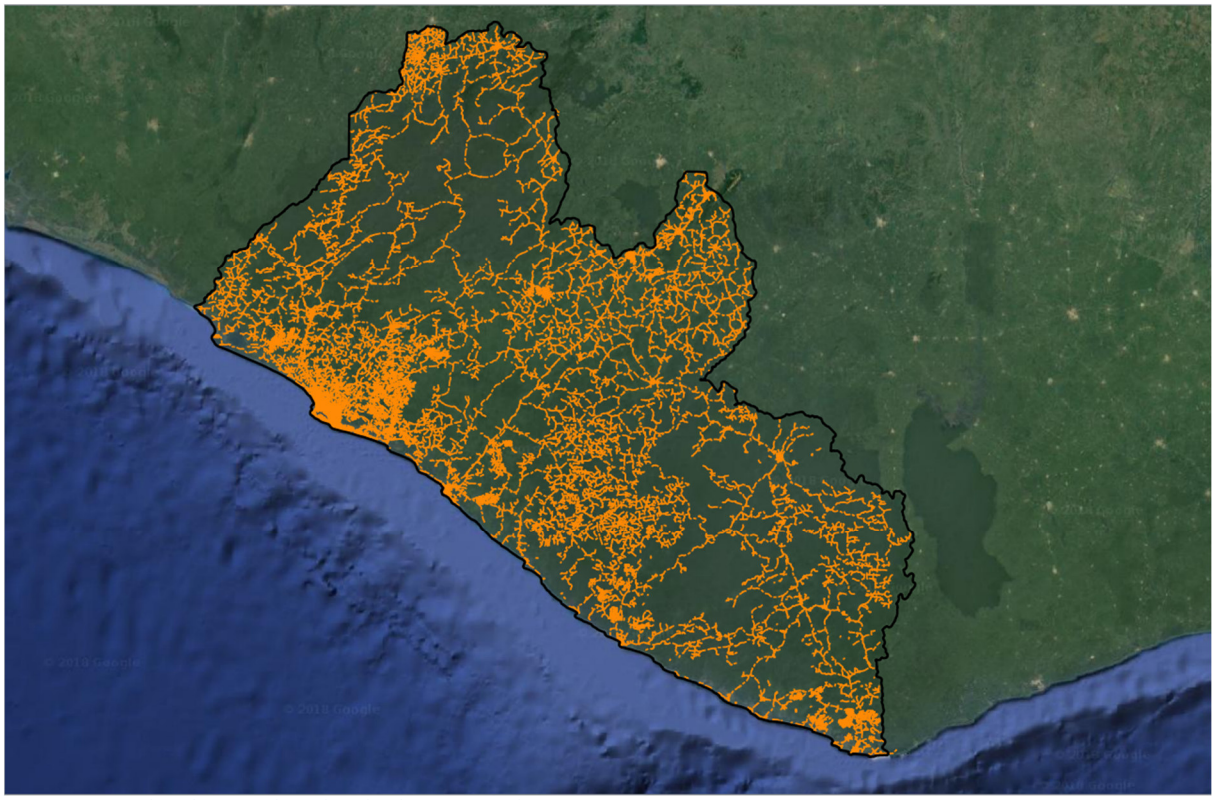

Figure 15: Updated national road and railway network (2015).

3.6. Task 2.4 - Intersection with concession layers

Intersecting existing ancillary data on concessions, protected areas, etc. with the final Updated Land Cover and Forest Map 2015 as a derived product was intended to achieve a more land use oriented representation of forest and non-forest land and identify areas of high conservation value.

In consultation with FDA, a list of suitable datasets has been reviewed and defined for integration along with a ruleset to specify how the information from these layers is to be incorporated into the derived product. For each of the selected ancillary data layers listed below, a target class was defined for every class from the forest domain that intersects the respective layer. Figure 16 illustrates the selected data layers used for the production of the derived map product under this task while Table 3 illustrates the 7 newly defined target classes and their respective codes for the derived map product. Table 3 also specifies which original class is reclassified into which target class wherever polygons of the selected layer intersect areas of the original forest class.

