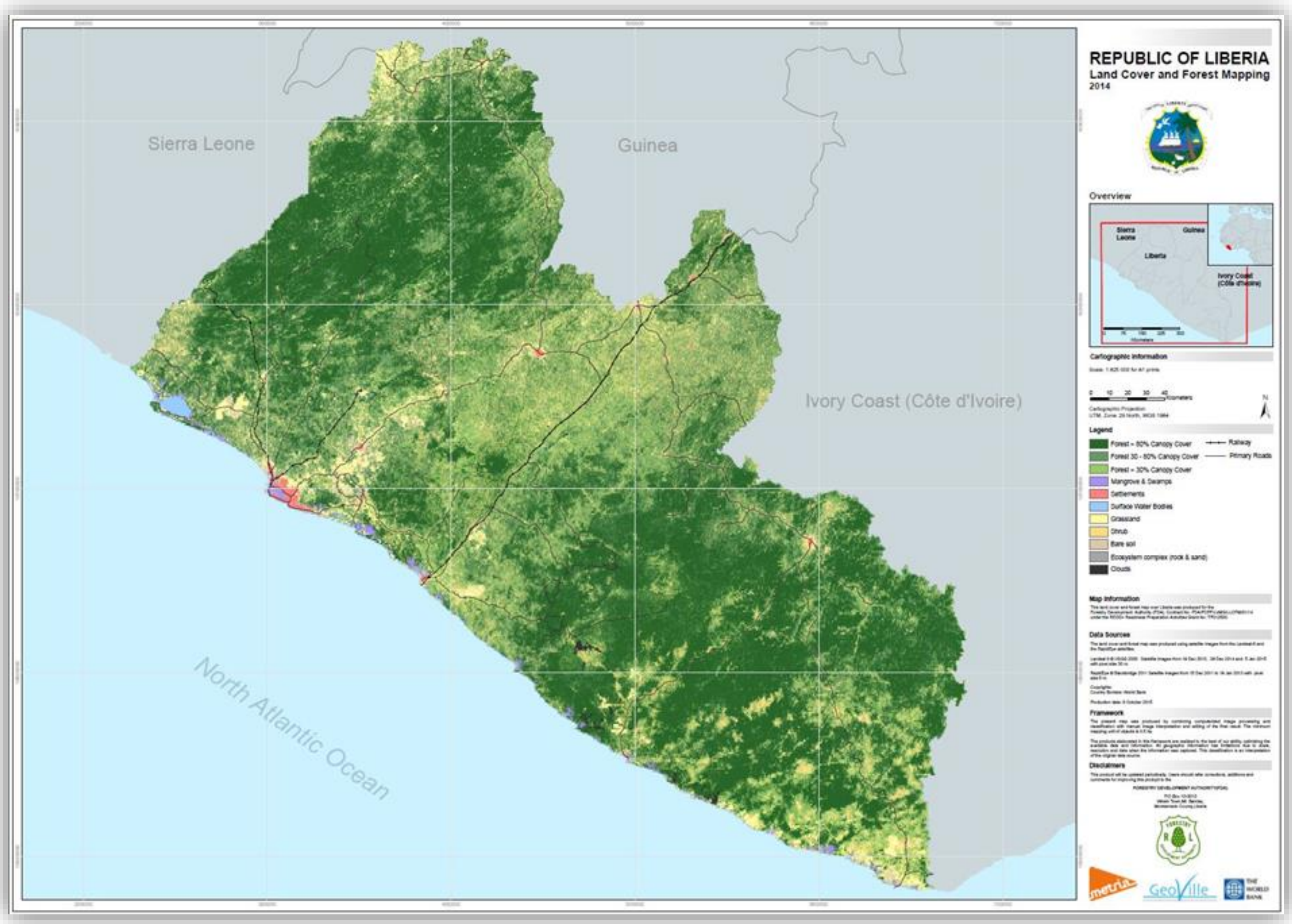
Final Report

LIBERIA LAND COVER AND FOREST MAPPING

FOR THE READINESS PREPARATION ACTIVITIES OF THE FORESTRY DEVELOPMENT AUTHORITY



PREPARED BY METRIA AND GEOVILLE

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1 Definitions, acronyms and abbreviations

CE95	Circular standard Error at the 95% confidence level
CEOS	Committee on Earth Observation Satellites
DEM	Digital Elevation Model
EO	Earth Observation
EPSG	originally "European Petroleum Survey Group" now: Geodetic Parameter Dataset (EPSG codes) maintained by IOGP
FAO/UNEP	The Food and Agriculture Organization of the United Nations / United Nations Environment Programme
FDA	Forestry Development Authority
GADM	Global Administrative Areas Database
GEO	Group on Earth Observations
GIS	Geographic Information system
IOGP	International Association of Oil & Gas Producers
IT	Information Technology
LCCS	Land Cover Classification System
LISGIS	Liberia Institute of Statistics and Geo-Information Services
LU/LC	Land Use / Land Cover
MMU	Minimum Mapping Unit
MRV	Monitoring Reporting and Verification
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra-Red
OLI	Optical Land Imager (sensor on Landsat-8)
OSM	Open Street Map
QGIS	Quantum GIS (open source)
REDD+	Reducing Emissions from Deforestation and forest Degradation - Plus
RMSE	Root Mean Square Error
SRTM	Shuttle Radar Topographic Mission
SWIR	Short Wave Infra-Red
TOA	Top Of Atmosphere
UTM	Universal Transverse Mercator (map projection)
WGS84	World Geodetic System 1984
WB	World Bank

2 Applicable Documents

AD01	Consulting Services Contract "To Conduct Liberia's Land Cover and Forest Mapping" Contract No.: FDA/FCPF/JVMG/LLCFM/01/14 between FDA and JV Metria/GeoVille; February 24,2014
AD02	Technical specifications; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; July 14, 2014
AD03	Project management plan; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; March 5, 2014
AD04	Inception Report; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; August 25, 2014
AD05	Validation report - initial 10%; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; August 25, 2014
AD06	Internal Validation Report; December 16, 2015
AD07	Draft Roadmap for Training, ; Contract No.: FDA/FCPF/JVMG/LLCFM/01/14; December 23, 2014

3 References

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4 Executive summary

The Government of Liberia through the Forestry Development Authority (FDA) has received a grant from the Forest Carbon Partnership Facility (FCPF) for advancing the REDD+ readiness work in Liberia. The establishment of a geospatial inventory of forest cover and land cover is a crucial step towards taking stock of Liberia's forest and providing a baseline for future Monitoring, Reporting and Verification (MRV) in REDD+.

Based on the mapping of selected areas in North-Western Liberia completed by Metria AB, Sweden, and GeoVille Gmbh, Austria, funded by the European Space Agency (ESA) in 2012, FDA recognized that a nation-wide mapping of forest and land cover could be most efficiently implemented using an approach utilizing high-resolution, multispectral satellite imagery. Therefore, FDA procured through an international public tender the production of a satellite based land cover and forest map of Liberia for advancing their REDD+ readiness preparation activities. The objectives of the assignment were to select existing digital mapping software programs for forest cover mapping to be applied in Liberia, produce the digital forest and land cover map covering entire Liberia along the technical specifications of FDA as well as conduct training of local staff in using and updating the map data.

The Liberia Forest Mapping project, summarized in this report, kicked-off in March 2014. A Joint Venture of Metria AB and GeoVille GmbH has produced the first ever high resolution forest and land cover map of Liberia over about 96 320 km² land area. The map was obtained from a cloud-free, homogenous satellite image database acquired over Liberia in the years 2013-2015 in in 5-30 meter spatial resolution and delivered to FDA in GIS-ready format in autumn 2015. The thematic content of the forest and land cover database was decided together with FDA, LISGIS, World Bank and other stakeholders in a workshop in Monrovia held in late April 2014. Importantly, the nomenclature for the recent baseline map produced in this project is oriented at the global LCCS (Land Cover Classification System) standard, adopted by FAO/UNEP, and also thematically compliant to the 2004 historic land cover map created by Bayol/Chevalier in 2004. **In terms of thematic content, a range of forest and land cover classes has been mapped, characterizing tree-covered areas with varying canopy densities (> 80% / 30 – 80% / <30%), as well as specific land cover types related to the rural, agricultural and particular domain, such as urban and rural settlements, shrubland, grassland, surface water bodies, bare soil, rocks and sand.** In addition, a consistent linear network of major roads as well as rivers was created. Further characterization of the landscape was provided through a classification of slope classes derived from an Elevation Model. Compared to the existing 2004 map, the spatial detail is increased from a minimum mapping unit of 10 ha to down to 0.5 ha area for land cover and forest patches and ≥10m width for linear features, while the required geometric accuracy (geolocation accuracy) is better than 1 pixel (30m) RMSE / CE95.

Accuracy assessment and thematic validation of the resulting map data was performed in a two-tier approach: 1) Initial validation was done through ground control data collected by FDA experts during a 2-week field campaign in selected regions in South-Eastern Liberia in late 2014; 2) Country-wide validation in conformance to ISO9000 standards for Quality Management, 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) was completed in autumn 2015 by an independent team at the Joint Venture using very-high resolution reference image data. **Both, the field based (90.22%) and independent image based method (90.57%) yielded an overall thematic accuracy well above the required target accuracy of 90%.**

A dedicated one-week training and capacity building mission was done by two experts from the JV Metria/GeoVille in May 2016, where local stakeholders were informed and trained in the usage and potential of satellite-based mapping and monitoring of forest and land cover.

The new forest and land cover map of Liberia constitutes a baseline very close to the national forest definition, which was adopted after the finalisation of the map product in January 2016. This new forest definition requires stocktaking of Liberia's forest cover with a 30% minimum canopy cover, a 5 meter minimum height and a 1ha minimum area. The new high spatial resolution baseline map represents the ideal basis for future regular, computer-assisted monitoring, as different types of forest definitions (e.g. REDD+, FAO, UNFCCC) can be derived through GIS-based spatial aggregation. Nevertheless, the current map does not fully conform to the new forest definition in its thematic content, as it does not yet exclude industrial agricultural plantations from its forest class. , as this was not known to be of importance at the time the map specifications were set by FDA. **In order to be fully compliant with Liberia's national forest definition and serve as a baseline to enable forest monitoring in support of REDD+ Monitoring, Review and Validation (MRV) activities, specific thematic refinements (e.g. mapping of industrial plantations and generalization of the forest cover class with less than 30% cover according to the 1 ha MMU definition) shall be implemented.**

New generation high-resolution satellite data, such as offered by the Sentinel-2 mission operated by the European Space Agency, provides a new capacity for delivering high-quality, recurring image coverages for long-term monitoring systems. Coupled with novel data mining, image classification and pattern recognition techniques, the above mentioned refinements can be implemented by applying cost-efficient, automated feature detection methods for improving the information base of Liberia’s natural resources.