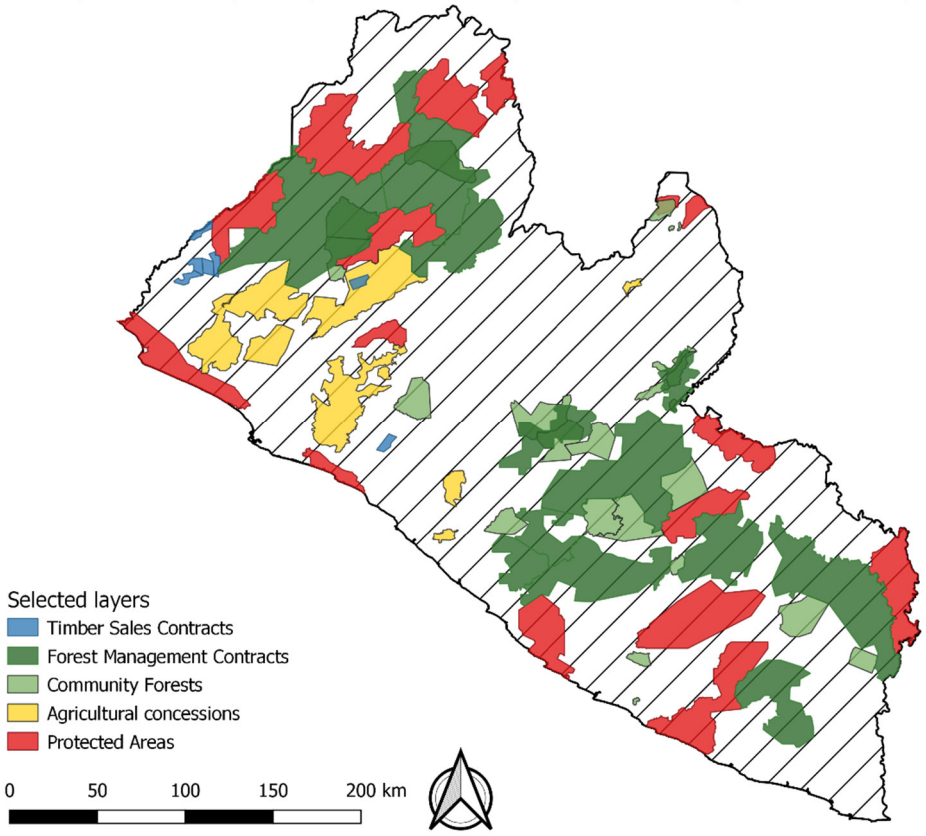

Figure 16: Selected ancillary data layers used for the intersection map product.

- ***Agricultural concessions***
  Forested areas within Agricultural concessions are converted into their respective HCV class (i.e. "*Forest (80% - 100%)*" within an Agricultural Concession polygon is converted to "*HCV (80% - 100%)*" and so on for other forest density classes and Mangrove Forests).
- ***Community Forests***
  Forested areas other than Mangrove Forest are reclassified into Primary Forest (PF_100), Secondary Forest (SF_80) and Disturbed Secondary Forest (DSF_60) in order of decreasing density.
- ***Forest Management Contracts | Protected Areas | Timber Sales Contracts***
  For each of these layers, the original forest classes "Natural and Semi-natural forest (80% - 100%)" and "Natural and Semi-natural forest (60% - 80%)" have been reclassified into Primary Forest (PF_100) and Secondary Forest (SF_80), respectively.

Wherever there are overlaps in the selected data layers, the assignment of the target class follows the ranking with which the layers are listed in Table 3. This is the case, for example, for a TSC feature that overlaps the agricultural concessions layer. In that case, the HCV classes are ranked higher and are thus mapped instead of the PF_100 and SF_80 classes that would have been the result of an intersection with the TSC layer only. The derived product has been subjected to standard formal quality checks but no thematic accuracy is guaranteed as that depends on the accuracy in terms of topicality, accuracy and precision of the input data layers.