5 Scope of Document

This document is the Final Report which is summarizing the work and results of the Liberia Land Cover and Forest Mapping project performed by the Joint Venture JV Metria/GeoVille under contact from the Liberian Forestry Development Authority as part of the REDD+ readiness preparation activities.

The document describes the project tasks, data requirements, thematic and technical specifications, input data and processing steps performed and validation results. A list and description of all the datasets and results in the final deliverables is appended.

The objective of the Consultant assignment has been to provide a forest and land cover mapping covering Liberia as well as conducting training in using and updating the maps, in particular regarding the monitoring of forestry activities.

The report is concluded with a discussion on the suitability of the results to serve as the baseline information required for the Monitoring Reporting and Verification (MRV) System. The conclusion is that, although the results were produced based on a slightly different forest definition than the recently adopted official forest definition agreed upon at the National Forest Definition Conference in Voinjama, Lofa County (Jan 25-29th, 2016), the produced Land Cover and Forest Map data of Liberia can be updated by excluding industrial oil palm and rubber tree plantations.

6 Project Background

The Government of Liberia, through the Forestry Development Authority (FDA), has received grants from the Forest Carbon Partnership Facility (FCPF) for advancing of the REDD readiness work in Liberia. One part of this work involves 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 implementation of an MRV system requires the establishment of the the historic rate of forest loss and the initial forest area at the start of the monitoring period which in combination will define the reference level for comparisons of the real forest area change and carbon loss. The baseline forest map will assist Liberia in monitoring the carbon stocks and is of importance to calculate greenhouse gas (GHG) balances. Important information to identify the market potential of a financing mechanism for carbon stock through carbon sequestration and how sustainable forest management practices can mitigate the vulnerabilities of climate change (global warming) at the local, regional and global levels.

The growing importance of forestry sector demands rapid appraisal of forest status, socio-economic conditions and factors responsible for depletion of forest resources and conversion of forest to other land uses. The spatial and statistical data produced within the Liberia Forest Mapping project will be important input to the policy process directed at sustainable development and forest management.

The Government of Liberia has, based on the results of a mapping exercise in North-Western Liberia concluded that national mapping of forest cover and resources should be undertaken. The initial mapping exercise was led by Metria and performed in cooperation with GeoVille. It was selected as a prioritised World Bank project and was part of the EOWORLD project, a joint program with the World Bank that was sponsored by the European Space Agency in 2012.This has now been followed by a nation-wide mapping done with similar technical specifications. The forest and land cover mapping of Liberia is hence based on consistent, scientifically sound, technically proven and successfully validated specifications.

Liberia's forest constitute by far the largest remaining blocks of the Upper Guinean Forest Ecosystem (according to previous forest assessments), making Liberia a global hotspot for biodiversity. If managed sustainably, the forest resources will generate income over time and support rural livelihoods. As a driver for economic development the forest sector should contribute to poverty alleviation and has a responsibility to ensure good governance and public accountability of its activities. Liberian forest authority should support both the forestry industry as well as the community forests widely spread over the country as well as safe guard the ecosystems services, including the remaining biodiversity hotspots of the Upper Guinean Forest.

Forestry production has decreased since the cancellation of all forest concessions in 2005 according to FAO. All FAO figures actually show the need for an updated forest map and inventory as they are rather uncertain over time. According to FAO figures there are 4 329 000 hectares of forest land and other wooded land and a total land area of 11 137 000 hectares, also including 1 505 000 of inland water. According to FAO figures the forest trend since 1990 is a loss of 600 000 hectares, although the figures indicate a linear trend showing the need for improved forest statistics. The growing stock is by FAO estimated to 684 million m^3 and an average of 158 m^3/hectare on forest land.

The latest forest policy and the national forest programme, from 2006 and 2008 respectively, are currently implemented and the forest law is likely to be updated accordingly. Liberia has ratified a large number of international conventions and agreements including CBD, UNFCC, Kyoto Protocol, ITTA, CITES, Ramsar, World heritage convention and NLB. The high ambition requires a baseline of the forest area as well as efficient tools for monitoring of changes. Expanding mining- and agriculture concessions are also part of the pressure on the forests to be taken into consideration. It is clear that extraction of these nature resources will play an important role in the development of Liberia.

For overview and planning of land use in forested areas, assessments and mapping of environmental values and forest resources are needed. Several forest assessments have been made in Liberia. At the end of 1960’s a detailed forest inventory was undertaken in the planned concession areas. After that forest mapping was conducted in a project mapping the natural resources of Liberia in the late seventies and early eighties. No or very limited forest assessments was performed during the civil wars. A post war forest assessment was made with funding from the World Bank. The assessment was based on interpretation and classification of satellite imagery, performed in 2004, and a forest inventory that was designed and partly performed in 2006. The outcomes of these efforts constitute the basis for the current forest concessions. The usefulness of the forest map and forest inventory data forest concession planning and monitoring has been questioned as it has a coarse resolution and changes in forest cover have not neither been monitored with mapping techniques nor has the forest inventory been densified or repeated to continuously monitor the status of the forest areas.

6.1 Task description

The tasks defined by the contract has been to

a. Develop/select existing digital mapping software programs for forest cover mapping to be applied in Liberia;
b. Conduct mapping and produce validated land cover and forest maps for Liberia; and
c. Conduct trainings for the staff of the Forestry Development Authority, LISGIS and other relevant stakeholders on digital mapping of forest cover and its changes, and on the assessment and extent of illegal harvesting.

7 Technical Specifications of Mapping Products

7.1 Requirements

The technical specifications applied in the current project represent the ideal basis for future computer-assisted monitoring, as similar mappings can be repeated based on new, recurrent satellite observations (e.g. Sentinel-2, Landsat). Based on such map data, different types of forest definitions (e.g. FAO, UNFCCC, REDD+) can be derived by spatial aggregation and/or specific thematic refinements (e.g. considerations of plantations, depending on national needs).

The current map constitutes a baseline very close to the national forest definition adopted in January 2016 with a 30% minimum forest cover, a 5 meter minimum height and a 1ha minimum area. See Chapter 11 on ‘Conclusions and Outlook’ for more information.

A Technical Specifications Document (D2) was submitted in May 2014 and updated in July 2014. The report describes the Technical Specifications of the Earth Observation based mapping products as agreed by FDA, LISGIS, World Bank and local stakeholders as well as the JV Metria/GeoVille in the Technical Workshop held in Monrovia in late April 2014. The Technical Specifications are based on the initial mapping activity in North-Western Liberia funded by the European Space Agency in 2012, and the intensive exchange with World Bank and Liberian users in early 2014 (as documented by the Inception Report).

Based on the user consultations and feasibility analyses, the technical specifications for the new Liberia-wide forest and land cover inventory have been fine-tuned and adapted to match with the following requirements:

- The target area to be covered is all of Liberia
- Geographic thematic content, i.e. thematic classes, must be suitable for a reliable national forest and land cover baseline of Liberia, and serving REDD+ requirements
- Overall thematic accuracy has a target of 80-90% on landscape domain level
- Input data must comprise of an appropriate coverage of recent high-resolution, optical satellite images (spatial resolution between 5 and 30m) and ancillary geospatial data useful for map production,

These specifications formed the basis for the Liberia-wide mapping of forest and land cover from high-resolution satellite data by the JV Metria/GeoVille. The goal was to i) directly serve the needs of REDD+ to create adequate baseline information on Liberia's forest and land cover, ii) apply a widely acknowledged, standardized nomenclature (LCCS), and iii) provide spatially much more detailed and accurate information compared to the previous forest/land cover inventory available for the reference year 2004.

In addition, information on existing IT capacities and expertise in the fields of GIS (Geographic Information Systems), image processing, land mapping and statistical data analysis were systematically collected from local Liberian stakeholders in preparation of upcoming efforts to establish new local capacities and expertise. For future operational updates of the forest and land cover mapping database, utilization of the open-source QGIS system, a powerful software environment for satellite image processing and digital mapping, has been proposed. Additional recommendations with respect to operational implementation of a satellite-based monitoring system, such as internet bandwidth and data storage capacities, have been elaborated and documented as well.

7.2 Digital Map Specifications

7.2.1 Thematic content

The primary technical deliverable is a digital geospatial map database with national forest and land cover of Liberia (about 96 320 km^2 land area) in GIS-ready format (i.e. GeoTiff). In the workshop in Monrovia held in late April 2014, the thematic content of the forest and land cover database was finally decided together with WB, FDA, LISGIS and other stakeholders. Importantly, the envisaged nomenclature for the generating the new 2013 year baseline is thematically compliant to the 2004 historic land cover map created by Bayol/Chevalier in 2004[1]. Hence, the nomenclature follows the top-level domain characterization into forest domain, rural, agricultural and particular domain as well as the road network.

A signed version of the technical specifications as endorsed by the local stakeholders is appended to this document in the Annex 1.

The nomenclature for Liberia is oriented at the global LCCS (Land Cover Classification System) standard, originally adopted by FAO/UNEP. The definition of forest/land **cover** is fundamental, because in many existing classifications and legends it is confused with land use. It is defined as the observed (bio)physical cover on the earth's surface, and does not include a differentiation according to forest/land use and management practices (e.g. plantations).

The services provided within this project are a combination of two specific EO services, a forest classification and a land cover classification.

- The **forest classification** delineates the forest extent and classifies the forest in three forest density classes (> 80% / 30 – 80% / <30%). Moreover, specific elements for classifying woody features from the satellite data include shrubs and mangrove forest.
- The **Land cover mapping** involves a range of non-forest classes compatible to the LCCS classification system and to previous WB activities based on the Bayol 2004 map. For the land cover information the following classes are included: settlements differentiated into urban and rural settlements (given that ancillary data is provided by LISGIS), grassland, surface water bodies, bare soil, rocks and sand. Further characterization

[1] Forest Inventory in Liberia, May 2006, WB contract 71351657, DFS Deutsche Forest service GmbH

of the landscape is provided by a classification of slope classes derived from an Elevation Model, and mapping of the road and railway network (depending on the availability of ancillary data from LISGIS).

In LCCS, land cover classes are defined by a combination of a set of independent diagnostic criteria – the so-called classifiers. By flexibly combining this 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. 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 Annex 2.

It has to be noted that the mapping was done according to tree canopy and land cover observable from satellite imagery. Tree height was reflected by the spectral differentiation between trees and shrub. Besides area, canopy cover and height, **no further criteria for 'forest' definition, such as land use, legal or management aspects were applied. In that sense, we recommend to consider a renaming of the class 'forest' into 'tree cover'.**

7.2.2 Spatial resolution and accuracy

The spatial resolution and accuracy requirements defined and agreed by the Technical Specifications defines the spatial resolution as "minimum mapping unit 0.5 hectares and minimum width 10 m"

- ≥0.5 ha area for land cover and forest patches
- ≥10m width for linear features

Features smaller 0,5ha or narrower than 10m are not mapped.

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

7.3 Input Data

7.3.1 Satellite imagery

The Earth Observation (EO) data procured and used for the forest and land cover mapping of Liberia is a combination of satellite imagery from RapidEye with 5m resolution and 30m resolution satellite imagery from Landsat-8.

RapidEye data

The almost full coverage with RapidEye satellite data (Figure 1) with a spatial resolution of 5 meter available in the archive was collected between December 2011 and February 2013, all during the months of December, January and February. The data were funded by ESA as a continuation of the eoworld project finalised in 2011/2012 at a total cost of approx. 50 000 Euros. These images were acquired with a single user licence with FDA as the End User licensee. All imagery were ortho-corrected data (level 3A) and projected into standard UTM zone 29N covering all of Liberia. A full list of all RapidEye images acquired for the project is found in Appendix I. In total 209 individual images.

The total area possible to cover by cloud-free RapidEye data was approximately 90% of the country. For the additional 10% of the area there were no cloud–free RapidEye images available.

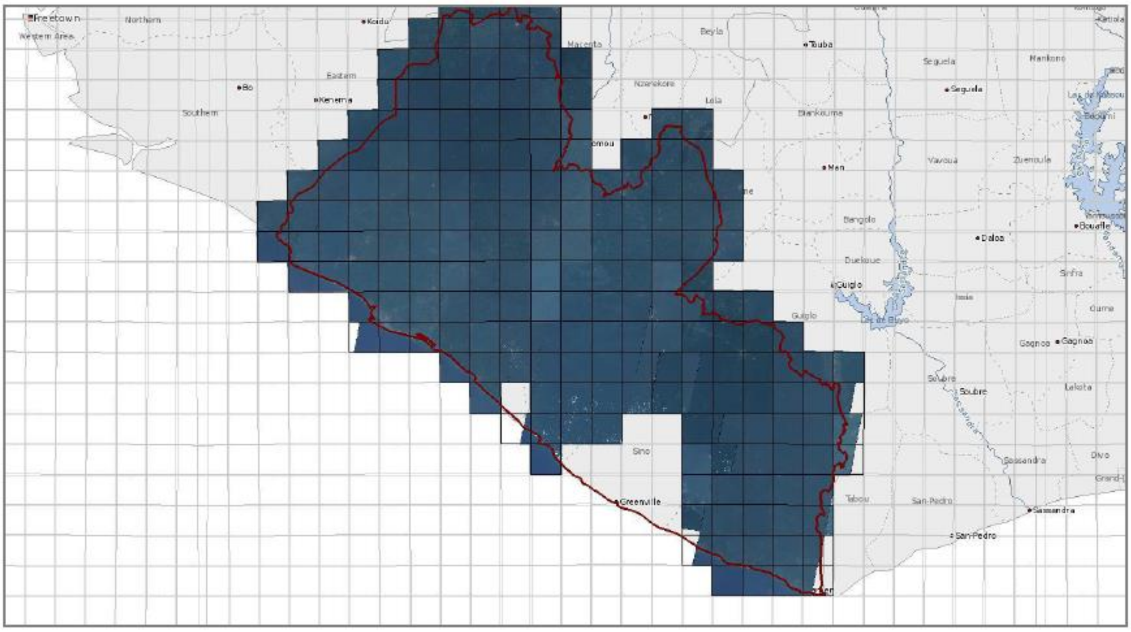

Figure 1. Coverage of RapidEye satellite data – 219 individual image files (90% of the country).

Landsat-8 data

Landsat-8 imagery from 2013 and early 2014 were initially assembled to perform the mapping. A test area corresponding to 10 percent of the total area of Liberia in the eastern part of the country was produced from Landsat-8 data from 19 December 2013.

The delayed full scale production enabled us to assemble an almost cloud-free coverage of up to date Landsat-8 data acquired between mid-December 2014 and mid-January 2015 which was used for the completion of the nation-wide mapping. Landsat-8 data are ortho-corrected into UTM projection of the zone in which the scene center is located. All Landsat-8 scenes covering Liberia are available in UTM zone 29N except the single most western scene (track/frame 201/055) covering a very small piece of Liberia which is delivered in UTM zone 28N and was reprojected into UTM zone 29N before further processing.

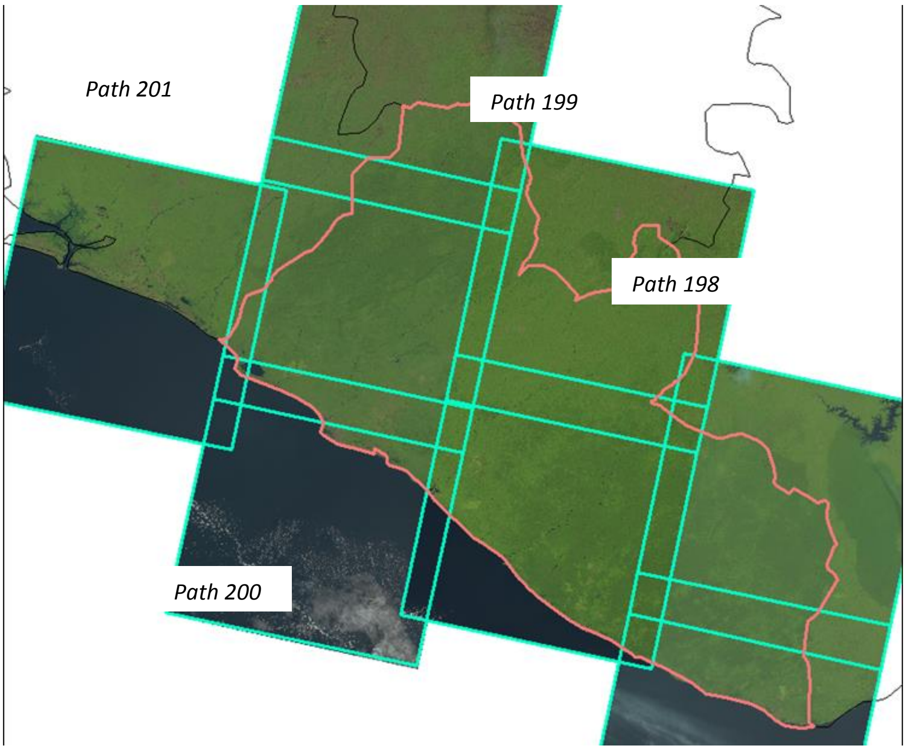

Figure 2. Nationwide coverage of Landsat-8 satellite data – 8 scenes – 4 path mosaics

7.3.2 Ancillary data

In addition to the EO-data from satellites, access to several additional geospatial datasets could be established. Table 1 shows a summary of the ancillary data used as support in mapping and validation.

Table 1. List of ancillary data

Name	Description	Format	Source
Administrative Borders	Country borders of Liberia and surrounding countries	Vector	Global Administrative Boundaries GADM
Land cover	Existing land cover data (e.g. Bayol Liberia Land cover 2004, Globcover 2009, Global Forestwatch)	Vector/ Raster	Various
Settlements	Allowing a differentiation of urban and rural settlements based on inhabitants	Vector	OSM
Primary and secondary roads	Lines of streets and roads	Vector	LISGIS OSM
Hydrology Network	River courses and water bodies	Vector	OSM
Digital Elevation Model	Elevation of surface features and terrain	Raster	SRTM DEM
Concession boundaries	Borders of forest management concessions, community forests, timber sale contracts, agricultural concessions in Liberia	Vector	Provided by Ministry of Agriculture Liberia World Bank
Virtual globe satellite data	High to very high resolution optical satellite images	Images	Google Earth BingMaps
Photos	Geotagged photographs for selected locations in Liberia	Images	Panoramio

7.3.3 Cartographic reference system

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/

Projection parameters used in ArcGIS prj-file:

```
PROJCS["WGS_1984_UTM_Zone_29N",GEOGCS["GCS_WGS_1984",DATUM["D_WGS_1984",
SPHEROID["WGS_1984",6378137.0,298.257223563]],PRIMEM["Greenwich",0.0],
UNIT["Degree",0.0174532925199433]],PROJECTION["Transverse_Mercator"],
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PARAMETER["central_meridian",-9.0],PARAMETER["scale_factor",0.9996],
PARAMETER["latitude_of_origin",0.0],UNIT["Meter",1.0]]
```