Table 3: Ruleset for the integration of selected ancillary data sources into a derived map product.

Domain	Original class	Agricultural concessions	Community forests	Forest Management Contracts	Protected Areas	Timber Sales Contracts
Forest	Natural and Semi-natural forest (80% - 100%)	HCV80_100	PF_100	PF_100	PF_100	PF_100
	Natural and Semi-natural forest (60% - 80%)	HCV60_80	SF_80	SF_80	SF_80	SF_80
	Natural and Semi-natural forest (30% - 60%)	HCV30_60	DSF_60			
	Mangrove forest (>30%)	HCV_MF				

Target class list			Comments
Code	Abbreviation	Name	
19	HCV80_100	Natural Primary forest (80% - 100%) - HCV	
20	HCV60_80	Secondary forest (60% - 80%) - HCV	
21	HCV30_60	Disturbed Secondary forest (30% - 60%) - HCV	
22	HCV_MF	Mangrove forest - HCV	These are less commons but maybe seen along the coast
23	PF_100	Primary Forest (climax forest)- 80%-100%	Intact forest with practically invisible human activities
24	SF_80	Secondary Forest -60% - 80%	Secondary forest with few human impacts but native species are common
25	DSF_60	Disturbed Secondary Forest/Degraded secondary forest - 30%-60%	The forest is distubred or degraded by human activities such as logging, farming & others. Fallow is common

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3.7. Task 3 – Map Accuracy Assessment and Delivery

The target overall thematic accuracy for the existing baseline map had been agreed to be at least 90% for the forest and land cover classes on domain level and this threshold is also applicable to the updated product. Validation is aiming at deriving a reliable statistical quality estimate of the final forest and land cover map. Validation of the resulting map data was using the approach described in the Inception Report, where the updated classes are validated against very high resolution imagery of the reference year 2015. In addition to the statistical evaluation of the map quality (validation), standardized quality checking procedures have been implemented throughout the whole production process in compliance with ISO Quality Management standards. The validation was performed by the JV GeoVille / Metria and is considered as an 'internal', i.e. producer-side validation. The validation of the updated areas throughout the whole country was implemented using the Laco-Wiki validation tool[1], in conformance to ISO9000 standards for Quality Management and the guidelines from the CEOS Working Group on Calibration and Validation, Land Product validation subgroup, and the GEO Quality Assurance Framework for Earth Observation (QA4EO). The evaluation is based on the standard principles for a sampling design, response design and an analysis design including state-of-the-art quality metrics.

3.7.1. Sampling design

A stratified random point sample was used to assess the overall accuracy of the map. The overall point sample is composed of all samples from the previous sample file that fall outside the updated areas and a new stratified random point sample of the updated areas. This way the overall accuracy of the updated map is determined.

The stratified random point sample used in the previous mapping project consisted of 2853 points, of which 717 were removed as they fall within an area affected by the updates to produce a sample of 2136 samples within Liberia but outside of updated territory.

Following the same approach, a stratified random point sample has been produced for all of the updated land cover / land use classes. For each updated class, a minimum of 75 points was used to assure representativeness for local conditions and a narrow confidence interval. For the purpose of the sampling design, industrial and smallholder plantations of each crop type have been combined as their sub-categorization is based entirely on their feature size and not on classification results. For, example, industrial and smallholder oil palm plantations have a combined sample size of at least 75 points spread over the two sub-categories. A total of 1733 samples were created for the updated area of Liberia.

The overall number of applied sampling points finally comprises a set of **3869** (2136 + 1733) samples, 2074 of which were located in the forest domain, 573 in the particular and 1222 in the rural & agricultural domain.