Projection parameters in standard WKT (Well-Known Text) format).

```
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  DATUM["World Geodetic System 1984",
   ELLIPSOID["WGS 84",6378137,298.257223563,LENGTHUNIT["metre",1.0]]]],
 CONVERSION["UTM zone 29N",
  METHOD["Transverse Mercator",ID["EPSG",9807]],
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  PARAMETER["Longitude of natural origin",-9,ANGLEUNIT["degree",0.01745329252]],
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  AXIS["northing (N)",north,ORDER[2]],
  LENGTHUNIT["metre",1.0],
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ID["EPSG",32629]]

See http://docs.geotools.org/stable/userguide/library/referencing/crs.html

8 Map Production Methodology

8.1 EO Data Preparation

EO-data are delivered with different file format, map projections and radiometric calibration standards. The preparation of the data for integrated analysis within our internal project standards is an important step for the reduction of many practical data handling problems. The preparation involves the data ingestion and reformatting and the alignment of all datasets into the same map projection, pixel size and radiometric calibration scaling followed by mosaicking of datasets from the same acquisition date to a single dataset.

8.1.1 Data calibration

All satellite images have been radiometrically calibrated into Top Of Atmosphere (TOA) reflectance values with the support of the metadata information about sun elevation angles and radiometric absolute calibration parameters for all individual datasets. This will roughly put all the datasets into a common intensity scale although all atmospheric disturbances from clouds and haze are still present. The haze is a major disturbance present in most of the datasets over Liberia.

8.1.2 Cloud masking

Cloud masks which delineate clouds and cloud shadows were manually drawn for all Landsat-8 and RapidEye images and stored as shape format files. These “cloud masks” were used for removing pixels from all images which could not be used for further processing and mapping. Where overlapping images data were available, the missing data gaps could be filled in by cloud free data from overlapping scenes when mosaicking the final results. In this way the remaining cloud covered area within the Landsat-8 and RapidEye coverage could be minimized. In the Landsat-8 coverage the still cloudy areas amounts to 0.15% of the total area while the area not covered by RapidEye data due to clouds and the unavailability of suitable data in the archives amounts to approximately 10% of the total area.

8.1.3 Mosaicking

In order to simplify the handling and further processing and analysis, all individual satellite images from each individual date and satellite were assembled and combined into separate mosaics. In the case of Landsat-8 these mosaics correspond to the north-south path of the satellite, in total 4 mosaics, while the RapidEye data with acquisition dates between December 2011 and January 2013 are from 30 different dates resulting in 30 different mosaics. Figure 3 shows the single data mosaics of RapidEye images simultaneously acquired.

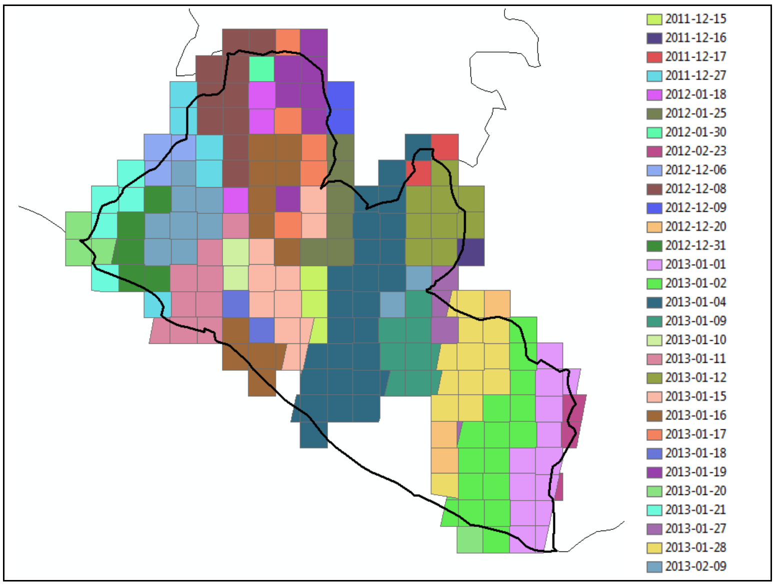


Figure 3. Single date mosaics of RapidEye satellite data

8.1.4 Resolution merging

By combining the RapidEye image mosaics with the Landsat-8 data it has been possible to use the best properties of the different datasets in an optimal way. The higher resolution of the 5m RapidEye data enabled the detailed mapping into 0.5 ha MMU while the better radiometric and spectral properties of the 30m Landsat-8 data enabled better vegetation and forest type classification specifically due to the SWIR (Short Wave Infra-Red) spectral bands of the Landsat-8 OLI sensor. The two datasets were merged into a combined 5 m pixels size dataset through the following steps:

- Resampling of Landsat path mosaics to 5 m pixel size.
- Resolution merge of Landsat-8 Band5 (NIR) and RapidEye Band5 (NIR) where the mean intensity values comes from Landsat while the image sharpness or resolution is defined by RapidEye
- Combination of the 5 m resampled Landsat spectral bands merged with the RapidEye sharpened NIR band into one 5m multispectral dataset to be used for segmentation and segment based classification.

8.2 Segmentation

Segmentation of an image is the process of grouping similar pixels based on spectral, textural and shape properties into homogeneous objects or image segments which are different from the surrounding areas.

Segmentation was performed using the eCognition software from the combined RapidEye and Landsat-8 datasets with 5m pixels. The minimum size of the resulting segments cannot be exactly defined when setting up this process in eCognition. Segment sizes range from single pixels to large homogeneous areas which are classified into a single class in the following steps described below. The filtering into the specified 0.5 ha MMU is performed as the final stage after all classification and interpretation work has been done.

8.2.1 Classification and Interpretation

Following the segmentation, the land cover and forest classification was performed in several steps. In the first step the delineation of forest according to the technical product specifications was performed. The second step included the categorization of the forest designated segments into three tree cover classes; 10-30%; 30-80% and > 80% tree cover. These two steps were based on the spectral information from the Landsat-8 image coverage and is representing the status of the forest cover dates corresponding to the of the Landsat-8 images.

In the third step, the non-forest areas were further divided into land cover classes according to the technical specification legend based on the 5m resolution RapidEye images. This involves the classes “settlements”; “surface water bodies”; “grassland”; “shrubs” and “bare soil”.

Additional vector layers of the road network and hydrology were also interpreted from the RapidEye 5 m images.

8.2.2 Forest delineation and classification

The delineation of forest according to the specifications where the forest class is defined based on tree cover density > 10%, tree height > 5 m on the segment level. This definition was used to assign each segment to a forest or non-forest class. This and the subsequent division of the forest area into tree cover density based subclasses were performed using an unsupervised classification k-means clustering method. The cluster classes were then interpreted and labeled with the resulting tree cover classes with 10-30%; 30-80% and > 80% tree cover. Mangrove forests were extracted as a separate class for further refinement.

The forest according to this definition also includes plantations and secondary forest areas meeting this tree cover and tree height criteria.

While the segmentation utilized the full 5m resolution of RapidEye, the classification was based on the spectral information from the Landsat-8 image coverage only within each segment and represents the status of the forest cover at the dates corresponding to the of the Landsat-8 images.

The second step includes the categorization of the forest designated segments into three tree cover classes; 10-30%; 30-80% and > 80% tree cover. These two steps were based on the spectral information from the Landsat-8 image coverage and the result is representing the status of the forest cover corresponding to the dates of the Landsat-8 images.

8.2.3 Land cover classification

All areas outside the forest delineation mask were independently mapped using a combination of Landsat-8 and RapidEye imagery.

Land cover mapping has been carried out following the FAO Land Cover Classification System (LCCS) and employing the GeoVille RegioCover© classification toolbox. Automated image processing and analysis was performed primarily on the optical multispectral Rapid Eye imagery, complemented by the Landsat satellite data in case of data gaps (e.g. cloud cover). RegioCover© is an automated processing chain that assembles state-of-the-art image processing and classification tools using leading industry software packages such as ERDAS Imagine, Definiens eCognition and ESRI ArcGIS.

A combination of unsupervised pixel-based classification and rule-based, object-oriented image segmentation and classification was applied. To consider seasonal changes a multi-temporal coverage of wet and dry season data from the preprocessed EO images was used for the LC classification. A layer-stack of dry season and wet-season imagery was prepared. The resulting images were automatically classified with hybrid unsupervised and supervised pixel based classification techniques using ERDAS IMAGINE Isodata and Maximum Likelihood classifiers.

In summary, the following production steps are performed

1. A pixel based automatic clustering of the RapidEye and Landsat data, leading to a primary, raw classification result containing spectral classes on a pixel basis.
2. Spectral vegetation indices such as the NDVI (Normalized Difference Vegetation Index) are used for a preceding stratification of the area into parts with different vegetation density, which will be separately clustered.
3. These spectral classes are then interpreted in terms of the requested land use/cover classes and coded accordingly.
4. Image segmentation is the second major automatic step, leading to a partition of the image into image objects. Depending on the parameter choice of the segmentation, the object size and internal heterogeneity is determined. The segmentation helps reduce the salt & pepper effect in EO imagery by building small image regions that contain in their edges the mixed transition pixels between different land surface objects. One criterion for the segmentation parameters will be the MMU of 0.5 ha.
5. In the next step, the derived segments are assigned their LU/LC class membership via majority or other rules using the interpreted pixel based classification results.
6. Next, the errors and missing elements of the automatic classification results are corrected primarily using visual interpretation techniques to assure the target accuracy of 90%. Reference information, i.e. the ancillary data layers, is crucial for this step. Especially primary roads and settlements are classes that need ancillary information and/or visual interpretation
7. The filtering of the map by application of the MMU of 0.5 ha finalizes the production of the LC classification.

8.2.4 Merging of Land Cover and Forest Classifications

The next step in the processing was the combination of the two separate segment based mapping results of forest cover classes with the delineated forest mask and the additional land cover classes outside the forest mask. The forest mask was used to control from which of the two datasets the classification result should be selected.

8.2.5 Mangrove interpretation

The interpretation and delineation of mangrove areas was performed as a final manual interpretation step based on the combined Landsat-8 and RapidEye images. The areas interpreted as mangrove em

8.2.6 Road and Hydrologic network

The existing road and river network has been extracted from different sources (e.g. LISGIS, Open Streetmap) and was geometrically improved and updated on the basis of the initial EO image classification and subsequent interpretation of the available satellite images. Connectivity of the network was maintained where possible even when the network was invisible in the satellite data. The road network is provided as separate vector dataset in ESRI shapefile format.

8.3 Pixel MMU Filtering

The MMU or Minimum Mapping Unit of the mapping results is 0.5 ha according to the specifications signed at the April 1024 workshop. The pixel size of the raster map is specified to be 10m.

This has been achieved using the “Clump” function in ERDAS Imagine, where objects were built from neighboring pixels having the same class within a 4-connectivity neighborhood as shown in Figure 4. This was followed by the “Sieve” function where a minimum object size is defined and small objects are filled with the majority of surrounding classes.

An identical result can be achieved using the ArcGIS Spatial Analyst function “RegionGroup” followed by the removal of small objects and filling using the “Nibble” function.

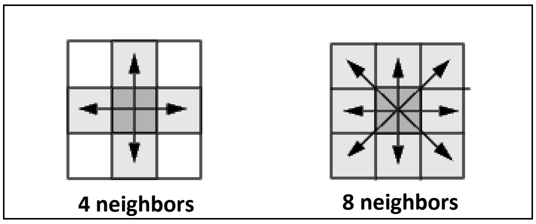


Figure 4. Pixel neighbors according to 4-connectivity definition (left) and 8-connectivity (right)

The MMU filtering was applied to the final merged dataset where all the forest and land cover classes in the Code List were present.

8.4 Project Deliverables

Table 2. Summary of Deliverables

Deliverable	TITLE	Content
D1	Inception report.	Technical report.
D2	Technical specifications.	Technical report.
D3a	Forest and land cover maps in digital format; test area results of appr. 10% of the total area.	Forest and land cover mapping of recent years covering all of Liberia;Map layout in pdf-format.
D3b	Short validation report from the initital 10%.	Report on validation results in pdf-format.
D3c	Forest and land cover maps in digital format; EO data used for mapping.	Forest and land cover mapping of recent years covering all of Liberia; Map layout in pdf-format; Hardcopy maps.
D4	Roadmap for training.	Training material; presentations; sample data; EO-data.
D5	Final and progress reports, including final presentation.	Final technical report; Presentation; Progress reports.

8.5 Land Cover and Forest Map

8.5.1 Digital raster map

The digital raster map data was color coded and exported in a GIS-compatible GeoTiff format for use in standard GIS systems. The class code list is given in Table 3 below.

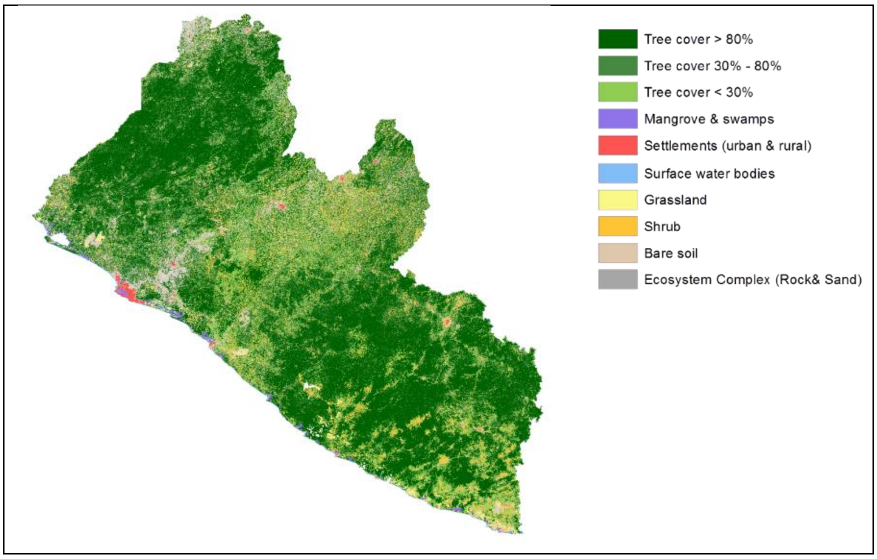


Figure 5 Visualisation of the digital raster map

Table 3. Class code list

Numerical code	Class name
0	NoData (outside Liberia)
1	Forest > 80%
2	Forest 30% - 80%
3	Forest < 30%
4	Mangrove & swamps
5	Settlements (urban & rural)
6	-
7	Surface water bodies
8	Grassland
9	Shrub
10	Bare soil
11	Ecosystem Complex (Rock& Sand)
25	Clouds

Minimum mapping unit is 0.5 ha for all land cover patches and minimum width is 10m for linear elements

8.5.2 Map layout for printing

A full cartographic map layout for A1 sized hard copy printing in scale 1: 825 000 covering all of Liberia was prepared and pdf-files for printing were delivered together with a number of hard copy maps. 4 additional layouts cover a quarter of the country each in scale 1:400 000 were also prepared and delivered as pdf files and hard copy maps. The layout of the nationwide map is shown in Figure 6 below.

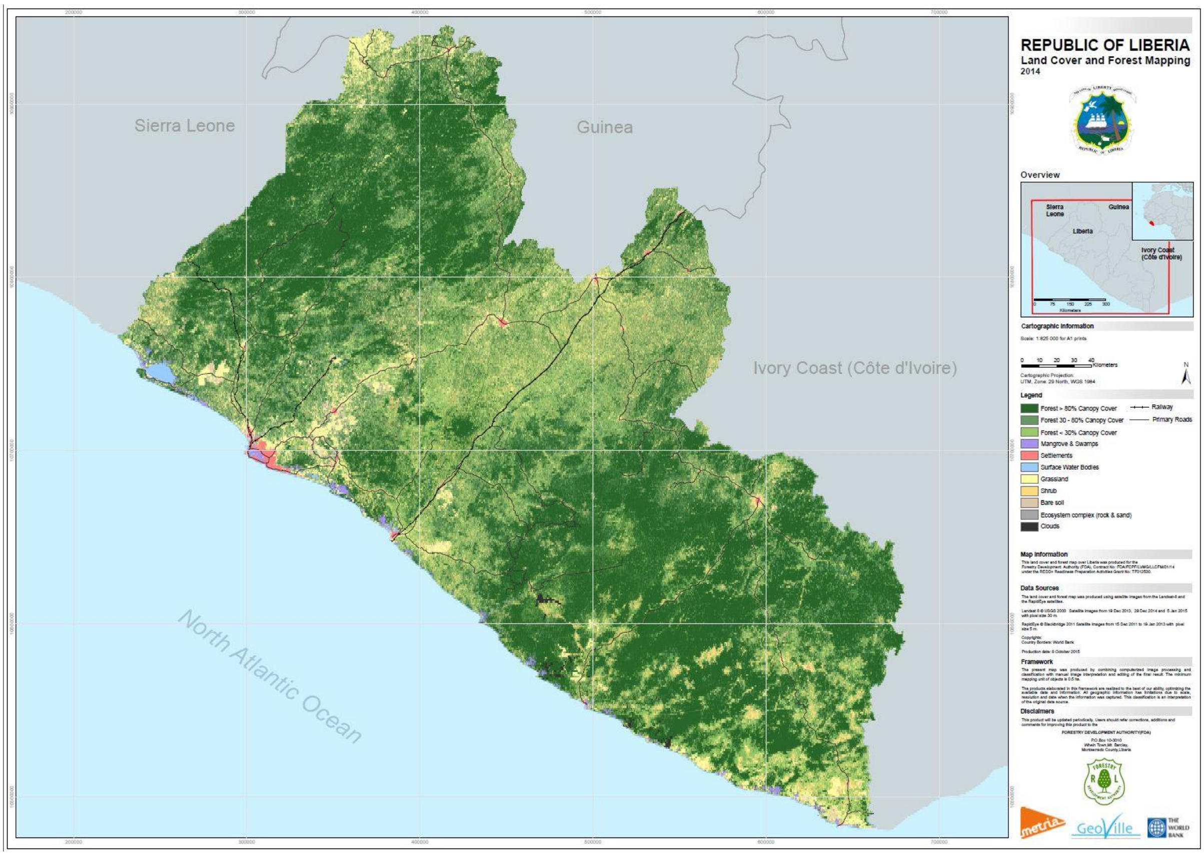


Figure 6. Scale 1:825 000 pdf format map for printing of Liberia Land Cover and Forest Map

8.5.3 Landsat image mosaic

A mosaic of the Landsat-8 images used for the mapping was produced and delivered both as a digital color raster image in GeoTiff- format with the three Infra-red spectral bands of Landsat-8 (near Infra-red and the two middle/short wave infrared) were combined into a color image. Using the infrared bands which are less affected by atmospheric haze than the visible spectral bands, a nearly cloud free and clear image mosaic map could be produced.

8.5.4 Landsat mosaic for printing

The Landsat-8 image mosaic map was also turned into a full cartographic image product in PDF-format suitable for printing in scale 1: 825 000. This map is shown in Figure 7.

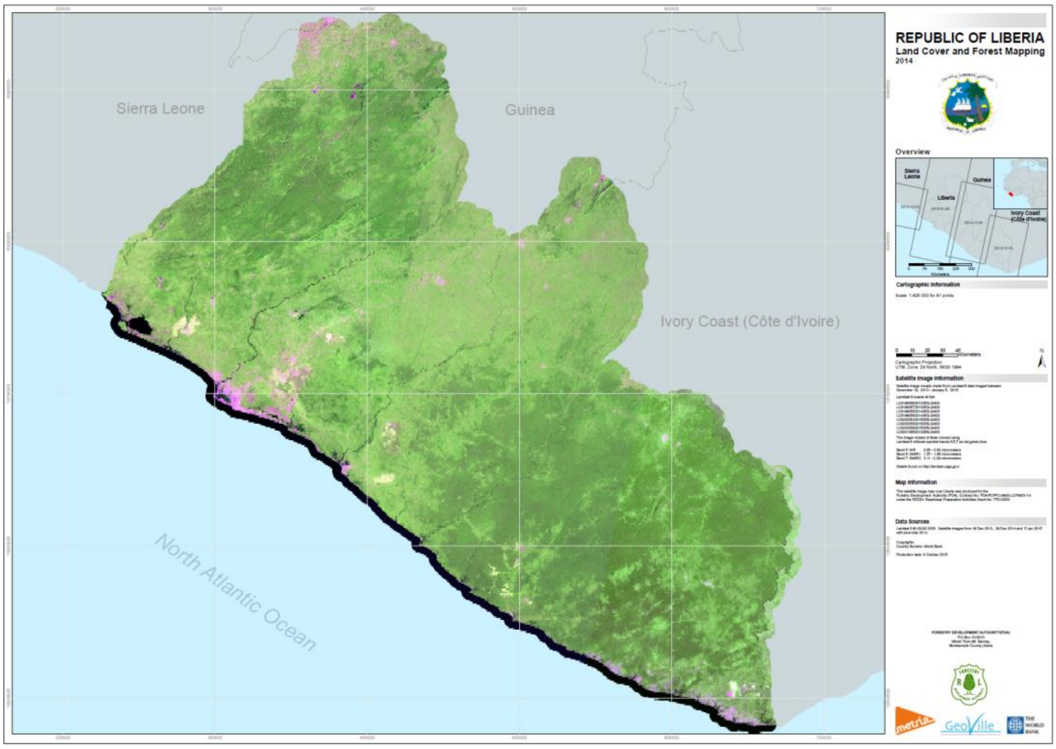


Figure 7. Scale 1:825 000 pdf format Landsat-8 image mosaic map for printing

8.5.5 Road and railway network

The road and railway network was updated with support of the 5 m resolution RapidEye images from December 2011- February 2013 and delivered in vector shapefile format.

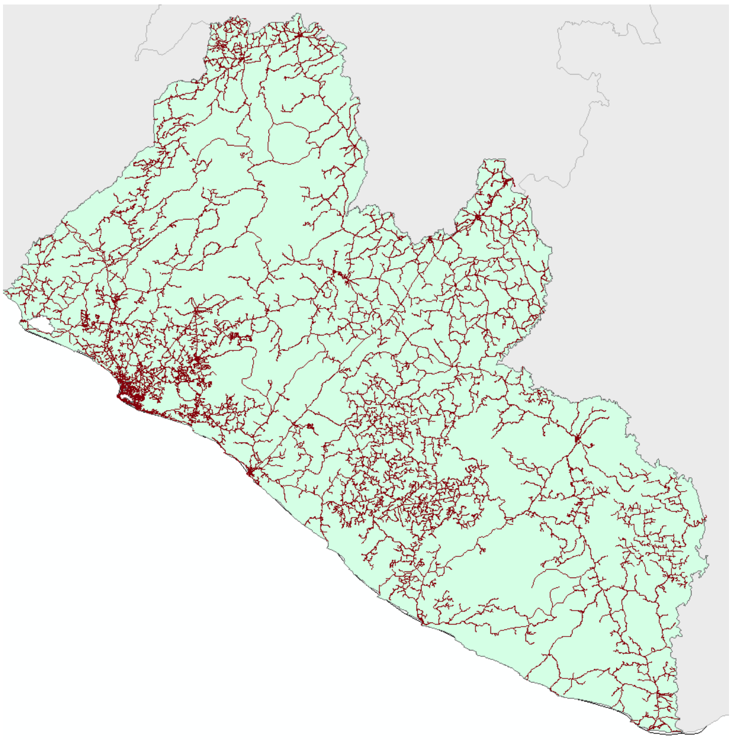


Figure 8. Overview of road and railway network layer

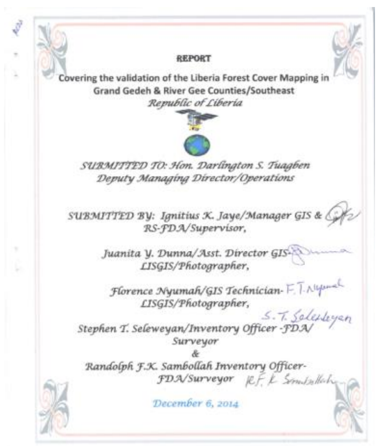
9 Validation results

9.1 Validation Methodology

The target overall thematic accuracy has been agreed to be at least 90% for the forest and land cover classes on domain level.

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 performed in a two-tier approach:

<table>
<tr>
<td>Initial validation / January -February 2015

Initial demo area</td>
<td>A first demonstration map was produced in 2014 for South-Eastern Liberia and validated with the support of an extensive field campaign to the region by local experts. Initial validation was done in early 2015 to support the mapping and initial quality assurance of the results achieved over 10% of the country in South-Eastern Liberia (cf. document Liberia_Validation_report_D1_2015_03_03).
Initial validation was commenced by the JV by setting up a sampling design and validation strategy in mid-2014. FDA has organized a field survey in Eastern Liberia (Grand Cedeh and River Gee counties) to capture in-situ data on forest and land cover in November 2014 (land cover depicted in survey forms, landscape photographs). A field survey report was received by the JV in December 2014.

REPORT
Covering the validation of the Liberia Forest Cover Mapping in Grand Gedeh & River Gee Counties/Southeast
Republic of Liberia