Detailed information on the number of points per class can be found in the following table:

[1] http://www.laco-wiki.net/en/Welcome

Table 4: Number of applied sampling points per land cover and forest class among updated classes

Domain	Class	Code	Number of samples
Forest	Natural and Semi-natural forest >80%	1	847
	Natural and Semi-natural forest 60% - 80%	2	300
	Natural and Semi-natural forest 30% - 60%	3	300
	Mangrove forest (>30%)	4	301
Rural & agriculture	Tree cover <30%	5	316
	Grassland (Savannah)	18	220
	Shrubs	6	215
	Rubber tree plantations	7	300
	Oil palm plantations	9	300
	Plantations of other crops	12	84
	Other mangroves and swamps	13	148
	Ecosystem complex (rocks & sand)	16	94
Particular	Surface water bodies	14	127
	Bare soil	15	76
	Settlements	17	241

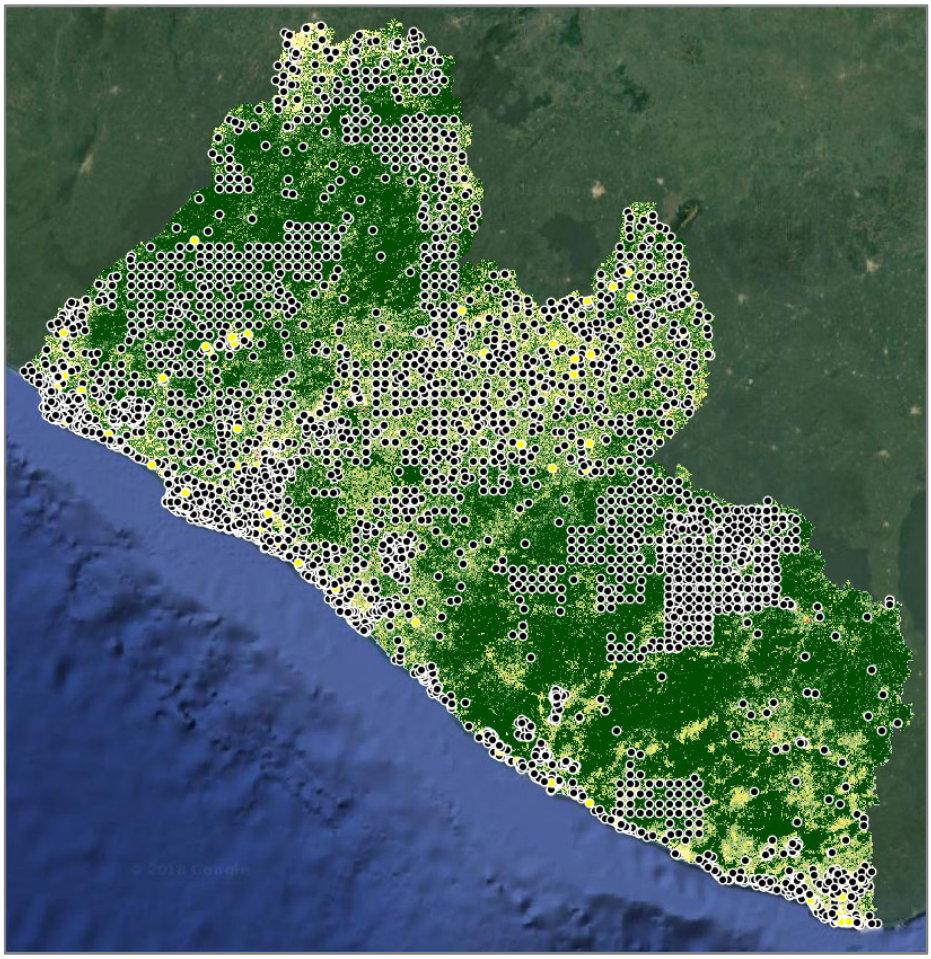

Figure 17: Distribution of the combined samples from the previous mapping (2136) and the samples added for the updated area (1733).

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3.7.2. Response design

Validation and accuracy assessment has been performed with independent very high resolution (VHR) satellite imagery available in Google Earth and Bing Areal Maps (1m resolution or better).

At each sampling point location, the best-possible approximation to ground-truth was extracted through visual image interpretation. The interpretation of the VHR imagery from Google Earth was made for each point, taking into account the minimum mapping area of 0.5 ha or 1 ha for each sample location.

3.7.3. Analysis design

Statistical evaluation was finally carried out by comparing the reference classification derived from the VHR imagery with the classification information contained in the map. The mapping rules with regard to geometric properties have been fully respected during validation, i.e. 0.5 ha minimum area for land cover and 1 ha forest patches.

For evaluation, all single forest and land cover classes are aggregated on landscape domain level.

Table 5: Overview of domain levels

Forest domain	Rural & agricultural domain	Particular domain
• **Forest >80%** • **Forest 60%-80%** • **Forest 30%-60%** • **Mangrove Forest**	• Tree cover <30% • Grassland (Savannah) • Shrubs • Rubber tree plantations • Oil palm plantations • Other/Unknown crop plantations • Other Mangroves & Swamps • Ecosystem complex (rocks & sand)	• Settlements • Surface Water Bodies • Bare soil

Roads were not considered for thematic validation, as these were delivered as a separate shapefile layer.

Internal Validation Results – Nationwide Map

Country-wide validation of the forest and land cover map conducted by the JV GeoVille / Metria reveals an **overall thematic accuracy of 92.63%** on domain level, above the target accuracy of 90%. The map is compliant with the agreed technical specifications.

The overall accuracy of the map is high, with some errors resulting from confusion between classes of the forest and rural & agricultural domain. This is to be expected due to their similar spectral properties in satellite imagery. The update not only made the map compliant with the official forest definition of Liberia but has also introduced more detail and higher accuracy in the definition and delineation of mapped features, especially in relation to plantations.

The validation results have been aggregated to domain level in conjunction with previous validation methodology. The results are presented in the confusion matrix below (Table 6**Fehler! Verweisquelle konnte nicht gefunden werden.**).

Table 6: Confusion matrix to show the accuracies in each landscape domain level as well as the overall correctness of the Updated Land Cover / Land Use Map 2015.

Reference → ↓ Classification	Particular	Rural	Forest	Row Total	*User's Accuracy*[2]	*Commission*
Forest	1946	50	78	**2074**	93.83%	6.17%
Particular	13	531	29	**573**	92,67%	7.33%
Rural & Agriculture	102	13	1107	**1222**	90.59%	9.41%
Column Total	**2061**	**594**	**1214**	3869		
Producer's Accuracy[3]	94.42%	89.39%	91.19%		**92.63%**	
Omission	5.58%	10.61%	8.81%			

Overall Accuracy	**92.63%**

The plantations were detected with very high accuracy due to both the high spectral difference of rubber trees and the use of very high resolution imagery for oil palms. The detection of oil palm plantations was focused on a 1km buffer around the road network and very minor omissions of smallholder plantations outside that focus area are possible. Some inner-domain confusion exists between the new forest density classes (30%-60% and 60%-80%) as the response in a satellite image is very similar between neighboring density classes.

[2] Portion of correctly classified samples in relation to all samples with that classification in the map; this is representing the "correctness" of a class

[3] Portion of correctly classified samples in relation to all samples with that class in reality; this is representing the "completeness" of a class

4. Technical specifications

The following sections outline the technical specifications of the final products in line with their definition during Task 1.1 and outlined in the Inception Report (AD04). Specifications have been updated from the previous activity to match with the new Liberian forest definition and technical requirements set out in the original ToR (AD01).

4.1. Map nomenclature

This section provides an overview of the updated nomenclature of the final map product. The nomenclature follows the top-level domain characterization into forest domain, rural & agricultural, and particular domain as well as the road network, and is compliant with the national forest definition. The updated nomenclature reflects the original ToR (AD01) as well as the recommendations from chapter 3 and is illustrated in Table 7. **Fehler! Verweisquelle konnte nicht gefunden werden.**New classes compared to the initial map are depicted in bold.