SUBMITTED TO: Hon. Darlington S. Tuagben
Deputy Managing Director/Operations
SUBMITTED BY: Ignitius K. Jaye/Manager GIS & RS-FDA/Supervisor,
Juanita Y. Dunna/Asst. Director GIS-LISGIS/Photographer,
Florence Nyumah/GIS Technician-LISGIS/Photographer,
Stephen T. Seleweyan/Inventory Officer -FDA/ Surveyor
&
Randolph F.K. Sambollah Inventory Officer-FDA/Surveyor
December 6, 2014

FDA TECHNICIANS COLLECTING FIELD DATA

Photograph by field team


Location seen in VHR satellite image
During January 2015, the JV has conducted an intensive initial validation incorporating the field survey data provided and additional reference Earth Observation images lately available via Google Earth. The result of this primary validation has been presented in the initial validation document.</td>
</tr>
<tr>
<td>Country-wide validation / November-December 2015</td>
<td>Country-wide mapping has been performed between May and September 2015. Internal validation was carried out by the producers JV Metria/GeoVille and a dedicated validation report was released in December 2015. The validation was performed by the JV Metria / GeoVille and is considered as an 'internal', i.e. producer-side validation.</td>
</tr>
</table>

For the initial validation of Liberia ground control data collected during the field campaign and visual comparisons with independent satellite data have been used for the evaluation, whereas the final validation was mainly performed on independent interpretation of the forest/land cover from Google Earth and Bing satellite data. The validation of the whole country was implemented using the Laco-Wiki validation tool[2], 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.

9.1.1 Sampling design

For the forest classes, a stratified systematic sampling scheme was created, while for the land cover classes a stratified random point sample was used. The approach is somewhat different to the initial validation as the location of the sample points was not restricted to locations nearby roads or pathways (to allow visitation in the field campaign).

The initial set of 317 samples captured for Eastern Liberia during initial validation was supplemented by additional 2536 samples. For each class, a minimum of 75 points was used to assure representativeness for local conditions and a narrow confidence interval. The overall number of applied sampling points finally comprises a set of 2536+317=2853 samples, 1828 of which were located in the forest domain and 1025 in the rural and particular domain.

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

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

Class name	Number of sampling points applied
Forest > 80%	806
Forest 30-80%	568
Forest <30%	334
Mangroves & Swamps	120
Settlements	241
Surface Water Bodies	120
Grassland	247
Shrubland	216
Bare soil	90
Ecosystem Complex	111
TOTAL	**2853**

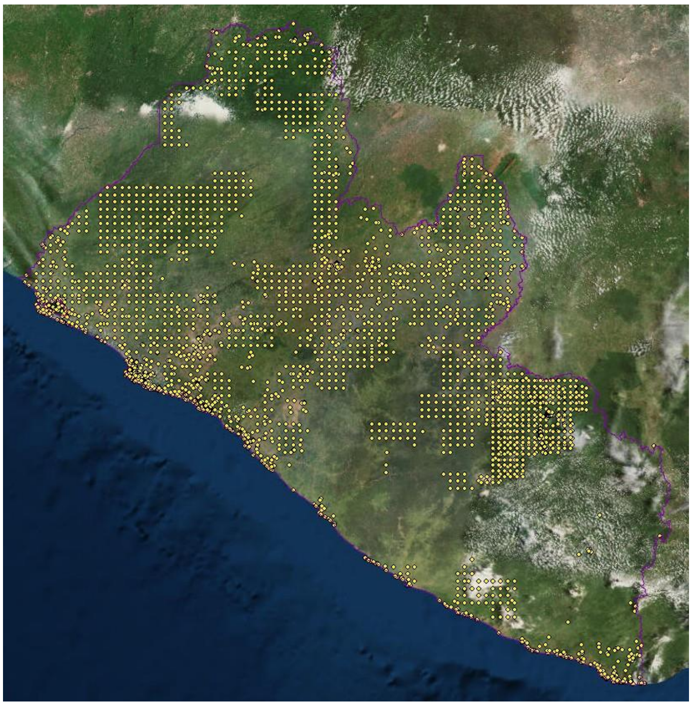


Figure 9: Distribution of sample points
Note: Localisation of sample points is guided by the availability of independent very high resolution reference satellite imagery

Almost 40% of the country is covered by high-quality, cloud-free imagery from Google Earth and Bing Maps, which are not older than 2011, and mostly from 2014 and 2015. In order to account for this limited availability of the reference data, a cluster-based approach needed to be chosen with sample placements only in areas with high-quality reference data (clusters).

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

Additional visual quality assessment confirms the overall high intrinsic consistency of the derived forest and land cover information (no calibration differences in single regions).

9.1.2 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 by 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 around each sample location. For settlements the land use was considered as a settlement area in most cases represents a mixture of land cover classes (building, roads, bare soil, trees located around buildings).

9.1.3 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 forest patches and 10 m width for linear features.

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

Table 5: Overview of domain levels and additional deliverables

Forest domain	Rural & agricultural domain	Particular domain
• **Forest >80%** • **Forest 30-80%** • **Forest <30%** • **Mangrove & swamps**	• Grassland (Savannah) • Shrubs • Ecosystem complex (rocks & sand)	• Settlements • Surface Water Bodies • Bare soil

Roads and elevation classes were not considered for thematic validation, as these were delivered as separate layers.

9.2 Validation Results – Initial 10 percent

The overall accuracy for forest and land cover map from the initial validation amounted to 90.22%, which is above the target threshold of 90%.

Validation of the country-wide product (see below) has revealed improvements compared to the initial mapping area in South-Eastern Liberia, both in terms of user's accuracy (measure of correctness) and producer's accuracy (measure of completeness). While the demonstration product has shown some calibration problems in the transition area of rural to forest domain, with an underrepresentation of low density tree cover areas (erroneously captured as grass- or shrubland), this was improved through better calibration with the field data.

9.3 Internal Validation Results – Nationwide Map

Country-wide validation of the forest and land cover map conducted by the JV Metria/GeoVille reveals an **overall thematic accuracy of 90.57%** on domain level, above the target accuracy of 90%. The map is compliant with the agreed technical specifications.

Overall accuracy can be considered as high, especially when considering the very small mapping units (0.5ha for land cover, 1ha for forest). Remaining errors in the map are predominantly related to confusions between forest and rural land cover classes (65+86 samples), mainly located in the transition areas from forest to rural domain, which is obviously the most difficult part in the satellite-based image classification.

Results are assembled in a confusion matrix (see table below) and various accuracy measures and statistics are calculated:

Table 6: Confusion matrix to show the accuracies in each landscape domain level as well as the overall correctness

Reference → ↓ Classification	Particular	Rural	Forest	Row Total	*User's Accuracy*[3]	*95% Confidence Interval*
Particular	560	31	17	608	92.11%	1.16
Rural	8	344	65	417	82.49%	2.21
Forest	62	86	1680	1828	91.90%	0.68
Column Total	630	461	1762	2853		
Producer's Accuracy[4]	88.89%	74.62%	95.35%		**90.57%**	
95% Confidence Interval	1.38	2.66	0.52			

Overall Accuracy	**90.57%**
Overall 95% Confidence Interval	**0.59**
Kappa	**0.82**

Most errors still persist in the transition area of rural to forest domain. Transitions of trees, shrubs and grassland are the most difficult land cover types to be mapped from satellite imagery, as the spectral response in a satellite image is often very similar. Moreover, such transition areas are often slowly progressing over time and characterized by a very heterogeneous, small-scale pattern of different land cover types (various vegetation lifeforms intermixed with bare or artificial surfaces). Areas with high density tree canopy cover >80%, man-made structures (settlements, agricultural fields) and water surfaces often show a distinct pattern well visible in satellite images.

Further on, as the performed validation was not fully independent, we strongly recommend to take benefit of the knowledge of local experts in the interpretation of the validation samples and perform a full producer-independent validation. Additional GPS field data should be collected similar to the effort made for the demonstration area by the field team. Experience from the initial validation shows that the field data reveals invaluable complementary insight into the local distribution and composition of individual land cover and forest classes.

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

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

10 Training Documentation

In the long-term, effective training on the system shall help Liberian stakeholders to build up an autonomous capacity for putting forward the REDD/REDD+ readiness implementation in Liberia.

A dedicated training for satellite-based Land cover and forest mapping took place at the Liberia Institute of Statistics and Geo-Information Services (LISGIS) in the period from 16 to 20 May 2016. The training was held in accordance to the main objective of this activity - *to enable local experts in using the mapping data generated by the JV for operational applications and to update the forest and land cover mapping, in particular to do forest monitoring and keep track of forest cuttings/clearings* - the focus was set on the following main components