Table 7: Proposed nomenclature for updated map.

Domain	Class	Code	Description
Forest	Natural and Semi-natural forest >80%	1	Forest with tree crown coverages of more than 80%
	Natural and Semi-natural forest 60% - 80%	2	Forest with tree crown coverages between 60% and 80%
	Natural and Semi-natural forest 30% - 60%	3	Forest with tree crown coverages between 30% and 60%
	Mangrove forest (>30%)	4	Mangrove forest meeting the national forest definition >30%
Rural & agriculture	Tree cover <30%	5	Open land with sparse tree crown coverage less than 30% that does not qualify as forest
	Grassland (Savannah)	18	Grassland
	Shrubs	6	Shrubs below the minimum threshold of trees
	Rubber tree plantations (Smallholder)	7	Rubber tree plantations 1ha – 5ha in size
	Rubber tree plantations (Industrial)	8	Rubber tree plantations larger 5ha
	Oil palm plantations (Smallholder)	9	Oil palm plantations 1ha – 5ha in size
	Oil palm plantations (Industrial)	10	Oil palm plantations larger 5ha in size
	Plantations of other crops (Smallholder)	11	Plantations of undefined crop types 1ha – 5ha in size
	Plantations of other crops (Industrial)	12	Plantations of undefined crop types 1ha – 5ha in size
	Swamps	13	Swamps, and mangroves not meeting the national forest definition
	Ecosystem complex (rocks & sand)	16	Sandy and/or rocky landscapes

Particular	Surface water bodies	14	All permanent surface water bodies such as ocean, lakes and rivers
	Bare soil	15	Permanently unvegetated soil
	Settlements	17	Settlements
Infrastructure	Primary road	-	Paved roads
	Secondary road	-	Unpaved roads that are not classified as backroads
	Tracks	-	Backroads or tracks
	Railways	-	Railway tracks

The land cover nomenclature for Liberia is oriented at the global LCCS (Land Cover Classification System) standard, originally adopted by FAO/UNEP. The definition of land cover is fundamental, because in many existing classifications and legends it is confused with land use[4]. It is defined as the ***observed (bio)physical cover on the earth's surface***. The goal is to achieve a land cover and forest map excluding industrial (>5ha) and smallholder (>1ha) rubber tree and oil palm plantations, but not to achieve a complete Forest Land Use map. Forest land use, or changes thereof, is not directly observable in satellite imagery and would require additional in-situ data.

In LCCS, land cover classes are defined by a combination of a set of independent diagnostic criteria – the so-called classifiers. By flexibly combining these classifiers, every specific land cover class can be derived for different environmental conditions world-wide. **The selected forest and land cover legend for Liberia represents such a selective combination of LCCS classifiers** and is further explained below.

On the top-level (classifier 1), LCCS distinguishes two main classes according to the *presence of vegetation*:

- Primarily Vegetated Areas: areas that have a vegetative cover of at least 4% for at least two months of the year. This cover may consist of the life forms Woody (Trees, Shrubs), Herbaceous (Forbs, Graminoids) or a combination of them.
- Primarily Non-Vegetated Areas: areas that have a total vegetative cover of less than 4% for at least 10 months of the year.

The 2nd level (classifier 2) separates according to the area's edaphic condition:

- Terrestrial Areas: The vegetation or cover is influenced by the edaphic substratum.
- Aquatic or Regularly Flooded Areas: The environment is significantly influenced by the presence of water over an extensive period of time.

On the 3rd level (classifier 3) the artificiality of the land cover is added which allows determining 8 distinct land cover classes.

Finally, to achieve a distinct definition of each land cover class, each class is further described using a variety of environmental attributes, such as type of life form, cover, physical status or surface aspect.

[4] Land use is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. Definition of land use establishes a direct link between land cover and the actions of people in their environment.

The full classification of all forest and land cover classes to be mapped in Liberia according to the LCCS standard and the different classifiers is shown in Table 8.

Table 8: Description of class content according to LCCS standard

Classes for Liberia forest and land cover mapping	Class Content according to LCCS			
	Classifier 1: Presence of vegetation	**Classifier 2: Edaphic condition**	**Classifier 3: Artificiality of cover**	**Environmental Classifiers**
Natural and Semi-natural forest >80%	Primarily vegetated	Terrestrial	Natural & semi-natural vegetation	- Life form: trees - Cover: closed >80%
Natural and Semi-natural forest 60% - 80%			Natural & semi-natural vegetation	- Life form: trees - Cover: open 60% - 80%
Natural and Semi-natural forest 30% - 60%			Natural & semi-natural vegetation	- Life form: trees - Cover: sparse 30% - 60%
Tree cover <30%			Natural & semi-natural vegetation	- Life form: trees - Cover: very sparse ~10% - 30%
Grassland (Savannah)			Natural & semi-natural vegetation or cultivated & managed areas	- Life form: herbaceous / graminoids
Shrubs			Natural & semi-natural vegetation or cultivated & managed areas	- Life form: shrubs / herbaceous / graminoids
Rubber tree plantations			Cultivated & managed terrestrial areas	- Life form: Woody plants (trees, shrubs)
Oil palm plantations			Cultivated & managed terrestrial areas	- Life form: Woody plants (trees, shrubs)
Plantations of other crop type			Cultivated & managed terrestrial areas	- Life form: Woody plants (trees, shrubs)
Mangrove forest		Aquatic or regularly flooded	Natural & semi-natural vegetation or cultivated aquatic or regularly flooded areas	- Life form: trees - Water seasonality: water logged

Swamps			Natural & semi-natural vegetation or cultivated aquatic or regularly flooded areas	- Life form: shrubs - Water seasonality: water logged
Surface water bodies	Primarily non-vegetated		Natural or artificial waterbodies	- Physical status: water (standing or flowing)
Bare soil		Terrestrial	Bare areas	- Surface aspect: unconsolidated bare soil
Ecosystem complex (rocks & sand)				- Surface aspect: consolidated rock or sands
Settlements			Artificial surfaces	- Surface aspect: built-up, non-linear
Primary road (paved)				- Surface aspect: built-up, linear - Road, paved
Secondary road (unpaved)				- Surface aspect: built-up, linear - Road, unpaved
Tracks (backroads)				- Surface aspect: built-up, linear - Road, unpaved
Railways				- Surface aspect: built-up, linear - Railway, unpaved

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4.2. Technical characteristics

The primary technical deliverable is a digital geospatial map updated to be compliant with Liberia's national forest definition, including an updated road network. All datasets are delivered in digital GIS-ready format (GeoTiff for raster, shp,kml,kmz for vector) with ISO conform metadata for the map product.

The target overall thematic accuracy has been agreed for the initial Forest and Land Cover map to be at least 90% for the forest and land cover classes on domain level. The spatial resolution and accuracy requirements defines the spatial resolution as

- ≥1 ha area for land cover and forest patches
- ≥10m width for linear features

The required geometric accuracy (geolocation accuracy) of the EO derived maps is better than 1 pixel RMSE / CE95.

The cartographic reference system used within the project for the processing and delivery of all imagery and the map layers is WGS 84 / UTM zone 29N; with EPSG code: 32629 See https://www.epsg-registry.org/

The following specifications apply to the final map product:

Coverage:	Liberia (national coverage)
Area:	approximately 97'078 km^2
Geometric accuracy:	<1 pixel
Spatial resolution:	10 meters
Geographic Datum:	WGS 84
Spatial Reference System:	UTM Zone 29N
EPSG code:	32629
Format:	GeoTIFF
Reference year:	2015

The following specifications apply to the updated road network:

Coverage:	Liberia (national coverage)
Digitizing scale:	1 : 25'000
Target scale:	1 : 50'000
Geographic Datum:	WGS 84
Spatial Reference System:	UTM Zone 29N
EPSG code:	32629
Format:	ESRI Shapefile
Reference year:	2015