- the core principles of remote sensing and GIS
- how forest and other land cover types look like in a multispectral satellite imagery (spectral bands, spatial resolution)
- the basics of digital mapping in an open-source GIS (QGIS)

and further to

- get a detailed introduction to the geo-information products produced and delivered
- receive hands-on training to apply the methodology for visual interpretation of forest and land cover from satellite imagery
- conduct different processing for preparing, pre- and post-processing of the satellite images and resulting map data
- perform a validation employing independent reference data

An activity plan was distributed prior to the training (cf. Table 7). It was also acknowledged that in case of time constraints, not all items could be covered in full details. The activity plan would be subject to consolidation with the participants during training to ensure focus is set on enabling them in using the mapping data for operational applications and updating the forest and land cover mapping.

Table 7: Activity plan of the Liberia Land cover and forest mapping training at LISGIS (Monrovia).

Day		Activity
Monday 16th of May	**Morning**	Welcome, formal opening and introduction of participants
		Current status of Liberia's activities in REDD+ readiness preparation
	Afternoon	Overview on Liberia Land Cover and Forest Mapping project and its specific contribution to REDD+. Presentation of the Liberia Land Cover and Forest Map 2015.
Tuesday 17th of May	**Morning**	General introduction to satellite-based Earth Observation – sensors and systems relevant for REDD+ MRV
		Introduction to Geographic Information Systems and the open-source QGIS software.
	Afternoon	Installation of the software and data products to the local system is supervised
		Practical hands-on. Introduction to the QGIS graphical user interface, providing insight how to handle, load and display raster and vector datasets
Wednesday 18th of May	**Morning**	Practical hands-on. Introduction to the QGIS graphical user interface, providing insight how to handle, load and display raster and vector datasets
		Practical hands-on. Introduction to access, download and use freely available satellite date from the web
	Afternoon	Practical hands-on. Introduction to manual and unsupervised classification and application by the participants
Thursday 19th of May	**Morning**	Practical hands-on. Introduction to supervised classification and application by the participants
	Afternoon	Practical hands-on. Introduction to post-processing operation final map composition within QGIS
Friday 20th of May	**Morning**	Practical hands-on. Introduction to statistical analysis with QGIs for a region of interest
		Overview to concepts and procedure for validation and accuracy assessment
	Afternoon	Training wrap-up, discussion & training evaluation

10.1 Participants

A list of participants for the Liberia Land cover and forest mapping training at LISGIS is given in 3, along with professional background and institution.

Figure 10: Pictures from the training at LISGIS in Monrovia, Liberia.

10.2 Overall assessment

The user comments and feedback received from the participants at the LISGIS in response to the Liberia Land cover and forest mapping training are positive. The provided training and hold exercises largely meet the expectations of the participants. The overall success and quality of the training was therefore positive and successful.

As the performed training covered a broad range of exercises, highlighting most relevant tools within QGIS to enable the participants to use the mapped data and providing them insights in applying forest monitoring on their own, only a glimpse of the myriad of functionalities within the QGIS could be covered. One week training allows only first impression of functionalities within a GIS and the potential for mapping of forest and land cover from satellite data. However, all defined requirements could be covered, giving the participants insight on how using QGIS, referring to their data or satellite images in order to extract relevant information for their region of interest. Due to the heterogeneity of the group composition regarding technical GIS knowledge, a one week training and associated exercises revealed to be too much work for several participants.

Several participants expressed the wish for a continuation of the training in order to improve their skills. Especially interest was stated to further deepen insight into processing and image classification techniques, statistical analysis as well as into the manifold processing utilities of QGIS. This could be covered by an additional, advanced course.

11 Conclusions and Outlook

Suitability for MRV of REDD+

In general, the Land Cover and Forest Map data of Liberia was produced with the primary aim of advancing the REDD readiness work of FDA, specifically to generate the baseline information required for the Monitoring Reporting and Verification (MRV) System that will track the temporal and spatial changes in forest cover and associated drivers of deforestation and degradation.

At the time of the project implementation and map production with delivery in December 2015, Liberia did not 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.*"

While the Land Cover and Forest Map data of Liberia produced under this contract includes a 30% minimum forest cover class which was mapped at a 0.5 ha minimum mapping unit, it does not exclude industrial agricultural plantations from its forest class, as this was not identified to be of importance at the time the map specifications were set by FDA. The exclusion of the industrial agricultural plantations and the forest cover class with less than 30% cover means the remaining forest areas must be generalized according to the 1 ha MMU after this step has been performed in order to be compliant.

The produced map data is therefore **not fully compliant with the Liberia's National Forest Definition** and **not suitable as baseline for MRV**, as significant areas of the mapped forest is covered by industrial oil palm and rubber tree plantations as well as areas with forest cover less than 30%.

It is still technically feasible to adapt the produced map to the new forest definition through the following steps:

1. Separation of industrial rubber and oil palm plantations from natural forest area using a semi-automated classification approach. Rubber tree plantations may be identified by automatic methods while the identification of oil palm plantations requires additional manual interpretation work.
2. Thematic reclassification based on the thematic classes of the currently produced map. This involves
    a. renaming the current class "Forest <30% Canopy Cover" into a suitable non forest class name;
    b. introducing new classes industrial plantations separated into areas with low and high tree cover and alternatively also separated into rubber and oil palm plantations;
    c. inclusion of the mangrove class into the forest area.
3. Aggregation of forest areas to the 1 ha MMU. This involves several steps.
    a. Combining of all classes into one single temporary forest / non-forest map;
    b. Applying the 1 ha MMU filter to this forest/ non-forest map;
    c. Reclassifying all resulting forest areas into the separate forest classes of the intermediate full legend map;
    d. Reclassifying all non-forest areas into the separate non-forest classes of the intermediate full legend map;

The reason for these complex MMU filtering steps is to ensure that the 1 ha MMU is applicable to the forest area. This also means that the subclasses of forest or non-forest areas will include single class areas smaller than 1 ha although the 1 ha MMU rule is applicable to the forest/non-forest.

4. In addition, the separately delivered road and railway network could be updated through manual interpretation using the satellite data acquired at later dates used for performing the work in steps 1-3 above.

Suitability for other users

As a result of the above listed steps to update the map to comply with the agreed forest definition, the updated map will also be better suited for alternative uses within other thematic than the REDD+.

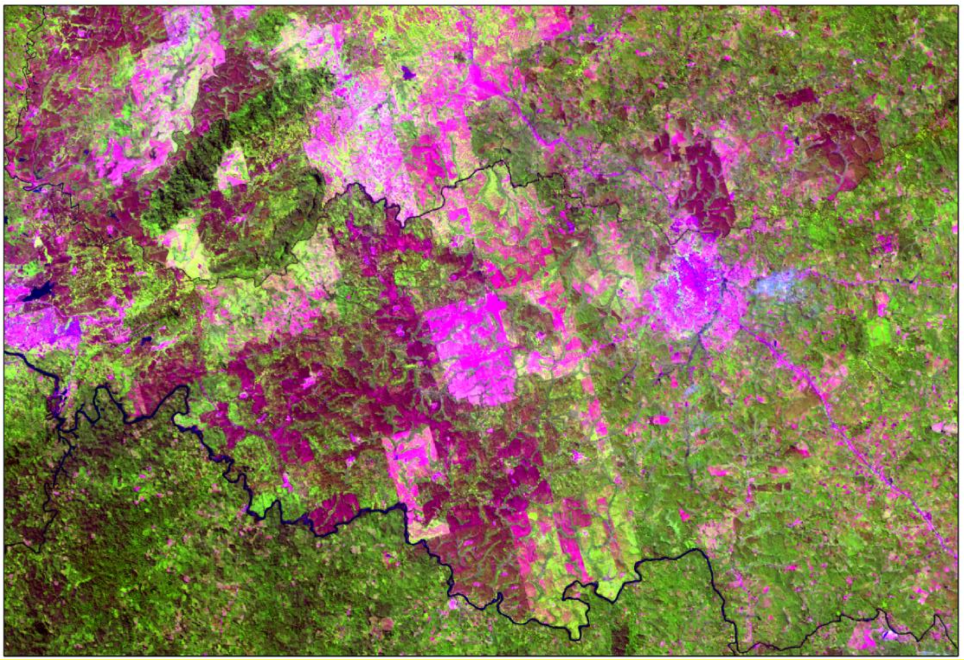