5. Deliverables

5.1. Inception Report (D1)

Name (file name)	Inception Report (D1_Inception_Report_v1_GeoVille-Metria_20180523.pdf)
Description	Technical Report including work plan and draft product specifications to be approved FDA.
Type	Report
Format	PDF
Submission date	24.05.2018
Details	

5.2. Progress Reports (D2)

Name (file name)	Progress Report 1 & 2 (D2a Progress Report 1.pdf, D2a Progress Report 1.pdf)
Description	Technical Report including work plan and draft product specifications to be approved FDA.
Type	Report
Format	PDF
Submission dates	18.06.2018 (Progress Report 1); 23.07.2018 (Progress Report 2)
Details	

5.3. Final Report (D3)

Name (file name)	Final Report (LCF_2015_Final_Report.docx)
Description	Final report summarizing project activities, incl. the presentation of all results, deliverables and validation statistics.
Type	Report
Format	PDF
Submission date	14.02.2019
Details	

5.4. Updated Land Cover and Forest Map 2015 (D3)

Name (file name)	Updated Land Cover and Forest Map 2015 (LCF2015_Liberia_32629_10m.tif)
Description	Technical deliverable
Type	GIS-ready digital map

Format	GeoTIFF, PDF, PNG, Analogue copies (3)
Submission dates	19.12.2018
Details	Analogue copies posted to FDA on February 14th, 2019

5.5. Metadata (D3)

Name (file name)	Land Cover and Forest Map 2015 metadata (LCF2015_Liberia_32629_10m_metadata.xml)
Description	ISO standard conform metadata file for the updated Land Cover and Forest Map 2015.
Type	Technical deliverable
Format	XML
Submission dates	19.12.2018
Details	

5.6. Road Network (D3)

Name (file name)	Updated Road Network 2015 (Liberia_road_and_railway_network.*)
Description	Updated road and railway network for 2015 consisting of railroads and three road classes.
Type	Technical deliverable
Format	SHP, KML, KMZ
Submission dates	19.12.2018
Details	

5.7. Derived product incl. concessions and protected areas (D3)

Name (file name)	Intersection product (ConservationMap_Liberia_32629_10m.tif)
Description	Conservation product derived from the intersection of conservation and management layers (shp) with the Updated Land Cover and Forest Map 2015 (LCF2015_Liberia_32629_10m.tif)
Type	Technical deliverable
Format	GeoTIFF, PDF, PNG, Analogue copies (3)
Submission dates	14.02.2019
Details	Analogue copies posted to FDA on February 14th, 2019

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6. Outlook

6.1. Monitoring Forest development using the Sentinel program

The updated Land Cover and Forest Map 2015 is intended as baseline for national REDD+.activities and as such subject to comparison with future monitoring of land cover and land use changes with a special focus on the domain of forestry.

The present baseline map for 2015 was predominantly based on Landsat-8 and RapidEye imagery and to some extent utilized the capabilities of the modern Sentinel program. The latter has launched in 2015 and has become the de-facto standard in modern satellite based monitoring at scales ranging from local to national and continental areas of interest. The unprecedented amount of **free and open data** available from the Sentinel satellites is owed to the high temporal frequency with which the satellites observe every location on Earth. Coupled with their high spatial and spectral resolution, they are perfectly suited for regular monitoring activities and hold the potential to inform REDD+ activities with very high accuracy, consistency and reliability. Modern satellite based monitoring is not restricted by data availability as much as it used to be, now that the Sentinel satellites are fully operational and have gathered up to three years´ worth of data. Leveraging information from this wealth of observational data requires **supercomputing power and advanced, highly automated algorithms** to consistently repeat the assessment of forest resources at predefined intervals.

This potential is currently leveraged all over the globe and it is strongly recommended to build on the results of this project to establish consistent, satellite based monitoring of Liberia´s rich forest resources and inform national policies aimed at their sustainable management and protection of Liberia´s forest resources.

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