Figure 11. Sentinel-2 composite of area in Margibi, identifying rubber tree and oil palm plantations as dark purple.

Moreover, such an update would lend itself to estimate changes in forest area at national level, as required for MRV, as well as estimate activity data for forest degradation. Ideally, such procedures would be built into an open-source software solution, capable of closing the fully cycle of MRV requirements (ie. comprehensive Forest Information System, enabling FDA staff to automatically establish and report forest activity data, Figure 12).

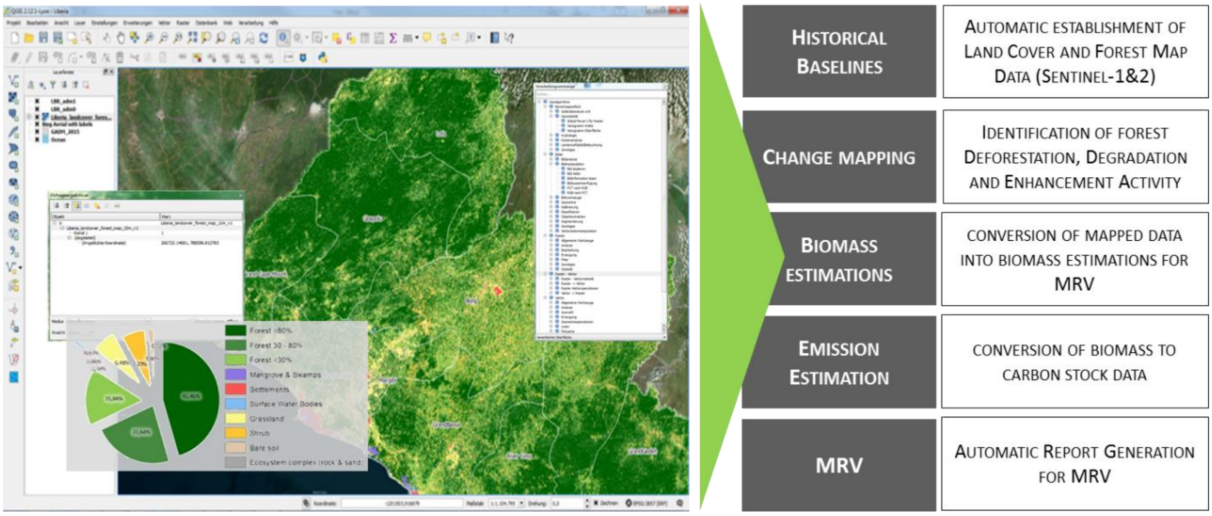


Figure 12. JV GeoVille/Metria National Forest Monitoring and MRV System based on QGIS PlugIn and pre-processed Sentinel satellite data stream.

Recommendations

Along the defined roadmap actions for setting up a National Forest Monitoring and MRV System to support REDD+ participation of Liberia[5], we **recommend to update the produced Land Cover and Forest Map data of Liberia to exclude industrial oil palm and rubber tree plantations from the forest classes**. The new Sentinel-2 satellite of the European Commission, providing cost fee data and a full coverage of entire Liberia every 10 days, is particularly well suited to cost-efficiently implement such post-mapping procedure (eg. Figure 11).

This will also give the opportunity to revise the MMU according to the new forest definition of more than 30% forest cover.

We also recommend that efforts should also be put on **renaming the thematic classes** of the revised map in order to minimize the risk of misinterpreting the mapping results when used for other purposes then the REDD+ activities.

In addition we also **recommend the updating of the road and railway network is** using the same imagery as for the Land cover and forest map update for the interpretation of new roads.

As a result from the training held in Monrovia in May 2016, substantial interest was raised by participants to receive **additional focused and deepened training** aiming at further increasing the local capabilities. This could address a smaller team of GIS professionals on site for a longer session (2-3 weeks) in order to start the build up of long term local expertise in handling and analysing the satellite data for REDD+/MRV in Liberia.

[5] "Terms of Reference for Developing Capacities for a National Forest Monitoring and Measurement, Reporting and Verification System to support REDD+ participation of Liberia", Background, Capacity Assessment and Roadmap, *Final draft, January 12, 2015*

Annex 1 – Signed Technical Specifications

Thematic content for nationwide forest and land cover mapping 2014-05-01

	Land Cover (Bayol 2004)	Liberia Land Cover 2013
Forest domain	• Closed dense forest • Open dense forest • Agriculture degraded forest	• Forest >80% • Forest 30-80% • Forest <30%
Rural, agricultural and particular domain	• Predominant rural agricultural domain • Agricultural areas with small forest presence • Mixed agricultural and forest area • Agroindustrial plantation	• Mangrove & swamps

	• Urban Area
	• Free water
	• Major river
	• Savannah or bare soil
	• Coastal ecosystem complex
	• Mountains
		• Settlements
		  • Urban (>2500 inhabitants – provided ancillary data by LISGIS)
		  • Rural (< 2500 inhabitants)
		• Hydrology
		• Grassland (Savannah) & Shrubs
		• Bare soil
		• Ecosystem complex (rocks & sand)
		• Slope classes (<10%, 10-20 %, 20-30 %, 30-90 % separate layer
		• Altitude (separate layer)

	• Main public road
	• Secondary public road
	• Main forestry road
	• Secondary forestry road
		• Road and railway network (* provided ancillary data, to be amended by interpretation)
		  • Primary road
		  • Secondary road
		  • Tracks

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Minimum mapping unit 0,5 hectares and minimum width 10 m

[signature]
May 26, 2014

Updated version (2014-07-05)

Liberia Land Cover 2013
• Forest >80% • Forest 30-80% • Forest <30%
Note: Agricultural domain differentiated according to land cover (bare soil, grassland, shrubs, forest) • Mangrove & swamps

• Settlements
  • Urban (>2500 inhabitants – provided ancillary data by LISGIS)
  • Rural (< 2500 inhabitants)
• Surface Water Bodies
• Grassland (Savannah) & Shrubs
• Bare soil
• Ecosystem complex (rocks & sand)
• Slope classes (<10%, 10-20 %, 20-30 %, >30 %; separate layer
• Elevation (separate layer)

• Road and railway network (* provided ancillary data, to be amended by interpretation)
  • Primary road (paved)
  • Secondary road (unpaved)
  • Tracks (backroads)
  • Railways

Minimum mapping unit is 0,5 ha for all land cover patches and minimum width is 10m for linear elements

Annex 2 – Description of class content according to LCCS standard

<table>
<tr><th rowspan="2">Classes for Liberia forest and land cover mapping</th><th colspan="4">Class Content according to LCCS</th></tr>
<tr><th>Classifier 1: Presence of vegetation</th><th>Classifier 2: Edaphic condition</th><th>Classifier 3: Artificiality of cover</th><th>Environmental Classifiers</th></tr>
<tr><td>Forest >80%</td><td rowspan="5">Primarily vegetated</td><td rowspan="4">Terrestrial</td><td>Natural & semi-natural vegetation or cultivated & managed areas</td><td>• Life form: trees
• Cover: closed >80%</td></tr>
<tr><td>Forest 30-80%</td><td>Natural & semi-natural vegetation or cultivated & managed areas</td><td>• Life form: trees
• Cover: open 30-80%</td></tr>
<tr><td>Forest <30%</td><td>Natural & semi-natural vegetation or cultivated & managed areas</td><td>• Life form: trees
• Cover: sparse <30%</td></tr>
<tr><td>Grassland (Savannah) & Shrubs</td><td>Natural & semi-natural vegetation or cultivated & managed areas</td><td>• Life form: shrubs / herbaceous / graminoids</td></tr>
<tr><td>Mangrove & swamps</td><td>Aquatic or regularly flooded</td><td>Natural & semi-natural vegetation or cultivated aquatic or regularly flooded areas</td><td>• Life form: trees / shrubs
• Water seasonality: water logged</td></tr>
<tr><td>Surface Water Bodies</td><td rowspan="8">Primarily non-vegetated</td><td>Aquatic or regularly flooded</td><td>Natural or artificial waterbodies</td><td>• Physical status: water (standing or flowing)</td></tr>
<tr><td>Bare soil</td><td rowspan="7">Terrestrial</td><td rowspan="2">Bare areas</td><td>• Surface aspect: unconsolidated bare soil</td></tr>
<tr><td>Ecosystem complex (rocks & sand)</td><td>• Surface aspect: consolidated rock or sands</td></tr>
<tr><td>Settlements</td><td rowspan="5">Artificial surfaces</td><td>• Surface aspect: built-up, non-linear</td></tr>
<tr><td>Primary road (paved)</td><td>• Surface aspect: built-up, linear
• Road, paved</td></tr>
<tr><td>Secondary road (unpaved)</td><td>• Surface aspect: built-up, linear
• Road, unpaved</td></tr>
<tr><td>Tracks (backroads)</td><td>• Surface aspect: built-up, linear
• Road, unpaved</td></tr>
<tr><td>Railways</td><td>• Surface aspect: built-up, linear
• Railway, unpaved</td></tr>
<tr><td>Elevation (separate layer)</td><td colspan="3" rowspan="2">Additional LCCS attribute</td><td rowspan="2">• Land form / elevation classes
• Slope classes: flat / undulating / rolling / hilly / mountaineous</td></tr>
<tr><td>Slope classes (<10%, 10-20 %, 20-30 %, >30 %; separate layer</td></tr>
</table>

Annex 3 – Participants to training at LISGIS, May 2016

First name	Last name	Institution	Background
Omega J.	Paye	FDA	GIS Officer
George T.	Kardar	LISGIS	Cartographer
Bleedee Jr.	J. Wrobeh	FDA	General forestry
Victoria	Z. Karlon	FDA	Inventory officer
Randolph	F.K. Sambolah	FDA	Forestry - forest inventory officer
Daniel	G. Teah	FDA	Forestry - forest inventory officer
Stephen	Seleweyan	FDA	Forestry - forest inventory officer
Torwon T.	Yantay	SCNL	Geographer - GIS technician
Andy	Tugbah	LISGIS	GIS assistant
P. Albert	Gebeh	LISGIS	Demographer / GIS technician
Anthony F.S.	Dymacole	LISGIS	Demographer / assistant statistician
Edmund C.	Kaine	ILTF / Land Commission	Data analyst / GIS officer
Whymah M.	Goyanvator	FDA	Forestry / RS & GIS / acting GIS manager
Pesoe M.	Greene	FDA	Forestry/ RS & GIS student
Arthur B.	Cassell III	SDI	Application development / GIS
James	Valenza	SDI	GIS
Gordon B.	Sambola	SCNL	Conservationist
Jenebu	Toure	LISGIS	GIS technician
Kayloe R.	Frank	LISGIS	GIS technician
Thomas I.	Davis	LISGIS	Director - Geo-Information services
James Akio	Kollie Jr.	University of Liberia	General forestry
Weegie	Mulbah	University of Liberia	General forestry
Garwolo F.	Gbazawulu	University of Liberia	General forestry
Michael P.	Bohlen	University of Liberia	Lecturer
Jerry S.	Yekeh	University of Liberia	Lecturer
John K.	Jallah Jr.	EPA	Assistant manager, environmental research and standards